An Enactive Approach to Perceptual Augmentation in Mobility

Dissertation

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Abstract

Event predictions are an important constituent of situation awareness, which is a key objective for many applications in human-machine interaction, in particular in driver assistance. This work focuses on facilitating event predictions in dynamic environments. Its primary contributions are 1) the theoretical development of an approach for enabling people to expand their sampling and understanding of spatiotemporal information, 2) the introduction of exemplary systems that are guided by this approach, 3) the empirical investigation of effects functional prototypes of these systems have on human behavior and safety in a range of simulated road traffic scenarios, and 4) a connection of the investigated approach to work on cooperative human-machine systems. More specific contents of this work are summarized as follows:

The first part introduces several challenges for the formation of situation awareness as a requirement for safe traffic participation. It reviews existing work on these challenges in the domain of driver assistance, resulting in an identification of the need to better inform drivers about dynamically changing aspects of a scene, including event probabilities, spatial and temporal distances, as well as a suggestion to expand the scope of assistance systems to start informing drivers about relevant scene elements at an early stage. Novel forms of assistance can be guided by different fundamental approaches that target either replacement, distribution, or augmentation of driver competencies. A subsequent differentiation of these approaches concludes that an augmentation-guided paradigm, characterized by an integration of machine capabilities into human feedback loops, can be advantageous for tasks that rely on active user engagement, the preservation of awareness and competence, and the minimization of complexity in human-machine interaction. Consequently, findings and theories about human sensorimotor processes are connected to develop an enactive approach that is consistent with an augmentation perspective on human-machine interaction. The approach is characterized by enabling drivers to exercise new sensorimotor processes through which safety-relevant spatiotemporal information may be sampled.

In the second part of this work, a concept and functional prototype for augmenting the perception of traffic dynamics is introduced as a first example for applying principles of this enactive approach. As a loose expression of functional biomimicry, the prototype utilizes a tactile interface that communicates temporal distances to potential hazards continuously through stimulus intensity. In a driving simulator study, participants quickly gained an intuitive understanding of the assistance without instructions and demonstrated higher driving safety in safety-critical highway scenarios. But this study also raised new questions such as whether benefits are due to a continuous time-intensity encoding and whether utility generalizes to intersection scenarios or highway driving with low criticality events. Effects of an expanded assistance prototype with lane-independent risk assessment and an option for binary signaling were thus investigated in a separate driving simulator study. Subjective responses confirmed quick signal understanding and a perception of spatial and temporal stimulus characteristics. Surprisingly, even for a binary assistance variant with a constant intensity level, participants reported perceiving a danger-dependent variation in stimulus intensity. They further felt supported by the system in the driving task, especially in difficult situations. But in contrast to the first study, this support was not expressed by changes in driving safety, suggesting that perceptual demands of the low criticality scenarios could be satisfied by existing driver capabilities. But what happens if such basic capabilities are impaired, e.g., due to poor visibility conditions or other situations that introduce perceptual uncertainty? In a third driving simulator study, the driver assistance was employed specifically in such ambiguous situations and produced substantial safety advantages over unassisted driving. Additionally, an assistance variant that adds an encoding of spatial uncertainty was investigated in these scenarios. Participants had no difficulties to understand and utilize this added signal dimension to improve safety. Despite being inherently less informative than spatially precise signals, users rated uncertainty-encoding signals as equally useful and satisfying. This appreciation for transparency of variable assistance reliability is a promising indicator for the feasibility of an adaptive trust calibration in human-machine interaction and marks one step towards a closer integration of driver and vehicle capabilities.

A complementary step on the driver side would be to increase transparency about the driver's mental states and thus allow for mutual adaptation. The final part of this work discusses how such prerequisites of cooperation may be achieved by monitoring mental state correlates observable in human behavior, especially in eye movements. Furthermore, the outlook for an addition of cooperative features also raises new questions about the bounds of identity as well as practical consequences of human-machine systems in which co-adapting agents may exercise sensorimotor processes through one another.

Zusammenfassung

Die Vorhersage von Ereignissen ist ein Bestandteil des Situationsbewusstseins, dessen Unterstützung ein wesentliches Ziel diverser Anwendungen im Bereich Mensch-Maschine Interaktion ist, insbesondere in der Fahrerassistenz. Diese Arbeit zeigt Möglichkeiten auf, Menschen bei Vorhersagen in dynamischen Situationen im Straßenverkehr zu unterstützen. Zentrale Beiträge der Arbeit sind 1) eine theoretische Auseinandersetzung mit der Aufgabe, die menschliche Wahrnehmung und das Verständnis von raum-zeitlichen Informationen im Straßenverkehr zu erweitern, 2) die Einführung beispielhafter Systeme, die aus dieser Betrachtung hervorgehen, 3) die empirische Untersuchung der Auswirkungen dieser Systeme auf das Nutzerverhalten und die Fahrsicherheit in simulierten Verkehrssituationen und 4) die Verknüpfung der untersuchten Ansätze mit Arbeiten an kooperativen Mensch-Maschine Systemen. Die Arbeit ist in drei Teile gegliedert:

Der erste Teil stellt einige Herausforderungen bei der Bildung von Situationsbewusstsein vor, welches für die sichere Teilnahme am Straßenverkehr notwendig ist. Aus einem Vergleich dieses Überblicks mit früheren Arbeiten zeigt sich, dass eine Notwendigkeit besteht, Fahrer besser über dynamische Aspekte von Fahrsituationen zu informieren. Dies umfasst unter anderem Ereigniswahrscheinlichkeiten, räumliche und zeitliche Distanzen, sowie eine frühere Signalisierung relevanter Elemente in der Umgebung.
Neue Formen der Assistenz können sich an verschiedenen grundlegenden Ansätzen der Mensch-Maschine Interaktion orientieren, die entweder auf einen Ersatz, eine Verteilung oder eine Erweiterung von Fahrerkompetenzen abzielen. Die Differenzierung dieser Ansätze legt den Schluss nahe, dass ein von Kompetenzerweiterung geleiteter Ansatz für die Bewältigung jener Aufgaben von Vorteil ist, bei denen aktiver Nutzereinsatz, die Erhaltung bestehender Kompetenzen und Situationsbewusstsein gefordert sind. Im Anschluss werden Erkenntnisse und Theorien über menschliche sensomotorische Prozesse verknüpft, um einen enaktiven Ansatz der Mensch-Maschine Interaktion zu entwickeln, der einer erweiterungsgeleiteten Perspektive Rechnung trägt. Dieser Ansatz soll es Fahrern ermöglichen, sicherheitsrelevante raum-zeitliche Informationen über neue sensomotorische Prozesse zu erfassen.

Im zweiten Teil der Arbeit wird ein Konzept und funktioneller Prototyp zur Erweiterung der Wahrnehmung von Verkehrsdynamik als ein erstes Beispiel zur Anwendung der Prinzipien dieses enaktiven Ansatzes vorgestellt. Dieser Prototyp nutzt vibrotaktile Aktuatoren zur Kommunikation von Richtungen und zeitlichen Distanzen zu möglichen Gefahrenquellen über die Aktuatorposition und -intensität. Teilnehmer einer Fahrsimulationsstudie waren in der Lage, in kurzer Zeit ein intuitives Verständnis dieser Assistenz zu entwickeln, ohne vorher über die Funktionalität unterrichtet worden zu sein. Sie zeigten zudem ein erhöhtes Maß an Fahrsicherheit in kritischen Verkehrssituationen. Doch diese Studie wirft auch neue Fragen auf, beispielsweise, ob der Sicherheitsgewinn auf kontinuierliche Distanzkodierung zurückzuführen ist und ob ein Nutzen auch in weiteren Szenarien vorliegen würde, etwa bei Kreuzungen und weniger kritischem longitudinalen Verkehr. Um diesen Fragen nachzugehen, wurden Effekte eines erweiterten Prototypen mit spurunabhängiger Kollisionsprädiktion, sowie einer Option zur binären Kommunikation möglicher Kollisionsrichtungen in einer weiteren Fahrsimulatorstudie untersucht. Auch in dieser Studie bestätigen die subjektiven Bewertungen ein schnelles

Verständnis der Signale und eine Wahrnehmung räumlicher und zeitlicher Signalkomponenten. Überraschenderweise berichteten Teilnehmer größtenteils auch nach der Nutzung einer binären Assistenzvariante, dass sie eine gefahrabhängige Variation in der Intensität von taktilen Stimuli wahrgenommen hätten. Die Teilnehmer fühlten sich mit beiden Varianten in der Fahraufgabe unterstützt, besonders in Situationen, die von ihnen als kritisch eingeschätzt wurden. Im Gegensatz zur ersten Studie hat sich diese gefühlte Unterstützung nur geringfügig in einer messbaren Sicherheitsveränderung widergespiegelt. Dieses Ergebnis deutet darauf hin, dass die Wahrnehmungsanforderungen der Szenarien mit geringer Kritikalität mit den vorhandenen Fahrerkapazitäten erfüllt werden konnten.
Doch was passiert, wenn diese Fähigkeiten eingeschränkt werden, beispielsweise durch schlechte Sichtbedingungen oder Situationen mit erhöhter Ambiguität? In einer dritten Fahrsimulatorstudie wurde das Assistenzsystem in speziell solchen Situationen eingesetzt, was zu substantiellen Sicherheitsvorteilen gegenüber unassistiertem Fahren geführt hat. Zusätzlich zu der vorher eingeführten Form wurde eine neue Variante des Prototyps untersucht, welche räumliche Unsicherheiten der Fahrzeugwahrnehmung in taktilen Signalen kodiert. Studienteilnehmer hatten keine Schwierigkeiten, diese zusätzliche Signaldimension zu verstehen und die Information zur Verbesserung der Fahrsicherheit zu nutzen. Obwohl sie inherent weniger informativ sind als räumlich präzise Signale, bewerteten die Teilnehmer die Signale, die die Unsicherheit übermitteln, als ebenso nützlich und zufriedenstellend. Solch eine Wertschätzung für die Transparenz variabler Informationsreliabilität ist ein vielversprechendes Indiz für die Möglichkeit einer adaptiven Vertrauenskalibrierung in der Mensch-Maschine Interaktion. Dies ist ein Schritt hin zur einer engeren Integration der Fähigkeiten von Fahrer und Fahrzeug.

Ein komplementärer Schritt wäre eine Erweiterung der Transparenz mentaler Zustände des Fahrers, wodurch eine wechselseitige Anpassung von Mensch und Maschine möglich wäre.
Der letzte Teil dieser Arbeit diskutiert, wie diese Transparenz und weitere Voraussetzungen von Mensch-Maschine Kooperation erfüllt werden könnten, indem etwa Korrelate mentaler Zustände, insbesondere über das Blickverhalten, überwacht werden. Des Weiteren ergeben sich mit Blick auf zusätzliche kooperative Fähigkeiten neue Fragen über die Definition von Identität, sowie über die praktischen Konsequenzen von Mensch-Maschine Systemen, in denen ko-adaptive Agenten sensomotorische Prozesse vermittels einander ausüben können.

Preface

This thesis presents research I conducted at the Honda Research Institute Europe (HRI-EU). At HRI-EU my research was supervised by Heiko Wersing and supported by Frank Joublin as an independent academic advisor. Through participation in the Doctoral Consortium of the international conference on *Automotive User Interfaces and Interactive Vehicular Applications*, I got to know Lewis Chuang, who introduced me to the *Human-Centered Ubiquitous Media* group led by Albrecht Schmidt at the Ludwig-Maximilians-Universität Munich (LMU). I joined this group as an external doctoral researcher under the supervision and guidance of Albrecht Schmidt and Lewis Chuang. This thesis is partially based on a series of publications that have resulted from collaborations with multiple researchers. In the corresponding chapters I have used the scientific plural in reference to this collaborative nature. For the remaining chapters I have chosen to use an impersonal style to put the focus on the content.

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CONTENTS

Abstract v

Zusammenfassung vii

Preface ix

Acknowledgements xi

1 Introduction 1
1.1 Dissertation Outline . . . 1
1.1.1 Part I: From Driver Awareness Challenges to Augmented Perception . . 2
1.1.2 Part II: The Lateral Line: Biomimetic Augmentation of Driver Awareness 3
1.1.3 Part III: Beyond Driver Awareness Augmentation . . . 4
1.1.4 Contributions . . . 4
1.2 Contributing Publications . . . 4
1.2.1 Primary Publications . . . 5
1.2.2 Auxiliary Publications . . . 6

I From Driver Awareness Challenges to Augmented Perception **11**

2 Challenges in Forming Situation Awareness While Driving 13
2.1 Why Driving Can Be Difficult . . . 14
2.1.1 Situation Awareness . . . 14
2.1.2 Perception Challenges . . . 15
2.1.3 Comprehension Challenges . . . 19
2.1.4 Projection Challenges . . . 22
2.2 Supporting Situation Awareness with Driver Assistance Systems . . . 28
2.2.1 Why Driving Can Still Be Difficult . . . 30
2.3 Chapter Summary . . . 33

3 Three Approaches to Driver Assistance 35
3.1 Publication Disclosure . . . 36
3.1.1 Bibliographic Information . . . 36
3.1.2 Author's Contribution . . . 36
3.2 Substitution . . . 37
3.2.1 Substitution Opportunities . . . 37

3.2.2 Substitution Challenges . . . 38
3.3 Cooperation . . . 39
3.3.1 Cooperative Driver Assistance . . . 40
3.3.2 Cooperation Definitions . . . 41
3.3.3 The Price of Cooperation . . . 41
3.4 Augmentation . . . 42
3.4.1 Augmentation in Driving . . . 45

4 Enacting a World of Anticipations 47
4.1 Reafference . . . 48
4.1.1 Reafference Theory . . . 49
4.2 Information . . . 50
4.2.1 Multimodal Integration . . . 50
4.3 Sensory Modalities . . . 51
4.4 Enaction . . . 52
4.5 Augmented Driving as a Sensorimotor Process . . . 54
4.5.1 Sampling from the Future . . . 55

II The Lateral Line: Biomimetic Augmentation of Driver Awareness 57

5 Improving Driving Safety through Tactile Perception of Traffic Dynamics 59
5.1 Publication Disclosure . . . 60
5.1.1 Bibliographic Information . . . 61
5.1.2 Author's Contribution . . . 61
5.1.3 Copyright Notice . . . 61
5.2 Introduction . . . 62
5.2.1 The Lateral Line . . . 62
5.3 Concept . . . 63
5.3.1 Application Scenario . . . 64
5.3.2 Interface . . . 65
5.4 Methods . . . 67
5.4.1 Participants . . . 67
5.4.2 Experimental Setup . . . 67
5.4.3 Procedure . . . 69
5.4.4 Experimental Blocks and Trials . . . 69
5.4.5 System Exploration Block . . . 70
5.4.6 Independent Variables . . . 70
5.4.7 Dependent Measures . . . 71
5.4.8 Hypotheses . . . 71
5.5 Results . . . 72
5.5.1 Trial Validity . . . 72
5.5.2 Subjective Understanding and Utility . . . 73
5.5.3 Safety . . . 73
5.5.4 Velocity . . . 75

5.6 Discussion 76
5.7 Chapter Summary 78

6 Direction and Temporal Distance Encoding 79
6.1 Publication Disclosure 81
6.1.1 Bibliographic Information 81
6.1.2 Author's Contribution 81
6.1.3 Copyright Notice 81
6.2 Introduction 82
6.2.1 Open Questions 82
6.2.2 Research Hypotheses 83
6.3 Materials and Methods 84
6.3.1 Tactile Interface 84
6.3.2 Stimulus Encoding 85
6.3.3 Driving Simulator 87
6.3.4 Data Acquisition 88
6.3.5 Data Analysis 92
6.4 Results 94
6.4.1 Subjective Reports 94
6.4.2 Driver Behavior 99
6.5 Discussion 102
6.5.1 Subjective Effects 102
6.5.2 Objective Effects 103
6.5.3 Binary and Continuous Stimuli 104
6.5.4 Long-Term Exposure 106
6.5.5 LLI Function Expansion 107
6.6 Chapter Summary 108

7 Spatial Ambiguity 109
7.1 Publication Disclosure 111
7.1.1 Bibliographic Information 111
7.1.2 Author's Contribution 111
7.1.3 Copyright Notice 111
7.2 Introduction 112
7.2.1 Related Work 112
7.2.2 Current Study 114
7.3 Materials and Methods 115
7.3.1 Participants 115
7.3.2 Experimental Setup 115
7.3.3 Stimuli 116
7.3.4 Experimental Design 118
7.3.5 Procedure 119
7.3.6 Analysis 123
7.4 Results 126
7.4.1 Subjective Reports 126

7.4.2 Gaze Distribution - H2 (Subjective Benefit) and H4 (Safety) 130
7.4.3 Trial Safety - H4 (Safety) 131
7.5 Discussion 132
7.5.1 Signal Understanding and Experiment Validation 132
7.5.2 Uncertainty Signaling in Human Uncertain Conditions 133
7.5.3 Uncertainty Signaling in Human Certain Conditions 134
7.5.4 Limitations 134
7.6 Chapter Summary 135

III Beyond Driver Awareness Augmentation 137

8 Cooperative Driver Support 139
8.1 Publication Disclosure 140
8.1.1 Bibliographic Information 140
8.1.2 Author’s Contribution 141
8.2 Open Challenges 142
8.3 A Window to the Mind 142
8.3.1 Passive Gaze Monitoring 143
8.3.2 Active Gaze-Based Communication 143
8.3.3 Cooperative Eyes 144
8.4 Reaching Limits 145
8.5 Inclusivity 145

9 Conclusions and Future Work 149
9.1 Recapitulation 150
9.1.1 Motivation and Approach Development 150
9.1.2 Exemplary Systems and Empirical Investigation 151
9.1.3 Connecting HMI Strategies 152
9.2 Future Research 152
9.2.1 Opaque Risk Predictions 152
9.2.2 Long-Term Adaptation 153
9.2.3 Perceptual Scaling 153
9.2.4 Embodied Cooperative Mobility 155

Acronyms 157

Glossary 159

List of Figures 163

List of Tables 165

Bibliography 167

1
Introduction

Motion is the active pursuit of one's future, a notion that becomes more elusive the further it expands. Foreseeing the future with no bad surprises can additionally be complicated by an increase in motion speed, situation complexity, or situation ambiguity. Moving faster means that information about elements in one's surrounding becomes outdated faster. Moving through complex environments means that more variables must be taken into account for an accurate scene prediction. Moving through scenes with high entropy means that more possible future scene developments must be considered when planning the next steps.
Driving is an example of motion where these conditions can apply. The speed of driving typically surpasses that of walking by orders of magnitude so that elements in the environment require particularly frequent monitoring, e.g., to be able to foresee and avoid potential hazards. Traffic scenes can be complex and contain multiple vehicles on different trajectories. Some of these may be occluded and most of them are steered by independent actors, which can create substantial ambiguity about upcoming events.
Human error is considered to be the decisive cause of about 90% of traffic accidents [21–23]. With a share of 41%, recognition errors are the most frequent reason, followed by decision errors (33%) and performance errors (11%) [22]. This suggests that drivers frequently fail to anticipate traffic development correctly or early enough to ensure safety. Conversely, means for improving recognition and understanding of elements in the environment may be particularly beneficial for facilitating event predictions in traffic to increase safety. This dissertation motivates, develops, and investigates approaches for creating such means.

1.1 Dissertation Outline

The dissertation consists of three parts that comprise eight chapters in total.
Part one introduces the challenge of safe mobility from the perspective of situation awareness formation. By reviewing existing work on driver assistance, open challenges in driver situation awareness formation are identified. It then introduces three general principles in human-machine interaction that may be applied to address such issues and draws on selected theories and findings about human sensory integration to provide the theoretical foundation for the further development of methods to augment driver awareness.

Part two comprises the empirical part of this work. It introduces methods and prototypes for supporting a driver's perception and understanding of traffic dynamics through a form of augmentation. Individual chapters of this part are concerned with specific research questions and revolve around studies and publications in which these questions have been addressed.
Part three contains work that goes beyond the direction of the main approach. It addresses the topic of mobility support from a cooperative perspective, emphasizing the value that can be gained from gaze monitoring and intuitive forms of communication between human and machine, as well as from a joint utilization of cooperation and augmentation. The dissertation concludes with a presentation of possible future research topics.

1.1.1 Part I: From Driver Awareness Challenges to Augmented Perception

Chapter 1 - Introduction

Chapter 1 introduces the topic of this dissertation, provides an overview for how it approaches this topic, and specifies the publications that have contributed to its making.

Chapter 2 - Challenges in Forming Situation Awareness While Driving

Chapter 2 describes a selection of driver awareness-related challenges in the domain of driving and reviews examples for existing or proposed solutions to these challenges. This results in an identification of the open challenge to make drivers more aware of dynamically changing aspects of a scene, such as event probabilities, spatial and temporal distances, and to improve such an awareness at an early stage in risk development to minimize escalation. The chapter is structured as a thorough problem description and review that motivates various topics that are addressed in later chapters. Readers who are generally interested in details of the problem domain could benefit from this overview while those who would mainly like to learn about the new approaches and their investigations introduced in this thesis may also enter from Chapter 3 onwards.

Chapter 3 - Three Approaches to Driver Assistance

Chapter 3 discusses how novel forms of assistance to addressing some of the challenges described in the previous chapter can be guided by different fundamental classes of human-machine interaction (HMI) that may partially be differentiated based on their embedding within human and machine feedback loops. It argues in favor of a class that is labeled *augmentation*, and describes properties that would make an augmentation-guided HMI particularly suitable for addressing the previously identified challenges. Aspects of this chapter were first introduced in the publication Krüger et al. [1].

Chapter 4 - Enacting a World of Anticipations

Chapter 4 subsequently establishes a theoretical basis for an augmentation of driver awareness by connecting fundamental theories and established findings on human sensorimotor processes, resulting in what may be termed an enactive approach to perceptual augmentation in mobility.

1.1.2 Part II: The Lateral Line: Biomimetic Augmentation of Driver Awareness

Chapter 5 - Improving Driving Safety through Tactile Perception of Traffic Dynamics

In Chapter 5, which is based on the publications Krüger et al. [2] and [3], a concept and functional prototype for augmenting the perception of dynamically changing traffic hazards is introduced. This first example for applying the principles of the enactive approach, developed in Part 1, utilizes a tactile interface that communicates directions and temporal distances to approaching hazards by a continuous variation of stimulus intensity. An evaluation of effects of this assistance in a driving simulator study is presented and discussed.
The following research questions are addressed within this chapter:

1. Do drivers perceive and understand direction and temporal distance information encoded in tactile stimuli of the introduced perceptual augmentation prototype?
2. Do drivers benefit from the availability of tactile perceptual augmentation in a driving context in terms of a) subjective support or b) objective driving safety?
3. How are potential effects of the perceptual augmentation prototype moderated by the difficulty of the driving situation?

Chapter 6 - Direction and Temporal Distance Encoding

Chapter 6 is based on the publication Krüger et al. [4]. It addresses questions raised by the results of the study discussed in Chapter 5. For this purpose an expanded assistance prototype that is capable of true two-dimensional, lane-independent risk assessment and which additionally has an option for binary instead of continuous signaling is introduced. Its investigation in a driving simulator study and corresponding results are presented and discussed in detail.
The following research questions are addressed within this chapter:

1. Do subjective benefits of tactile perceptual augmentation in driving transfer to scenarios with low criticality and intersections with crossing traffic?
2. Do safety benefits of tactile perceptual augmentation in driving transfer to scenarios with low criticality and intersections with crossing traffic?
3. Can benefits of tactile perceptual augmentation in driving be attributed to a continuous time-intensity encoding or can they be explained by stimulus presence alone?

Chapter 7 - Spatial Ambiguity

Chapter 7 is based on the publication Krüger et al. [5]. It investigates the applicability of the assistance introduced in the preceding chapters to scenarios that contain substantial perceptual uncertainty. Additionally, an extension of the assistance that adds an encoding of spatial uncertainty in tactile stimuli is presented. A driving simulator evaluation of the effects of this extended assistance, compared to its base form and unassisted driving, is presented and discussed. The following research questions are addressed within this chapter:

1. Can a spatial uncertainty encoded in tactile stimuli on top of hazard direction and temporal distance be perceived and understood by drivers?
2. Do drivers benefit subjectively from the added dimension of spatial uncertainty?
3. Are drivers disturbed by the added dimension of spatial uncertainty?
4. Does driving safety improve through tactile perceptual augmentation that further encodes spatial uncertainty?

1.1.3 Part III: Beyond Driver Awareness Augmentation

Chapter 8 - Cooperative Driver Support

Chapter 8 reaches beyond the scope of perceptual augmentation by revisiting the concept of cooperation in human-machine interaction, which was first addressed in Chapter 3. One of its requirements, an increase in the transparency of a person's mental states, is discussed in particular and exemplified by a range of recent publications (see Section 1.2.2).

Chapter 9 - Conclusions and Future Work

Chapter 9 recapitulates the main conclusions made throughout this thesis and uses these conclusions to derive possible future research topics.

1.1.4 Contributions

Briefly summarized, this dissertation thus makes the following contributions:

1. The motivation and theoretical development of an approach for enabling people to expand their sampling and understanding of spatiotemporal information
2. Introductions of exemplary systems that are guided by this approach in the context of driver assistance
3. Empirical investigations of effects functional prototypes of these systems have on driver perception, behavior, and safety in a range of simulated road traffic scenarios
4. A connection of the primarily augmentation-guided approach of this dissertation to work on cooperative human-machine systems

1.2 Contributing Publications

A substantial part of the work on which this dissertation is based has been published in a variety of academic journals, conferences, and workshops. This section provides an overview of those contributing publications I have authored or co-authored. The publications are grouped into primary publications (Section 1.2.1) and auxiliary publications (Section 1.2.2). The terms

primary and *auxiliary* refer to the role a publication plays in this dissertation. *Primary publications* are those that form the basis of individual chapters or have contributed substantially to their creation. *Auxiliary publications* are publications that are being referenced within this dissertation as contributions to individual sections or statements but which do not form the primary foundation of the respective chapter. Beyond this classification, the two terms should not be taken as indicators for the respective publication's informative value.
The convention for authorship ordering that has been applied for the listed academic publications is as follows: The first author is the primary author of the publication, i.e., the person who has contributed most to the writing process. Furthermore, in most cases the first authorship entails having been the main contributor to the research reported in the respective publication. An exception to the latter convention is the publication [5], where contributions were equal for the first two authors. For a subset of the publications, i.e., [1–5, 9, 12, 13], the last author indicates a senior or supervisory role in the respective research project.
Tables 1.1 and 1.2 provide an overview of my personal roles in the work associated with each of the publications listed in Section 1.2.1 and Section 1.2.2 using the Contributor Roles Taxonomy (CRediT) [24]. For the chapters that cite or introduce work from these publications in more detail, descriptions of my contributions can also be found in the chapters' publication disclosure sections. In addition to the academic publications, several inventions that relate to this dissertation have been filed and published. These are listed as further auxiliary publications in Section 1.2.2.1 but should be understood as novel approaches for solving technical problems rather than as research contributions.

1.2.1 Primary Publications

Publications that form the basis of individual chapters or have contributed substantially to their creation.

[1] Matti Krüger, Christiane B. Wiebel, and Heiko Wersing. "From Tools Towards Cooperative Assistants". In: *Proceedings of the 5th International Conference on Human Agent Interaction - HAI '17.* ACM. New York, New York, USA: ACM Press, 2017, pp. 287–294. ISBN: 9781450351133. DOI: 10.1145/3125739.3125753.

[2] Matti Krüger, Christiane B. Wiebel-Herboth, and Heiko Wersing. "The Lateral Line: Augmenting Spatiotemporal Perception with a Tactile Interface". In: *Proceedings of the Augmented Humans International Conference.* AHs '20. ACM. Kaiserslautern, Germany: ACM Press, 2020. ISBN: 9781450376037. DOI: 10.1145/3384657.3384775.

[3] Associated work-in-progress publication: Matti Krüger, Christiane B. Wiebel-Herboth, and Heiko Wersing. "Approach for Enhancing the Perception and Prediction of Traffic Dynamics with a Tactile Interface". In: *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI '18.* ACM. New York, New York, USA: ACM Press, 2018, pp. 164–169. ISBN: 9781450359474. DOI: 10.1145/3239092.3265961.

[4] Matti Krüger, Christiane B. Wiebel-Herboth, and Heiko Wersing. "Tactile encoding of directions and temporal distances to safety hazards supports drivers in overtaking and intersection scenarios". In: *Transportation Research Part F: Traffic Psychology and Behaviour* 81 (2021), pp. 201–222. ISSN: 1369-8478. DOI: 10.1016/j.trf.2021.05.014.

[5] Matti Krüger, Tom Driessen, Christiane B. Wiebel-Herboth, Joost CF de Winter, and Heiko Wersing. "Feeling Uncertain - Effects of a Vibrotactile Belt that Communicates Vehicle Sensor Uncertainty". In: *Information* 11.7 (2020). ISSN: 2078-2489. DOI: 10.3390/info11070353.

1.2.2 Auxiliary Publications

Publications that are being referenced within this dissertation as contributions to individual paragraphs and statements but which do not form the primary foundation of the respective chapter.

[6] Christiane B. Wiebel-Herboth, Matti Krüger, and Martina Hasenjäger. "Interactions between Inter- and Intra-Individual Effects on Gaze Behavior". In: *Adjunct Publication of the 28th ACM Conference on User Modeling, Adaptation and Personalization*. UMAP '20 Adjunct. Genoa, Italy: Association for Computing Machinery, 2020, pp. 35–40. ISBN: 9781450379502. DOI: 10.1145/3386392.3397595.

[7] Associated work-in-progress publication: Christiane B. Wiebel-Herboth, Matti Krüger, and Martina Hasenjäger. "Inter- and Intra Individual Differences in Gaze Behavior in a Visual Search Task". In: *ACM Symposium on Applied Perception* (2018).

[8] Christiane B. Wiebel-Herboth, Matti Krüger, and Patricia Wollstadt. "Measuring inter- and intra-individual differences in visual scan patterns in a driving simulator experiment using active information storage". In: *PLoS one* 16.3 (2021), e0248166. DOI: 10.1371/journal.pone.0248166.

[9] Chao Wang, Matti Krüger, and Christiane B. Wiebel-Herboth. ""Watch out!": Prediction-Level Intervention for Automated Driving". In: *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '20. Virtual Event, DC, USA: Association for Computing Machinery, 2020, pp. 169–180. ISBN: 9781450380652. DOI: 10.1145/3409120.3410652.

[10] Chao Wang, Thomas H. Weisswange, Matti Krüger, and Christiane B. Wiebel-Herboth. "Human-Vehicle Cooperation on Prediction-Level: Enhancing Automated Driving with Human Foresight". In: *IV21 - Workshop on Trust Calibration for Human-AV Interactions* (2021).

[11] Associated video publication: Chao Wang, Thomas H. Weisswange, and Matti Krüger. "Designing for Prediction-Level Collaboration Between a Human Driver

and an Automated Driving System". In: *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '21 Adjunct. Leeds, United Kingdom: Association for Computing Machinery, 2021, pp. 213–216. ISBN: 9781450386418. DOI: 10.1145/3473682.3481873.

[12] Matti Krüger, Martin Weigel, and Michael Gienger. "Visuo-tactile AR for Enhanced Safety Awareness in Human-Robot Interaction". In: *VAM-HRI 2020 The Second International Workshop on Virtual, Augmented and Mixed Reality for Human-Robot Interaction*. 2020.

[13] Matti Krüger, Bruce N. Walker, and Lewis Chuang. "The Embodied Vehicle". In: *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings*. AutomotiveUI '19. Utrecht, Netherlands: Association for Computing Machinery, 2019, pp. 50–55. ISBN: 9781450369206. DOI: 10.1145/3349263.3350763.

1.2.2.1 Published Inventions

[15] Matti Krüger. "Method for assisting a person in acting in a dynamic environment and corresponding system". U.S. pat. 10475348B2. Nov. 2019.

[16] Matti Krüger and Christiane Wiebel-Herboth. "Gaze-guided communication for assistance in mobility". U.S. pat. 10543854B2. Jan. 2020.

[17] Matti Krüger and Christiane Wiebel-Herboth. "Method for assisting operation of an ego-vehicle, method for assisting other traffic participants and corresponding assistance systems and vehicles". U.S. pat. 10636301. Apr. 2020.

[18] Matti Krüger, Heiko Wersing, and Julian Eggert. "Optical Flow Based Assistance for Operation and Coordination in Dynamic Environments". U.S. pat. 10937175B2. US Patent 10,937,175 B2. Mar. 2021.

[19] Matti Krüger and Christiane Wiebel-Herboth. "Method for assisting a person in acting in a dynamic environment and corresponding system". European pat. req. 3693943A1. EP3693943A1. Aug. 2020.

[20] Matti Krüger, Tom Driessen, and Christiane Wiebel-Herboth. "Method for assisting a person in acting in a dynamic environment and corresponding system". European pat. req. 3723066A1. EP3723066A1. Oct. 2020.

Publication ID & Title	Personal Contributions
[1] From Tools Towards Co-operative Assistants	Conceptualization, investigation, methodology, visualization, writing - original draft, writing - review & editing
[2] The Lateral Line: Augmenting Spatiotemporal Perception with a Tactile Interface	Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing - original draft, writing - review & editing
[3] Approach for Enhancing the Perception and Prediction of Traffic Dynamics with a Tactile Interface	Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing - original draft, writing - review & editing
[4] Tactile encoding of directions and temporal distances to safety hazards supports drivers in overtaking and intersection scenarios	Conceptualization, data curation, formal analysis, methodology, project administration, resources, software, supervision, visualization, writing - original draft, writing - review & editing
[5] Feeling Uncertain - Effects of a Vibrotactile Belt that Communicates Vehicle Sensor Uncertainty	Conceptualization, data curation, formal analysis, methodology, project administration, software, supervision, validation, visualization, writing - original draft, writing - review & editing

Table 1.1: Overview of my contributions to primary publications according to the CRediT taxonomy. Individual contributor roles may have been shared by multiple authors.

Publication ID & Title	**Personal Contributions**
[6] Interactions between Inter- and Intra-Individual Effects on Gaze Behavior	*Data curation*, software, *writing - review & editing*
[7] Inter- and Intra Individual Differences in Gaze Behavior in a Visual Search Task	*Data curation*, software, *writing - review & editing*
[8] Measuring inter-and intra-individual differences in visual scan patterns in a driving simulator experiment using active information storage	*Conceptualization*, data curation, investigation, *methodology*, *writing - review & editing*
[9] “Watch out!”: Prediction-Level Intervention for Automated Driving	*Conceptualization*, data curation, methodology, visualization, *writing - original draft*, *writing - review* & editing
[10] Human-Vehicle Cooperation on Prediction-Level: Enhancing Automated Driving with Human Foresight	*Conceptualization*, methodology, software, *writing - original draft*, *writing - review* & editing
[11] Designing for Prediction-Level Collaboration Between a Human Driver and an Automated Driving System	*Conceptualization*, methodology, software, *writing - original draft*, *writing - review & editing*
[12] Visuo-tactile AR for Enhanced Safety Awareness in Human-Robot Interaction	Conceptualization, investigation, methodology, project administration, software, visualization, writing - original draft, writing - review & editing
[13] The Embodied Vehicle	Conceptualization, project administration, visualization, writing - original draft, writing - review & editing

Table 1.2: Overview of my contributions to auxiliary publications according to the CRediT taxonomy. Individual contributor roles may have been shared by multiple authors. *Italicized* terms indicate secondary contributions where co-authors have taken the lead.

Part I

From Driver Awareness Challenges to Augmented Perception

2

Challenges in Forming Situation Awareness While Driving

"Eine zweite allgemeine Eigenthümlichkeit unserer Sinneswahrnehmungen ist die, dass wir auf unsere Sinnesempfindungen nur so weit leicht und genau aufmerksam werden, als wir sie für die Erkenntnis äusserer Objecte verwerthen können, dass wir dagegen von allen denjenigen Theilen der Sinnesempfindungen zu abstrahiren gewöhnt sind, welche keine Bedeutung für die äusseren Objecte haben [...]."

Hermann von Helmholtz, *[25, p. 361]*

The persistence of human-caused traffic accidents [21–23] indicates that driving a vehicle is a challenging task that cannot always be fulfilled successfully. The introductory section mentioned deficits in recognizing relevant scene elements or making appropriate decisions as primary reasons for human failure [e.g., 22]. This chapter provides a more detailed account of specific challenges that may underlie these deficits. It then introduces a selection of existing or proposed driver assistance systems to gain insights into how driver assistance systems can support driver awareness and to identify unresolved or underresolved issues.

Contents

2.1 Why Driving Can Be Difficult **14**
2.1.1 Situation Awareness 14
2.1.2 Perception Challenges 15
2.1.3 Comprehension Challenges 19
2.1.4 Projection Challenges 22
2.2 Supporting Situation Awareness with Driver Assistance Systems **28**
2.2.1 Why Driving Can Still Be Difficult 30
2.3 Chapter Summary **33**

2.1 Why Driving Can Be Difficult

This section delineates a selection of awareness-related challenges that can occur in mobility-related tasks. To simplify an initial differentiation of these challenges, it utilizes a framework for *situation awareness* (SA), which distinguishes between several levels of situation-related information processing as contributors to decision making processes in dynamic environments. The section thus starts with an introduction of this framework before illustrating awareness challenges in mobility that are grouped accordingly.

2.1.1 Situation Awareness

The introductory paragraph emphasized the role predictions play in ensuring safe mobility. It implied that predictions inform acts of motion whereas predictions themselves depend on the perception and understanding of elements in a scene. A part of this causal chain has previously been conceptualized in a framework model for the awareness about one's environment known as situation awareness (SA). Endsley [26] has defined situation awareness as follows:

> "Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future."

Accordingly, her framework for SA distinguishes between three sequentially interdependent stages or levels:

Perception (Level 1): The first and most basic stage consists of perceiving status, attributes, and dynamics of relevant elements in the environment. In the case of driving, this would correspond to the identification, localization, and monitoring of traffic elements, including the own vehicle.

Comprehension (Level 2): At the second stage the elements perceived in level 1 SA are processed and integrated into a holistic scene comprehension that should inform an understanding of their relevance for one's own objectives. In the driving example this could correspond to comprehending how the current setup of the driving scene affects one's momentary goals of driving along a specific trajectory without becoming involved in an accident.

Projection (Level 3): The purpose of the third and highest stage consists of projecting states of environmental elements into the future. This additional understanding can enable anticipatory decisions and actions that could lead to more foresighted behavior. In the case of driving it would correspond to predicting where other traffic participants are going to be in the near future relative to oneself based on their current locations and trajectories.

In addition to the three stages, the definition of SA includes two other important components: It states that SA applies within a volume of *space* and *time*. This implies that SA formation must take place over a distance that is far enough to meet task goals and that it requires dynamic updating at a rate that is appropriate to capture relevant actions and state changes in the environment in time. Because situation demands on spatial coverage and update frequency can vary

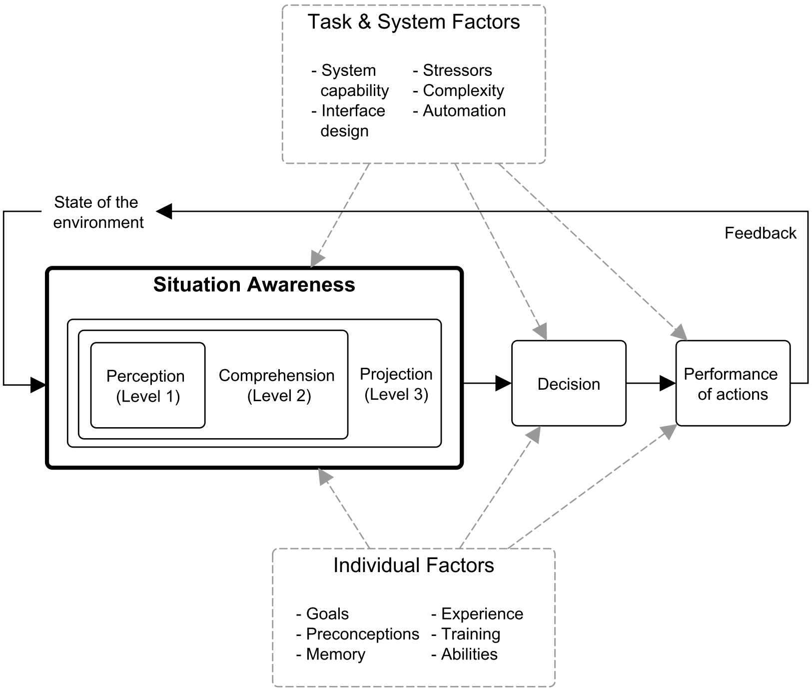


Figure 2.1: Model of situation awareness and contributing factors in dynamic decision making. Adapted from Endsley [27].

substantially, the volume of space and time required for SA formation should be considered as variable.

The SA framework provides a useful first conceptualization for loosely differentiating between existing challenges for safe driving. The following sections will therefore highlight several challenges in relation to each SA level. Nevertheless, references to SA levels are not intended to suggest that the SA framework may have a direct correspondence in human cognitive processes. Here it is solely used for its utility in an initial differentiation.

2.1.2 Perception Challenges

The primary task on the perception level lies in registering elements that are relevant to one's objectives within the required spatial and temporal constraints. Typically, a vehicle driver relies strongly on visual perception to sample information about the outside environment. This section describes different properties and limitations of mostly visual perception that can affect rate, capacity, and quality of this sampling.

2.1.2.1 Foveated Imaging

The density of photoreceptors in the retina of the human eye determines the spatial resolution or *visual acuity* at which visual information can be registered for a given scene projected onto the retina. However, photoreceptors are not uniformly distributed across the retina but are available at a high density in a central region called the *fovea centralis* while peripheral regions are only sparsely covered. This results in *foveated imaging*, i.e., an imaging with variable resolution that is high in the center and low in the periphery. To perceive elements in a scene with high visual acuity, the fovea, which roughly aligns with the center of the pupil but only covers about 2°of the visual field, must be directed towards the respective element. Additionally, accurate color perception requires foveal vision because the majority of color-sensitive photoreceptor cells are located in the fovea. To facilitate foveal alignment of eyes with elements of interest in a scene, eyes can move or rather rotate along three different axes.

A movement to align the fovea with a new region or direction of interest is called a *saccade*. The focus of the fovea on a specific region for some minimum time is called a *fixation*. With the exception of *smooth pursuit* and the compensation for self-motion, human vision is characterized by alternating fixations and saccades.

With an angular speed of up to 900°/s [28], a saccade can take between 15 and 100 ms [29], depending on its amplitude. Fixation durations are considered to be context-dependent [30]. For instance, the mean duration is around 225 ms during reading but 275 ms during visual search [31]. While driving, fixation durations tend to vary as a function of environment (e.g., 320 ms in suburban areas and 380 ms in rural areas [32]). Driving experience has been found to reduce fixation durations while increasing the horizontal spread of fixation locations [32]. Fixations on road signs have been found to only take 137 ms on average [33].

Eye movements can thus expand spatial coverage and resolution of vision at the expense of the time and energy required for the respective movement. Further expansion of spatial coverage can be achieved by head-movements [34] at additional time cost. For driving tasks this means that the nature of visual sampling imposes limits on how frequently relevant elements in a scene may change and still be perceived in time to enable safe vehicle operation. I.e., the larger the (potential) velocity differences between oneself and other traffic participants, the more frequent sampling is required.

Arguably, the saccade-driven perception is less of an issue during driving than for some other tasks that require detailed shape discrimination at close proximity, such as reading: For a start, distances to relevant objects in the front are often large enough to keep the corresponding objects within the 2°foveal or 6°parafoveal ("preview resolution") field of view. Furthermore, also peripheral vision, which is particularly sensitive to motion [35, 36], is utilized in dynamic movement tasks such as driving. However, the speed of peripheral object detection has also been shown to be impaired during driving [37], and because driving in dynamic environments at least requires fixation shifts between the driving direction, side-, rearview mirrors, and meter displays, the tradeoff between time and spatial coverage still applies. For some traffic situations, such as when crossing intersections, head and eye movement related delay is even reflected in explicit behavior guidelines (e.g., checking the left, the center, the right, and then the left side once more before proceeding).

In conclusion, an increase in the regions that need to be monitored as well as an increase in the frequency or magnitude of changes in relevant objects increases the burden on visual sampling and thus eventually also the probability of detection failure when time is limited.

2.1.2.2 Occlusion, Weather, and Illumination

Vision on its own only allows for perception of objects that are projected onto the retina. Several factors may thus prevent the perception of objects: Occlusion by another object is perhaps the most obvious case – a child that is hidden behind a parking car may not be seen until it moves "out of hiding" or until the car is passed. Other types of occlusion can be caused by weather conditions, such as fog, snow, or strong rain, which can severely restrict the spatial visibility range. More persistent occlusion is created by vehicle layout (blind spots), topography, and infrastructure layout, such as a curved road along a hillside or buildings. Furthermore, a lack or excess of illumination, i.e., darkness or glare, can interfere with visual perception and increase accident rates accordingly [38, 39]. This association is also supported by the increased incidence of traffic accidents by drivers with abnormal visual functions such as reduced mesopic vision and increased sensitivity to glare [40].

Besides affecting visibility, the environmental conditions can also impact the way a vehicle behaves on the road and how dangerous certain maneuvers are. For instance, a wet or frozen road can be much more slippery than a dry road and requires reduced driving velocities in curves or for any lateral movement. Especially for lighter vehicle classes or vehicles with a large vertical surface area also the wind can be a critical factor. Furthermore, these kinds of influences are not necessarily noticeable inside the vehicle. Passing the freezing point cannot be felt inside a heated vehicle and wind does not exert any force on the body but may at most be noticed indirectly through the drag it creates on the vehicle. By accounting for 7.5% of traffic accidents (in Germany) [23, 41], weather effects are still an important safety factor for which higher SA may be required.

2.1.2.3 Distraction and Salience

Distraction describes the allocation of attention resources to task-irrelevant elements in a way that impairs the perception of task-relevant information. Accordingly, distractors are task-irrelevant elements in the environment that compete with task-relevant elements for a person's attention.

As mentioned above, visual perception is saccade-driven. It is thus an active process in which each eye movement has the purpose to yield access to new information. Saccades to new locations are thereby not random but typically target specific regions of interest for fixation. The selection of fixation points is guided by a combination of bottom-up [42, 43] and top-down, i.e., task-dependent, factors [44, 45]. The presence or absence of salience-affecting features, such as a high contrast in color or orientation, can affect how likely it is for an object in the scene to be fixated. A bright red car creates a stronger color contrast to the environment than a cyclist in matte grey clothing and, accordingly, is more likely to be attended. It is thus possible for distractors with high bottom-up salience to capture a driver's attention and impair the driver's ability to perceive more relevant elements. Also distractors that meet criteria of high level goals, which compete with the driving task, have been found to negatively affect the perception of elements relevant to driving [46].

2.1.2.4 Experience

Besides bottom-up salience, also endogenous top-down factors can affect attention guidance and visual exploration strategies. For driving it has been found that experience is an important top-down modulator of visual information sampling behavior [32, 47–50]. Compared to experienced drivers, untrained drivers have been found to look less far ahead, check the mirrors less

frequently, let their gaze deviate more from the direction of movement, and make pursuit eye movements while experienced drivers only show fixations [47]. For novice drivers with limited experience, the scanning behavior changes and often shows more stereotypical patterns [50].
Fixation-sequence strategies also appear to differ between novice and experienced drivers in such a way that experienced drivers present more flexible fixation patterns while novice drivers tend to look towards the front following fixations to any other Area of Interest [50]. An example for higher flexibility of experienced drivers is a more selective use of side-mirrors that is coupled to behavior plans such as lane changes [49]. When comparing variance in search-space, experienced drivers show higher variance in horizontal fixation distribution. In contrast to novice drivers, they further reduce the amount of vertical fixation variation (looking close and far ahead) on quiet roads [32].
However, also contradicting results have been reported in which novice drivers have outperformed experienced drivers in their sampling strategies and overall driving performance [48]. According to Duncan, Williams, and Brown [48], the behavior of novice drivers often showed more similarities to the behavior of vigilant drivers with high expertise than the behavior of overconfident experienced drivers did.
In summary, although the exact impact of experience may vary across individuals, it exemplifies one way in which top-down factors can affect visual sampling and thereby lead to differences in scene perception across individuals.

2.1.2.5 Vigilance, Fatigue, and Exhaustion

A driver's ability to stay vigilant is limited by human biology. The maintenance of a functional body alone requires a continuous supply of resources as well as periods of rest. Perceptually demanding tasks, such as driving, further accelerate the depletion of energy resources. Accordingly, as people become tired their ability to perceive traffic elements and react to hazards declines [51, 52], leading to a substantial increase in accident probability [53–55]. The importance of wakefulness for traffic safety has long been recognized and, for many countries, has resulted in the implementation of rules that restrict the duration of uninterrupted driving and demand periods of rest between drives [56]. The limits imposed by these rules are general heuristics that might be considered appropriate on average. However, the impact of different traffic circumstances on peoples' vigilance varies. On the one hand, high workload can lead to faster exhaustion [57]. But perhaps counterintuitively, the negative impact of perceptual and cognitive underload, i.e., a lack of perceptual demands, appears to be even stronger [52, 58–60]. Furthermore, since each individual's level of wakefulness already varies at driving onset, it is important to not just follow simple rules and guidelines but also to pay attention to one's actual mental state. Situation awareness therefore also involves an awareness about one's own physical and mental abilities to safely carry out the driving task and to recognize when it is time to stop driving. Because the ability to monitor and judge one's own mental capacity is directly dependent on that same mental capacity, it is particularly important to recognize any deterioration early.

2.1.3 Comprehension Challenges

At the *comprehension level*, the elements registered at the perception level are processed and integrated. The comprehension further includes relating the perceived state of the environment to one's objectives. The following sections list a selection of challenges that are present at this level.

2.1.3.1 Motion, Acceleration, and Velocity

For safe driving it is crucial to perceive the own direction of motion, acceleration, and velocity relative to other traffic elements. Two sensory systems have been found to play a major role in acquiring the necessary information: the visual and the vestibular system [61–64]. An important visual cue for motion perception is known as *optical flow* (OF) [65]. Optical flow describes the motion-induced spatial displacement of visual elements across the visual scene over time. During self-motion, it is characterized by a radial expansion from the heading direction as well as from the directions of any approaching objects. The center of expansion thus provides information about the direction of movement. The rate of the flow created by self-motion is a cue for the velocity whereas acceleration and deceleration produce corresponding changes in that rate. The artificial creation of optical flow has indeed been found to induce the perception of self-motion [66, 67]. However, as optical flow is not just created by self-motion but also by the motion of other objects, it can be an ambiguous cue. Especially the approach by another object can generate radially expanding optical flow similar to that of self-motion. Yet its meaning for the driver, i.e., an upcoming collision with the approaching object, is different from the meaning of flow induced by self-movement towards a target direction. In dynamic environments optical flow-based motion perception thus requires mental source separation capabilities [61] in order to correctly disambiguate and utilize its encoded cues.

To support disambiguation the vestibular system offers further independent cues. The vestibular receptors, located in the inner ears, provide information about rotation and acceleration of the head in space. In particular the *otolith organs*, which serve as detectors for linear acceleration, have been linked to the perception of self-motion [68]. However, also vestibular signals can be ambiguous. On their own, the vestibular signals do not distinguish between acceleration and tilt due to gravity. This is one reason why dynamic driving simulators can utilize tilt to create a perception of acceleration. Conversely, the *somatogravic illusion* refers to a misinterpretation[1] of acceleration as tilt that can occur in the absence of visual cues [69] and after exposure to sustained linear acceleration [70]. Another adverse effect associated with a conflict between visual and vestibular signals is motion sickness [71].

The existence of these effects and the complementarity of visual and vestibular cues for the perception of self-motion suggests that an integration of information from both modalities would support accurate motion perception and appears to be taking place accordingly[2].

When utilizing optical flow for the perception of relative motion of other traffic participants

[1] The use of the term "misinterpretation" is not meant to argue for any physical difference between acceleration and gravity but to refer to an error in semantic attribution.

[2] Indeed, neurons in the dorsal part of the medial superior temporal area (MSTd) and the ventral intraparietal area (VIP) have been identified as likely candidates for the integration of self-motion-related optical and vestibular signals [61] and may thus offer direct physiological evidence.

several difficulties can arise: The effect, which relative motion of another object has on the optical flow of an observer, is proportional to the proximity of the object to that observer. A distant object that moves relative to the observer affects a smaller portion of the visual field than a nearby object that moves by the same amount. Although depth-perception can help in accounting for such differences, limits of visual acuity restrict the feasible range for reliable motion perception. A second issue lies in the need for temporal integration. Optical flow is the flow over time and hence relies on integration over subsequent samples. This creates a time-accuracy tradeoff, which can limit the visual information bandwidth in a similar way as described previously for foveated imaging, especially in the case of tracking distant or small objects. Both issues are further amplified when trying to perceive relative motion of objects through side- and rearview mirrors, which are often convex to cover a larger scene at the cost of distorting and shrinking the reflection of the scene.

In summary, an integration of multimodal information from optical and vestibular signals allows for a separation of optical flow sources so that drivers may distinguish between flow caused by self-motion and by the movement of other traffic participants relative to the ego-vehicle. Although the perception and comprehension of relative motion of other objects and traffic participants is enabled by optical flow, it is subject to a time-accuracy tradeoff and inherent physical constraints that limit spatial coverage.

2.1.3.2 Scene Complexity

Driving on an empty single-lane road is more relaxed than driving during rush hour on a busy intersection. The difference between these scenarios can be summarized as a difference in complexity. A busy road contains more traffic participants that may be relevant to one's own safety and mobility objectives than an empty road and an intersection presents more behavior options for each of these traffic participants than a simple straight road. Comprehension of a more complex scene entails a higher workload because more potential determinants of the environment state and their interactions need to be taken into consideration.

2.1.3.3 Ambiguity

The process of comprehension is not always guaranteed to converge on a single outcome. Sometimes the perceived input may be explained by different possible causes, especially in complex scenarios. Such ambiguity is typically a sign of incomplete information. The piece of information that would be required to decide between competing explanations is missing. For example, two red lights seen through fog in the distance could belong to two separate motorcycles driving on similar levels or to a single car. In many cases a driver can disambiguate incoming information based on prior experience in similar situations. If ambiguity should nevertheless prevail, drivers may follow different approaches. One approach would be to comprehend multiple versions of the environment. This would then allow the creation of behavior plans that either are compatible with all versions or a utilization of heuristics like assuming the worst among the available scenarios to be true and selecting the most conservative behavior plan.

Deciding on one of multiple competing explanations for sensory input entails a risk of selecting an erroneous explanation, leading to wrong conclusions and possibly dangerous actions. Unaccounted ambiguity is thus inherently problematic in driving.

2.1.3.4 Experience, Surprise, and Bias

Section 2.1.2.4 mentions how driving experience may help in resolving sensory ambiguity. Indeed, inexperienced drivers have been found to present lower comprehension of the driving scene than experienced drivers [72], even when accounting for the demands of vehicle control, which are likely to affect novice drivers more strongly [73]. Section 2.1.2.4 also describes how experience-related top-down factors can affect visual sampling behavior. The reported differences in comprehension [72, 73] could therefore be due to differences in available information, differences in the ability to integrate information, or a combination of both.

But as pointed out by Duncan et al. [48], comprehension and perception do not necessarily have to improve with experience. Experienced drivers can be overconfident, and that overconfidence can influence how carefully they scan their environment or how they estimate the potential impact of new information. While novice drivers tend to be cautious to avoid mistakes, experienced drivers may have been wrongfully rewarded for poor behavior in the past. An example of such a wrong experience-related reward is tailgating. When a driver accelerates or changes lanes in response to a tailgating vehicle, the tailgater is rewarded for reducing the distance to the front vehicle. The experience of being able to let other vehicles "make room" reduces the driver's aversion to small front vehicle distances (i.e., a high front collision risk) and encourages aggressive driving. In agreement with this example, driving experience has been identified as a predictor of aggressive driving behavior [74], and an incorrect sense of appropriate headway distance has been identified as a main determinant of tailgating for experienced drivers [75].

Another downside of experience can be routine. When a route is driven on a regular basis, a driver starts internalizing many aspects of it and may appear to be able to handle it effortlessly. However, driving experience and road-familiarity have also been associated with so called *looked but failed to see* accidents where drivers failed to respond appropriately to an upcoming hazard despite being logically able to perceive it [76, 77]. There seems to be a risk that experience and routine can reduce the ability to notice and react to surprising events. In other words, the internalized model of the environment is given a disproportionate weight compared to current perceptual evidence.

In summary, driving experience can support comprehension but may also create biases that conflict with an appropriate assessment of driving safety and the flexibility to handle surprising events. Accordingly, experience should not only be seen as a contributor to comprehension but may require specific treatment to overcome possible detrimental biases.

2.1.3.5 Theory of Mind

Each traffic participant is an individual with a personal travel goal, an own perspective, and an own understanding of the traffic scene. Furthermore, each traffic participant's unique history and state of mind contribute to a singular perception and understanding of a given traffic situation. The ability to attribute mental states such as beliefs, intents, perspectives, emotions, and knowledge different from one's own to others is referred to as *theory of mind* (ToM). In the driving context, this theory of mind may be roughly simplified to yielding answers to the following questions about another traffic participant X: "Where does X want to go?", "What is X aware of?", and, importantly, "Is X aware of me?". Answers to these questions can help drivers to sharpen their comprehension of the traffic situation and support planning and decision

making.
When observing pedestrians and cyclists, several cues that support ToM formation are easily available: A person's head-orientation reveals the momentary field of view. Furthermore, a person's age can be a valuable indicator for calibrating expectations about sensory capabilities and risk awareness. When traffic participants are concealed by their vehicles these cues can be much harder to obtain. In such cases the vehicle behavior may become a more reliable source of information about their mental state. For instance, the heading direction typically correlates with the direction of gaze [50, 78] so that one can generally assume that a driver perceives elements in their front. For other directions without such reliable correlates, more resource-intensive methods like behavior monitoring over time may have to be employed. However, the availability of such resources is also subject to other perceptual and cognitive demands of the situation and therefore further constrains ToM formation ability.
In summary, understanding the mental states of other traffic participants can support a driver in scene comprehension and action planning. While the traffic context reduces the extent to which such an understanding is required, it can also impede the ability to form the understanding in the first place. Means for providing further transparency about mental states might be required.

2.1.4 Projection Challenges

At the projection level, inferences about the future development of the scene are made based on processed information from the perception and comprehension levels. In particular, information that relates to identified dynamics of environmental elements can be used to project states of these elements into the future. By being able to predict how a situation can evolve, a driver can act in anticipation and not just by reaction. This is particularly helpful for accident prevention or, more generally, for averting undesirable scenario developments. The following sections describe a selection of challenges that can be associated with the projection level.

2.1.4.1 Future Uncertainty

In the case of road traffic, the state of a scenario can be described in terms of properties of its components such as the location, heading, and speed of individual traffic participants. Many of these components are variables that typically change within a relatively short time-frame. Formally, future prediction of a scenario thus also means predicting the future values of such state-describing variables. For a future time step, a variable may take one of multiple potential values. But how do we know which value a variable is going to take in the future?
The task of predicting the future based on knowledge about present and past conditions can be framed as a *constraint satisfaction problem*. Constraint satisfaction describes the process of reducing the set of possible values of one or more variables by considering the constraints that are imposed on these variables. Generally expressed, the fewer constraints for the distributions of relevant variables are known or set, the more uncertain future estimates become.
But for prediction, also any residual uncertainty that satisfies the identified constraints of future situation development can be problematic. When trying to predict states that lie further ahead in the future, one has to make predictions on predictions: The states at t+2 depend on the states at t+1. If multiple options are available at t+1, the t+2 estimates should account for all of these options. Uncertainty thus accumulates and can quickly make predictions that lie further ahead

in the future unfeasible. To partially mitigate this issue, one can attempt to not only narrow down the distribution of future states but also to prioritize subsets of this distribution according to relevance criteria. The following sections describe some of these relevance criteria.

2.1.4.2 Risk Judgement

Arguably, events that actually occur have a higher relevance than those that do not occur. Consequently, among the wide range of potential future situations, those that are more probable should be more relevant than those that are less likely to occur.

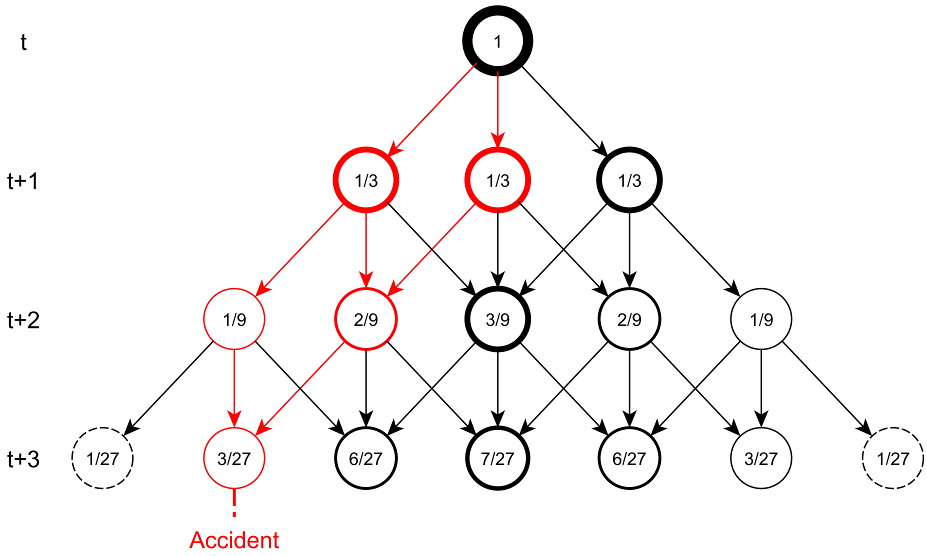


Figure 2.2: Graphical illustration of probability and relevance in the prediction of future states. Circles represent environment states, arrows show the possible transitions between states over time for three discrete future time steps (t+1, t+2, t+3). Fractions written inside a state show the relative number of paths leading to the respective state. Assuming each transition is equally likely, the fractions also represent the probabilities of reaching individual states. For illustration purposes the probabilities are also represented by circle line widths. States and transitions shown in red represent states connected to a predicted accident to highlight their relevance. The number of possible states increase over time. State probabilities and safety-relevance criteria may aid in limiting the number of considered states and increasing the prediction horizon.

The probability of a state is the relative number of ways in which the state can be reached. When imagining the evolution of possible future states as a graph of forking paths (see Figure 2.2) where each path is equally likely, the probability of each possible future state would correspond to the relative number of paths that lead to it. The long-term average outcome of similar states approximates the probability, allowing us to estimate state probabilities from experience rather than by counting the ways in which they could be reached. The probability can act as a filter to limit the ranges of potential future states that need to be considered.
Another indicator for state relevance can be its *severity*. The severity relates to the consequences of a state for a driver's goals rather than to its probability. In the case of driving, accidents or

control loss are examples for events with high severity related to the goal of safety-maintenance. With regards to the goal of successful navigation, a missed highway exit could be considered as an example for high severity.
The two factors, probability and severity, can be combined in one term known as *risk*, i.e., the product of the two [79]. Accordingly, as a priority or filter criterion to limit the distribution of potential future states that need to be considered, the risk puts an emphasis on probable future states that would affect the driver's goals. Indeed, as originally suggested by Näätänen et al. [79], human satisficing in driving has recently been found to resemble risk-threshold dependent behavior decisions [80].
The challenge lies in judging what risk is associated with different possible future states. One strategy that appears to be employed by drivers is dependent on the spatial distance to other traffic participants: Kolekar et al. [81] have found that the perceived risk originating from other objects is high near the ego vehicle and decays with increasing spatial distance. Following the *field of safe travel* by Gibson and Crooks [82], they conceptualize this risk-distance relationship as the Driver's Risk Field (DRF) [81][3]. While driving, estimates of spatial distance depend primarily on vision. Object size and parallax can inform distance estimates. In some countries the roads contain regularly repeating road markings that can serve as absolute references. Especially in the more close proximity also sounds can reveal distance information, e.g., through volume, high/low frequency balance, and reverberation. In addition to the spatial distance, Kolekar et al. [81] have linked the shape of the DRF to the speed and steering angle such that it expands linearly with increasing speed and curves according to the future vehicle trajectory. The following section will discuss the role of such dynamic features in more detail.

2.1.4.3 Temporal Judgement

Because speed ($v = \frac{d}{t}$) is defined as the distance (d) covered per unit of time (t), a co-dependence of the DRF on distance and speed can be understood as a dependence on the *temporal distance*. The temporal distance between a vehicle and a specific location is the time that is required for the vehicle to arrive at that location. One formalization of the temporal distance for short time scales in the mobility domain is the *time headway* (THW). In its most basic form it can be defined as the ratio of the spatial distance (d) towards a location on the vehicle's trajectory and the speed (v) of the vehicle: $THW = \frac{d}{v}$. Typically, the location of interest is the current position of the rear of another vehicle driving in the front. In this case the THW is an expression of *how long it takes to reach the current position* of the front vehicle.
Instead of calculating the temporal distance to the current position of another vehicle, one could also be interested in the temporal distance to the *expected future position* of another vehicle. More specifically, the time at which the expected future positions of the own and another vehicle start to overlap, i.e., a predicted moment of collision, can be of particular interest. In this case a different measure known as the *time-to-contact* or *time-to-collision* (TTC) can be used. Under the assumption that two vehicles drive behind each other on the same path, the TTC is defined

[3] See also Eggert and Puphal [83, 84], who have conceptualized personal risk in a similar manner, albeit with the goal of establishing an objective rather than a subjective estimate of risk in two dimensions.

as the ratio between their current spatial distance and their velocity difference:

$$TTC_{1D} = \begin{cases} \frac{d_{ab}}{v_b - v_a}, & \text{if } v_b > v_a \\ \infty, & \text{otherwise.} \end{cases} \tag{2.1}$$

The THW may thus be seen as a special case of the TTC where $v_a = 0$. This can be translated into a TTC under the expectation that the front vehicle may abruptly stop at any moment. Despite this relationship and the commonality as expressions of temporal distance, THW and TTC vary in their behavior.

The THW is a continuous function. It falls while approaching another vehicle and stays constant when matching that vehicle's velocity (see green curve in Figure 2.3). Once the distance increases it also increases at the same rate. The TTC behaves much more erratic. It also falls while approaching another vehicle but quickly returns to infinity once the front vehicle matches or surpasses the ego-vehicle's speed (see blue curve in Figure 2.3). This nonlinearity makes it sensitive only to periods of approach whereas the THW also has a sustained dependence on the spatial proximity. Both the THW and the TTC capture information about the safety-relevance of a preceding vehicle. A falling THW and a falling TTC both predict an approaching collision. At constant speed a constant THW indicates a constant spatial distance. A constant (non-infinite) TTC indicates a correction of prior TTC estimates that is likely caused by efforts to prevent or delay a collision, e.g., braking of the rear-vehicle or acceleration of the front vehicle.

There are indications that drivers use both THW and TTC, to guide their actions: Drivers have been found to show a tendency to maintain similar THW distances at different absolute velocities [85], and the TTC has been identified as a reliable predictor of human braking responses [86]. However, as drivers we do not consciously calculate temporal distances[4] but instead appear to use naturally available cues to estimate them. For instance, the divergence of optical flow (OF) related to another vehicle is proportional to the TTC towards that vehicle. Areas in human middle temporal visual cortex (V5/MT) have been associated with such OF-dependent collision predictions [87–90]. As in the case of distance estimates, collision predictions hence appear to be largely driven by visual input and, in accordance, are also subject to challenges on the perceptual level (see Section 2.1.2.4).

[4]Nevertheless, consciously applied heuristics that rely on verbal rhythms are commonly taught and applied. Example: uttering two double-digit numbers to estimate a two second distance at the current velocity.

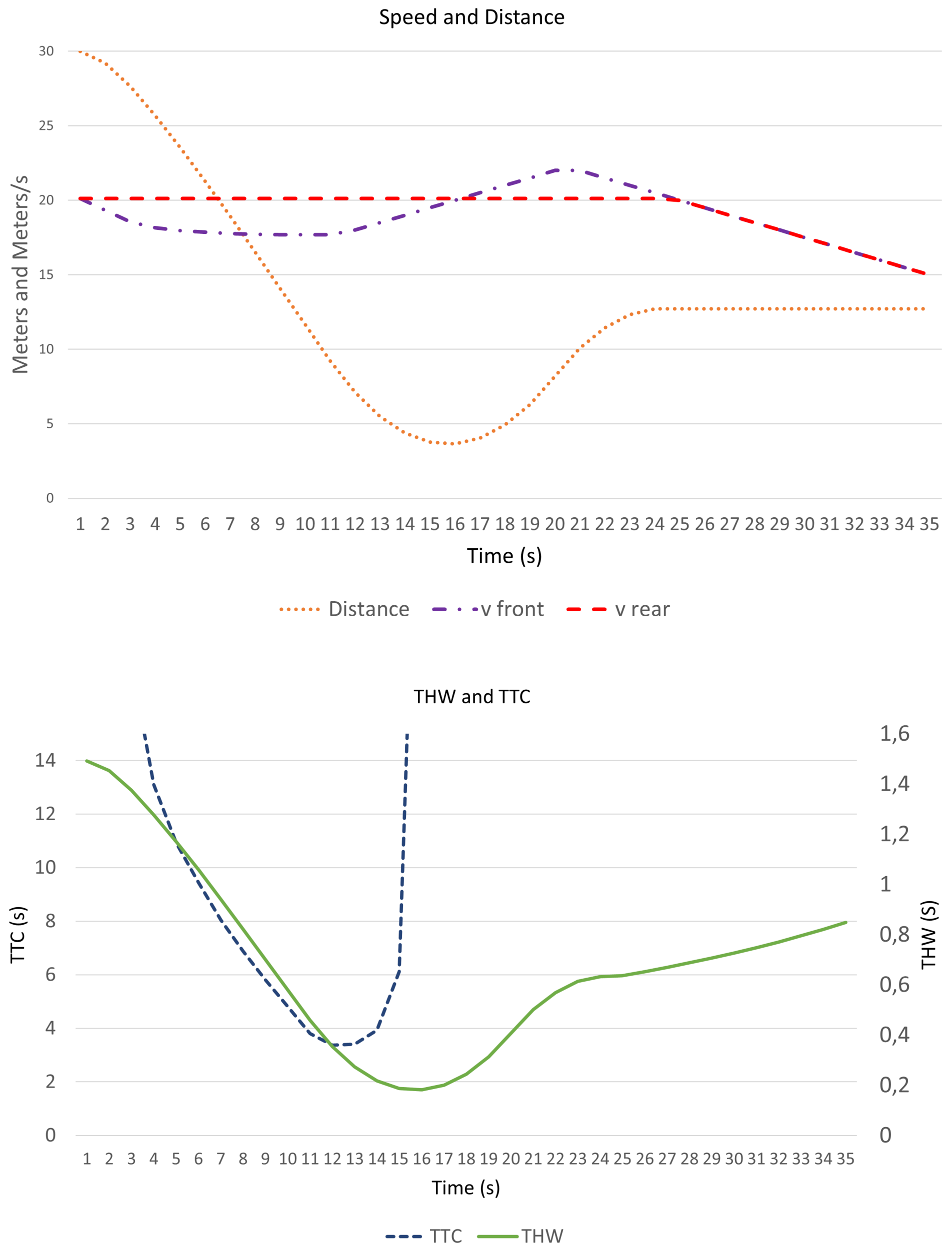


Figure 2.3: Top: Distance (orange) between two vehicles driving on the same lane as a function of each vehicle's speed (red, purple). Bottom: THW (green) and TTC (blue) for the same scenario.

2.1.4.4 Shaping the Future

So far, the process of projection has been described as a seemingly passive task where information is accumulated to narrow down the distribution of potential futures. However, one's own actions can also be a strong determinant of the future. In situations with high future ambiguity it is sometimes possible to change the odds of competing future scene developments through specific actions.

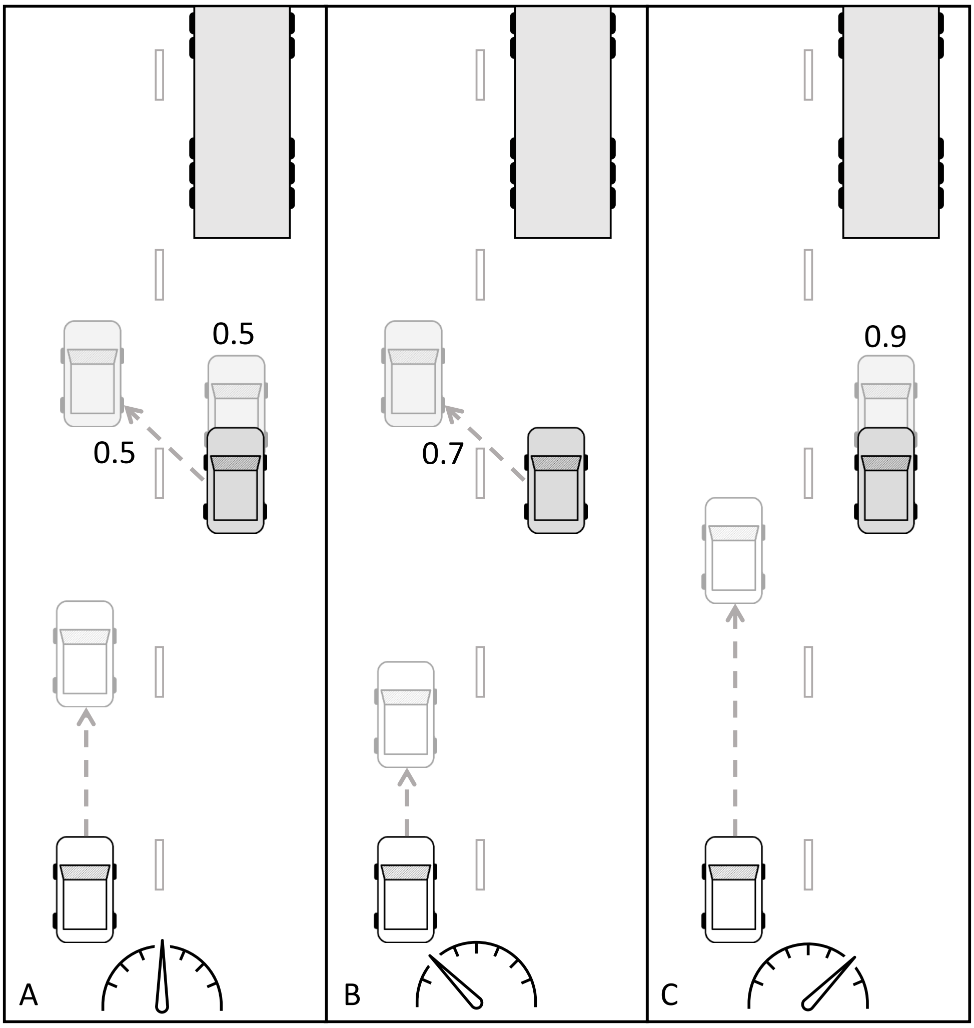


Figure 2.4: Illustration of a highway traffic scenario in which the behavior of a white vehicle on the fast lane can influence the probabilities of different possible actions for a grey vehicle driving behind a slow truck on the neighboring lane. A: If the white vehicle continues to drive at its current speed, the probabilities for the grey vehicle to change lanes or remain on its lane in the near future are roughly identical. B: If the white vehicle slows down, the probability of an imminent lane change by the grey vehicle is increased. C: If the white vehicle speeds up, the lane change probability is reduced.

As an example consider the scenario shown in Figure 2.4 where a grey vehicle on the right lane is driving behind a slow truck. The driver of that vehicle has an incentive to change lanes

in order to drive at a more desired speed. However, one's own presence (white vehicle) and approach on the faster target lane makes the near future behavior of that driver ambiguous (A). The driver behind the truck could either attempt to quickly change lanes prior to one's own arrival or wait until one's own vehicle has passed. To raise the probability for one of the two events one can either slow down (B) or speed up (C). Slowing down would widen the time gap and increase the probability of the other vehicle merging in in front of oneself. Speeding up would close the gap and increase the probability of the other vehicle staying behind the truck to delay merging, assuming that the driver behind the truck is aware of one's approach. Arguably, the gap closing comes with a higher risk because it assumes awareness about one's own vehicle and increases collision severity by the higher relative velocity.
Various situations of this kind exist in which the future decisions of traffic participants co-depend on the behavior of other agents and where one can utilize this co-dependence to actively promote particular scene developments. Such actions can serve personal goals but importantly, with respect to SA formation, can help in reducing ambiguity and complexity.

2.1.4.4.1 A Misconception of Succession

The ability for productive active interference requires an understanding about the consequences of one's own actions on the behavior of others. This relies on solving some of the comprehension and projection challenges mentioned previously, especially mental state and risk estimation. One could hence view active shaping of the future as a step that comes beyond level 3 SA. However, because here action was discussed in the context of narrowing the distribution of future states that require consideration, it is regarded not just as a result but also a contributor to situation predictions.
In fact, based on the description of challenges alone, it may have become apparent that a categorization into levels of SA has its limits and that a sequential and uni-directional SA formation, as suggested by a level terminology, may not accurately describe SA formation. For instance, when a prediction is validated by sensory evidence, then this sensory evidence was already understood before it was sampled. A pure bottom-up process only remains feasible for surprising sensory evidence. As illustrated by the current section, also action is less of a final step in a chain of information processing and decision making than an expression of understanding that is central to information sampling and may even cause some of the sensory evidence. Therefore, although a distinction between perception, comprehension, and projection can be helpful when structuring challenges to SA formation, approaches to address these challenges need not adhere to these conceptual bounds.

2.2 Supporting Situation Awareness with Driver Assistance Systems

Various forms of driver assistance to support driver situation awareness have been proposed and developed. A widely established form of assistance are methods to warn drivers about lane departures [e.g., 91–94]. Ideally, these activate prior to the actual lane departure by predicting unintentional lane departures from measures such as the time-to-lane-crossing (TLC) or sophisticated models that are personalized according to the individual driver's typical behavior [e.g., 95] to provide early and personally relevant notifications. In their reactive variants, such systems provide support either on perception and comprehension levels by compensating for failure to notice a lane departure or a failure to understand the impact of one's own current road alignment on the driving scene. Predictive variants may even directly supplement predictive SA.

Related to lane departure warnings are blind spot warning systems, which indicate the presence of vehicles in the own vehicle's blind spot using visual signals in the side mirror [e.g., 96], auditory stimuli [e.g., 97], or a combination of both. Such systems, which target spatial coverage and occlusion challenges (see Sections 2.1.2.1 and 2.1.2.2), can be particularly valuable for SA formation in preparation of a lane change maneuver and might further benefit from an increased personal relevance that may be attained by a coupling with personalized lane change predictions [see, e.g., 98]. Another type of notification about objects that are difficult to perceive or partially occluded are parking assistance notifications. These indicate, usually in auditory [e.g., 99] or visual [e.g., 100] form, how close nearby obstacles on each vehicle's side are. A distinguishing feature of these systems is that they utilize gradations of a signal component (e.g., tone repetition frequency) to encode the proximity towards an obstacle.

As described in Section 2.1.2.5, SA formation does not just include awareness about external events but also involves becoming aware of one's own physical and mental abilities to continue safe driving. Assistance systems designed to support this awareness are fatigue and driver attention monitoring systems [e.g., 101, 102]. Such systems detect irregularities in driver behavior that are characteristic for fatigue or decreased attention, such as sinking eyes or steering correction activities, to notify the driver about a supposed need for a break. Similarly subtle SA support is provided by notifications about outside temperatures approaching freezing levels, which prime drivers to pay increased attention to the roadway condition.

Another common form of assistance are forward collision warning systems [e.g., 103, 104]. Such systems typically monitor the velocity of the own vehicle, the velocity of the vehicle in front of it and the distance between the two to obtain an estimate of a collision risk in the form of a temporal distance, such as the THW or the TTC. A threshold for this risk metric is then used as a decision criterion to trigger a warning signal to a driver whenever the risk is considered high. To ensure that the warning is noticed, signals that target various sensory channels and have a high bottom-up saliency are utilized [105]. Collision warning systems hence support drivers in becoming aware of critical situations, i.e., understanding risk (see Section 2.1.4.2). As warning systems commonly utilize time criteria as a trigger, it can be argued that they facilitate temporal judgements or at least awareness about moments of transition into criticality (see Section 2.1.4.3).

For laterally crossing traffic, such as for left-turn scenarios at intersections without traffic lights, drivers must be able to judge crossing vehicle velocities and time gaps. Systems that monitor crossing traffic to trigger the presentation of warnings [e.g., 106–109] have been proposed as monitoring aids to facilitate the preparation of left-turn maneuvers on a perception, comprehension, and projection level. Notably, one such system introduced by Heckmann et al. [108] is activated explicitly on demand, and although it temporarily takes over a part of the traffic monitoring task, its verbal notifications are designed to selectively aid SA formation rather than to substitute part of it. Conceptually, it is designed to simplify the scene monitoring task (see Section 2.1.2.1) by telling the driver when it is worthwhile to check an unattended direction before initiating a driving maneuver. In line with the personal demand- or relevance-based system utilization, Orth et al. [110] found acceptance of system notifications to be further improved after personalizing acceptable gaps according to driver preferences.

The approach of taking over a sub-task but leaving action responsibility with the driver can also be found in other forms of driver assistance. A ubiquitous class are in-vehicle navigation systems, which combine map data with self-localization (e.g., GPS-based) for route planning and the creation of navigation instructions. This simplifies the task of finding a destination to just attending to and following occasional instructions and thus reduces overall perceptual and cognitive demand in driving. Reported improvements in SA [111] and driving performance [112] in unknown environments when using navigation systems suggest a shift in resource utilization by drivers. However, the use of navigation aids has also been linked to a reduction in learning and recognition of traversed environments [113, 114] as well as a deterioration of spatial orientation and unassisted navigation abilities [115]. Navigation systems that rely on graphical displays have further been associated with a reduction in road monitoring time and an increased variance in driving performance [116]. This example indicates that the introduction of assistance functions may be accompanied by tradeoffs and an emergence of dependencies. Chapter 3 will address this topic in more detail.

2.2.1 Why Driving Can Still Be Difficult

This chapter introduced several challenges that may arise in the task of gaining or maintaining situation awareness (SA) for each of the three levels proposed by Endsley [27]. Existing means and concepts for driver assistance (see Section 2.2) tackle some of these challenges, especially with regards to becoming aware of unnoticed or wrongly classified safety risks. However, it can be argued that some of the challenges for each SA level are still present despite existing assistance.

On the perception level blind spot, lane departure, temperature, and front collision warnings can help to compensate for some shortcomings of visual perception as the primary source of information. One property of such warnings is that they are the result of a classification procedure with a typically binary output: An event is either classified to meet notification criteria or not. Thus, they can also facilitate the comprehension level by directly communicating the occurrence of specific events, which reduces ambiguity. Because these events are assumed to be of high relevance to a driver (e.g., an imminent collision risk), the corresponding notifications are implemented with a high bottom-up saliency to quickly and reliably capture the driver's attention. One downside of this attention capturing property is that it can disrupt ongoing attention processes [105]. So if not just the notification-driven event but also previously attended elements of a scene are of high relevance, the assistance system may not only have disrupting but also distracting properties.

This potential issue becomes especially evident in cases of false positive (FP) classifications (false alarms) that conflict with the remaining sensory evidence. Frequent false alarms can lead to a so called cry wolf effect [117, 118], referring to the ignorance of alarms that have been wrong in the past and, in consequence, to an ineffectiveness of the warning system. The presence of false alarms is typically an indication of a conservative classification threshold, set to avoid missing any situations in which an alert would be justified. Conversely, changing this threshold in order to reduce the number of false alarms can introduce false negatives (misses), i.e., failures to alert in response to an existing hazard. Also false negative (FN) classifications produce discrepancies with other sensory evidence. They are not only problematic as a variant of system failure but also because they have been found to delay reactions to critical events compared to unassisted driving [119]. Binary warning systems or other forms of assistance that classify specific events hence require particularly high sensitivity and specificity[5] to avoid negative interference with driver competence. However, what level of risk is considered as *appropriate* for a warning is not necessarily agreed upon between different drivers. To improve sensitivity and specificity on a subjective level, warning systems with personalized threshold adaptations have been proposed [e.g., 95, 98, 110, 120, 121][6]. In general, personalization and the conceptually related *proficiency awareness* [123] thus appear to be promising approaches for improving the subjective relevance of driver assistance systems with notification or warning capabilities.

But also perfectly accurate and personalized notifications about relevant events can still be problematic. Among the challenges listed on the comprehension level were also those of overcoming negative effects of experience and routine (see Section 2.1.3.4). An event-triggered signal can help in mitigating negative effects of routine, including *looked but failed to see* cases, by creating an additional stimulus that informs about such cases when they are classified as relevant. However, risky behaviors, which experienced drivers may have gradually become accustomed to, are not necessarily made transparent by signals that only occur close to critical events. In extreme cases drivers may operate just below signaling thresholds and terrorize their environment by provoking near-accident situations [see, e.g., 74, 75].

Another issue of salient binary warnings is that they tend to be late: they indicate that an event of interest has just occurred or is about to happen. This property may help in mitigating cry wolf effects but also gives drivers relatively little time to utilize the conveyed information. Especially for collision warnings this property cuts across the need to react as early as possible in a foresighted manner and possibly even prevent a situation from escalating to dangerous levels in the first place. One might thus be inclined to conclude that there exists a fundamental trade-off between the time, which an assistance signal affords for a driver reaction and its acceptance by the driver, and that the selection of accurate and acceptable signaling thresholds marks the limits for effectiveness of SA-supporting driver assistance. But such a conclusion would be premature.

One strategy to mitigate classification-related issues lies in shifting the scope of signals to also respond to events of reduced urgency by design. Hoffmann and Gayko [124] have suggested that a cry wolf effect is more likely to occur for critical warnings than for less critical and rather informative signals [see 125]. Indeed, Naujoks et al. [125] who distinguished between *false alarms* (alarms without any obvious reason) and *unnecessary alarms* (alarms in the presence of traffic participants, which could be inferred as the cause of the alarm), found a link between alert compliance and warning urgency for *false* but not for *unnecessary alarms* [125]. However, Naujoks et al. distinguished between more and less urgent signals based on the number of modalities through which the warning is provided, rather than based on the presumed situation

[5] Sensitivity (true positive rate): $TP/(TP+FN)$; Specificity (true negative rate): $TN/(TN+FP)$

[6] See Hasenjäger, Heckmann, and Wersing [122] for a more comprehensive survey of personalization in advanced driver assistance systems.

urgency (early vs. late warnings). But also for what Sorkin, Kantowitz, and Kantowitz (1988) refer to as *likelihood alarm systems*, graded alerts that become more prominent with increasing event confidence, a reduction of the cry wolf effect has been observed alongside an increase in trust and more appropriate driver responses [127].
Graded signaling also has further theoretical advantages: With binary event-based situation classifications it is difficult to capture and convey dynamic aspects of a situation. Yet driving is an inherently dynamic activity in which the surroundings continuously change and must be sampled at corresponding rates. In the example of hazard recognition, a driver may not just benefit from knowing that an object is a hazard but also whether it approaches or recedes, and in the former case, at what rate this occurs so that appropriate future actions can be planned. Binary notifications can inform a driver about the presence of hazards but graded notifications can add further dimensions about dynamically changing aspects, such as event probability and spatial or temporal distances.
Another issue that may require further support is the understanding of the mental states of other drivers (see Section 2.1.3.5), especially their intentions and awareness of the environment. If such mental states could become more transparent, drivers could more accurately anticipate traffic events and might further be incentivized to adopt more empathetic behaviors. Means to monitor driver behaviors already exist for the purpose of informing in-vehicle systems such as fatigue [101] and workload [128] detection. However, relatively little effort has been put into promoting the transparency of mental states further on the level of SA-support[7].
Another introduced challenge that impacts SA formation on multiple levels is complexity (see Section 2.1.3.2). An increase in complexity can entail an increased perceptual demand, higher situation ambiguity, and reduced predictability. Accordingly, various driver assistance systems and concepts attempt to reduce situation complexity by taking over subsets of the driving task such as longitudinal vehicle control [e.g., 129, 130] and lane keeping [e.g., 92, 131]. This form of assistance alleviates the driver's burden and may help in coping with challenging situations. But does this also suggest a gain in driver SA? On the contrary, the previously mentioned link between task demand [52, 57, 58, 60] and vigilance suggests that a facilitation of the driving task may actually decrease driver task engagement, vigilance, and, in consequence, situation awareness.

In conclusion, while existing means of driver assistance address a subset of challenges in making drivers situation-aware and thus more competent in the driving task, limitations of these systems and promising alternative approaches suggest that there is still potential and need for more effective means of assistance. The following two chapters will discuss the impact of different classes of assistance on driver competence in more detail and then focus on one class of approaches that might be suitable for tackling some of the discussed open challenges.

[7]See, e.g., Krüger and Wiebel-Herboth [17] for an approach to achieve transparency about the perception states of other traffic participants.

2.3 Chapter Summary

This chapter described several challenges for the formation and maintenance of driver situation awareness (SA) on the levels of perception, comprehension, and projection. Visual perception was highlighted as a primary source of information that is subject to spatial and temporal processing limitations and which can be physically impaired by occlusion and lighting conditions. Further challenges on the perception level were the influence of distracting elements in the scene, which compete with more valuable sources of information, particularly for inexperienced drivers, and the fatigue level of the driver.

On the comprehension level, the integration of perceived visual and vestibular signals was introduced as one example for how perceptual limitations may propagate upwards. The effects of scene complexity and ambiguity on the validity of comprehensions was discussed. The opacity of mental states of other traffic participants was presented as one cause of ambiguity. Furthermore, a different perspective on the role of experience was adopted to highlight issues such as acquired bias and overconfidence.

On the projection level, the task to predict future states was depicted as a selection of feasible scene developments based on what is known about the current state of the environment. As predictions go further into the future, multiple feasible future states may have to be considered for each presently feasible future state. This relates to the previously discussed ambiguity of the current state, which further amplifies the combinatorial explosion of future predictions. The use of relevance criteria, such as probability and severity, was discussed as a tool for selecting subsets of future states. A challenge on the projection level thus lies in acquiring such severity and probability estimates. In addition, the possibility of further pruning the tree of the future through one's own actions was highlighted. Such active interference concludes the SA chain of perception, comprehension, projection, and action but also partially reverses it because actions are not just results of but also contributors to predictions. The first part of the chapter therefore concluded that an adherence to conceptual bounds between perception, comprehension, and projection may not be necessary for the development of situation awareness support systems.

The second part of the chapter discussed existing approaches to circumvent SA challenges by various means of driver assistance. These include lane departure warnings, blind spot signals, parking assistant systems, area monitoring systems, and forward collision warnings. Many of the systems rely on a risk classification threshold to trigger a warning, making them susceptible to a tradeoff between stimulus timing and assistance acceptance. Graded signaling was discussed as a possible remedy that could further help to address the challenge of making drivers more aware of dynamically changing aspects of a scene early on. The reduction of task demands, which many assistance systems have in common, was identified as another factor with potentially undesirable properties due to its influence on driver vigilance. It will therefore be further addressed in subsequent chapters.

3

Three Approaches to Driver Assistance

"That which is used – develops. That which is not used wastes away."

Hippocrates of Kos

Driver assistance systems follow a variety of general approaches. Some increase safety by taking over subtasks from the driver completely, others facilitate information perception and vehicle handling for the driver, and a third type of approach is characterized by shared control functions. They all have in common that they provide competence for driving-related tasks. This chapter describes how the approach by which such competence is supplied can vary on a fundamental level with distinct consequences.

Contents

3.1 Publication Disclosure 36
3.1.1 Bibliographic Information 36
3.1.2 Author's Contribution 36
3.2 Substitution 37
3.2.1 Substitution Opportunities 37
3.2.2 Substitution Challenges 38
3.3 Cooperation 39
3.3.1 Cooperative Driver Assistance 40
3.3.2 Cooperation Definitions 41
3.3.3 The Price of Cooperation 41
3.4 Augmentation 42
3.4.1 Augmentation in Driving 45

3.1 Publication Disclosure

Sections 3.2 (Substitution) and 3.3 (Cooperation) of this chapter contain elements that have been previously discussed in the publication "From Tools Towards Cooperative Assistants" by Krüger, Wiebel, and Wersing, which was published at the fifth international conference on Human-Agent Interaction (HAI 2017) in Bielefeld, Germany. Because the context of this publication varies from the purpose of this chapter, no section excerpts of this publication have been included in the main body of this dissertation. Unless specified otherwise, segments that semantically overlap are not quotes of publication segments but are newly written to better serve the reading flow and reasoning of this chapter. Several references to Krüger, Wiebel, and Wersing [1] are provided accordingly.

3.1.1 Bibliographic Information

[1] Matti Krüger, Christiane B. Wiebel, and Heiko Wersing. "From Tools Towards Cooperative Assistants". In: *Proceedings of the 5th International Conference on Human Agent Interaction - HAI '17*. ACM. New York, New York, USA: ACM Press, 2017, pp. 287–294. ISBN: 9781450351133. DOI: 10.1145/3125739.3125753.

3.1.2 Author's Contribution

Personal contributions to publication Krüger, Wiebel, and Wersing [1] according to the Contributor Roles Taxonomy (CRediT) [24]:
Conceptualization, investigation, methodology, visualization, writing - original draft, writing - review & editing

3.2 Substitution

When a technology is sufficiently advanced and reliable to assume autonomous control over a given task, it may not require any interference by a human user during system operation. If a given task was handled by the user prior to the technology introduction, this technology is *substituting* the user in the task[1]. Typical everyday examples are doing the laundry and dish washing. Both tasks can be carried out manually, but dedicated machines are available to take over various steps of the cleaning process. Within vehicles, manual gear shifting is successfully being substituted by automatic transmission, adaptive cruise control (ACC and iACC[2]) can take over longitudinal control of acceleration and braking, and autonomous driving ultimately targets a full substitution of driver tasks by an autonomous system. Indeed, the path towards autonomously driving cars is commonly depicted by successive levels between which human responsibilities are incrementally substituted by machine components [132].

3.2.1 Substitution Opportunities

Substitutive functions, which take over tasks previously assigned to people, can reduce workload and liberate human mental and physical resources: With automatic transmission a driver can keep both hands on the steering wheel and does not need to coordinate between clutch, gas, and gear shift while simultaneously monitoring traffic and maintaining a target trajectory. In theory, such free resources may then be utilized to improve performance in remaining tasks. But a substitution is not necessarily permanent and "autonomous systems" are often only autonomous within specific conditions. For example, in the case of adaptive cruise control, the automatic longitudinal vehicle control presently requires manual activation and is only available when specific traffic requirements are met [see 1]. The temporal substitution of longitudinal control is thus accompanied by at least two new responsibilities for drivers to a) monitor whether requirements for safe ACC use continue to apply and b) to be able to reassume longitudinal control flexibly when required by changed environmental conditions. Delayed driver reactions to critical events during ACC use [133–135] indicate that drivers may have difficulties in fulfilling these added responsibilities. On the other hand, such reduced reaction times might arguably be counterbalanced by benefits of workload reductions [136, 137] and potential improvements in situation awareness associated with ACC use [e.g., 136] [but cf. 137, who observed reductions in SA]. De Winter et al. [138] found an ACC-associated decrease in SA only when drivers were also engaged in non-driving secondary tasks. The continued need to monitor traffic for lateral control could offer an explanation for a partial mitigation of negative effects.

[1] Substitution may also occur without autonomous systems that are driven by their own feedback loops. Various everyday tools may be framed as substitutes of operator resources in specific tasks. However, as they are typically operated within a person's sensorimotor loop, enhancement might be a more fitting term then substitution in such cases. Accordingly, the present section only refers to substitutive technology with alleged autonomous capabilities.

[2] Intelligent adaptive cruise control: An extension of the classical ACC with added prediction capabilities about the behavior of other road users to create smoother anticipatory cruise control [129].

3.2.2 Substitution Challenges

Beyond the scope of pure ACC, e.g., with a joint substitution of longitudinal and lateral control by an automated system (SAE automation level 2 [132]), a sufficient mitigation of negative effects through monitoring might no longer occur. While the vehicle automation takes care of steering and accelerating, there is no or only rare need for driver action. Consequently, any sampling of information from the environment no longer serves continuous adjustments but rather an occasional interference in case the system reaches its limits. This kind of monitoring for rare events appears to be particularly problematic for human operators [134, 139–141].

As generalized by Parasuraman and Riley [142], automation in HMI cannot be assumed to only substitute human activity and responsibility but it changes it in ways that can be difficult to anticipate during design [see 1]. These changes may create new demands for human operators [143, 144]. Especially challenging appears to be the use of automation that takes over basic and frequently occurring tasks within defined function boundaries but leaves handling of rare and abnormal events in the hands of a human operator. A continued lack of engagement in the automated task has been found to make drivers more passive and less vigilant [140, 145]. This *loss of expertise* [145] has the consequence that identification, understanding, and handling of situations that surpass automation capabilities are even more difficult when interacting with an automated system than with one that is operated manually [see 1]. As Bainbridge [146] put it: “By taking away the easy parts of his task, automation can make the difficult parts of the human operator’s task more difficult”. More generally, substitutive automation is not only substituting a human in handling the specific task it carries out but also (indirectly) disturbs the ability of an operator to carry out any task that depends on the substituted skills or impaired expertise. This kind of dependency-related responsibility must be accounted for in the development of new functions targeted at making aspects of a task easier for users.

In an analysis of interaction failures with automation, Hoc [145] identified four main types of problems that can occur. In addition to the previously illustrated *loss of expertise*, also *complacency*, *poorly calibrated trust*, and *loss of adaptability* are typical issues [see 1]. Automation complacency refers to a phenomenon where operators of automated systems accept automation output without questioning it. It is a neglect of automation supervision or, more generally, a neglect to gather information that would be required for appropriate function utilization [147]. For some applications, complacency may hence be regarded as a possible outcome of continued disengagement and loss of expertise. Complacency is also an indicator for overtrust in automation, one direction of *poorly calibrated trust*. The other direction is distrust of a trustworthy automation. While overtrust can mean that automation failure will not be detected or corrected [148], high distrust can result in an automation simply not being used at all, thus rendering it useless. Experience with an automated system could help an operator to form a correct understanding of the automation and to calibrate trust appropriately. However, one crucial component of adapting one’s understanding is to have feedback that either confirms or contradicts prior assumptions. An inherent problem of basic automation is that it lacks feedback about the task it automates. Being *out-of-the-loop* due to automation therefore creates a *loss of adaptability*, which impairs the ability to correctly handle the automation itself. The loss of adaptability has been argued to promote reactive strategies in operators while discouraging anticipatory behavior [145, 149].

An employment of substitutive automation that does not reliably carry out its function in all target situations should hence generally be assumed to be accompanied by impairments for the person utilizing it. The *substitution myth*, one of the so-called *Seven Deadly Myths of "Autonomous Systems"* [141], denotes the assumption that machines should incrementally substitute human functions with increasing levels of automation. Bradshaw et al. [141] state that this substitution principle, as well as the mere concept of automation levels are ill-suited for guiding technological development in many cases. Instead, it is important to understand that the employment of machine automation fundamentally changes the role of the human operator, which has to be considered in the design of human-machine systems. The previously mentioned level-driven path towards autonomously driving vehicles [132] might be an example for an insufficiently reasoned strategy. Moreover, even perfectly reliable self-directed automation, which requires no monitoring, can have deteriorating effects on human performance in other tasks due to partial dependence on substituted activities and skills. Substitutive automation therefore carries responsibility beyond its intended scope. Because the scope of this responsibility and the requirement for mitigation efforts is not always known in advance, an empirically guided and iterative development may be advisable prior to any automation employment in human-machine systems.

In summary, autonomous technology that substitutes human responsibilities carries the potential to reduce workload and liberate human resources. At the same time, such substitution also entails a variety of risks for human operators, including loss of expertise, automation complacency, poorly-calibrated trust, and loss of adaptability [145] [see 1]. These risks can theoretically be linked to the disengagement created by removing the substituted operator from relevant feedback loops. Because such feedback loops do not necessarily only serve substituted functions but also remaining and newly emerged operator responsibilities, such as monitoring for automation boundaries, the responsibility scope of substitutive technology can go beyond the basic function it implements and should therefore be investigated prior to automation employment.

3.3 Cooperation

The previous section discussed substitution by automation as one approach for human-machine interaction that is accompanied by a change of human responsibilities, resulting in various challenges. In addition to these challenges, one major drawback of the use of substitutive technology is that it can leave valuable resources underutilized: Fundamentally, a substitution of one component by another makes the substituted component redundant or even obsolete. But this is not a necessary outcome. Replaced components can also find new purpose and be utilized in conjunction with newly introduced components to create synergies [see 1]. In such a case, *cooperation* appears to be a more appropriate description of the relationship between old and new components than substitution.

The Oxford dictionary of current English [150] defines the verb *cooperate* as "work or act together in order to bring about a result". Accordingly, a *cooperative* approach to HMI development is characterized by a synergy objective and may result in a more efficient and effective utilization of available capabilities and resources in some situations.

3.3.1 Cooperative Driver Assistance

As mentioned in Section 3.2, in the automotive domain driver assistance development is commonly described in terms of automation levels [132], thus taking a substitutive perspective in which driver responsibilities are replaced step by step.
From a cooperative perspective, driving responsibilities would not be replaced by another component but be shared with it. A driving system that relies on a joint engagement of driver and assistance can potentially broaden its application scope through access to each involved agent's capabilities. For example, consider a driver assistance system that is in charge of monitoring regions that are difficult for a driver to monitor such as blind spots on the sides. In case a detected object in the blind spot should become relevant to the situation, for instance, prior to a lane change attempt, the system could use this information to interfere with maneuver execution when necessary. To account for both the goal of maintaining safety and the driver's identified lane change intention, this interference should ideally consist of a defusion instead of a prevention of a lane change maneuver (e.g., a brief velocity reduction to allow the blind spot object to pass quickly). The realization of such a cooperative assistance has specific requirements:

3.3.1.1 Cooperation Requirements

First, the assistance system requires means of sensing the presence of possible blind spot hazards as well as events that are indicative of a driver's lane change intention. For instance, a driver's intention may be revealed by the actual lane change maneuver or through the use of the indicator handle. While the former event would only permit a late intention detection, the latter can be earlier but less reliable. A detection of behavior patterns that precede lane change initiation, such as characteristic eye movements, could increase the prediction horizon and accuracy.
Second, the assistance system requires the capability to estimate the safety of an intended lane change by relating it to identified hazards. Generalized, the desired state is compared to a safety goal that is shared between assistance and driver. If an incompatibility of the safety- and the lane change goals is detected, an interference must be planned. This interference can be guided by multiple goals such as a primary (shared) safety goal and a secondary lane change goal. When feasible, the interference delays lane change execution until safety can be guaranteed, otherwise it prevents it. Overriding the actions of a cooperating partner is a violation of the partner's autonomy for the sake of a prioritized cooperation goal. The authority for such interference may be justified by a difference in competence, i.e., the specialized assistance system may have higher awareness of hazards in blind spots than a driver who mainly focuses on the front. Nevertheless, a driver's higher awareness of elements in the front can also be argued to give him higher competence in maneuver planning. The initial interference by the assistance implicitly provides information about the blind spot presence of a hazard. The driver might still judge the risk of an imminent front collision to be higher than that of a side collision and still wish to carry out a lane change. Consequently, with such a competence distribution the driver would benefit from an ability to also interfere with assistance interference when necessary. The cooperation should thus allow for mutual interference and make each interference transparent to the partner.
In summary, in addition to the foundation of working together, cooperative driver assistance relies on an ability of each cooperating agent to sense and interpret aspects of a scene, relate these to the attainment of a common (safety-) goal, plan, and carry out interfering actions in

case the goal is in jeopardy. Such actions may constructively interfere with those of cooperating agents. Each agent's actions and intentions should therefore be sufficiently transparent to allow agents to form a mutual understanding and, if necessary, negotiate and exercise authority.

3.3.2 Cooperation Definitions

The elements of this summary align well with existing definitions of cooperation [see 1]. For example, Hoc [151] states:

> "Two agents are in a cooperative situation if they meet two minimal conditions. (1) each one strives towards goals and can interfere with the other on goals, resources, procedures etc. (2) each one tries to manage the interference to facilitate the individual activities and/or the common task when it exists. The symmetric nature of this definition can only partly be satisfied."

Notably, Hoc's definition includes both the guidance by goals and the management of interference with operations by both cooperating agents. It does not necessitate a sharing of the goals that drive the actions. Bratman [152] has added the concept of *mutual support* to his definition of *shared cooperative activity*. This mutual support describes the willingness of each agent to support the other in fulfilling their role in the cooperative activity.
Our own attempt [1] to grasp the concept of cooperation in a human-machine interaction context has led to the following definition:

> "Cooperation occurs between agents if they adapt to the states and actions of the other agent in a manner that facilitates the realization of a shared cooperation goal. This adaptation requires mutual models and understanding with respect to the intentions, actions, and plans that are relevant for goal realization. The development of such models requires mutual transparency and communication of relevant variables by the cooperating agents. Cooperative assistance is then the application of the cooperative human-machine interaction principles to a human-supporting system."

This definition necessitates a common goal and emphasizes the requirement for mutual transparency and communication as the basis for mutual modeling and adaptation of operations. Adaptations serve as a substitute for the interference term used by Hoc to allow for an inclusion of complementary non-interfering actions. Figure 3.1 illustrates the components and relations of this definition.

3.3.3 The Price of Cooperation

One factor that all definitions have in common is that all cooperating entities are understood as at least partially autonomous agents. Each agent has its own understanding of involved factors, its own means for sensing and operating in an environment, and its own feedback loops. Despite this autonomy, cooperating agents require means for making sense of and even interfering with other agents or adapting their actions in a constructive way. Requirements for cooperative systems do therefore even go beyond those of autonomous systems and can raise complexity.

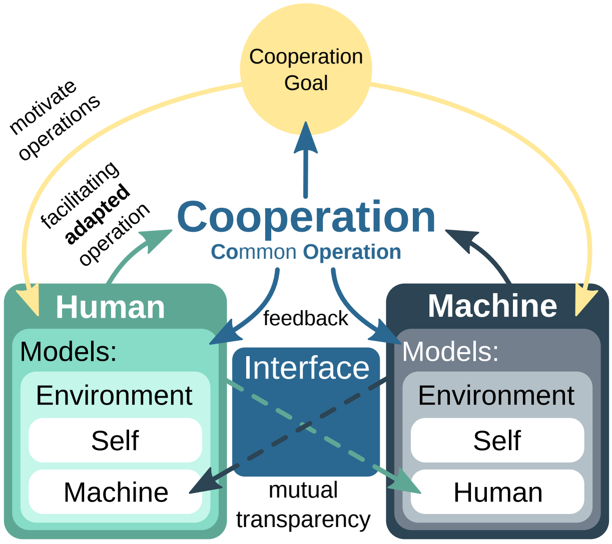


Figure 3.1: Illustration of components of cooperative assistance in human-machine interaction according to Krüger, Wiebel, and Wersing [1]. Each agent (human and machine) should be able to relate each other's states and actions to the realization of a common cooperation goal. Both should adapt their own states and operations such that goal realization is facilitated. Adapted operations require a mutual understanding (models) of one another in relation to the operation environment. To inform such models, the agents must provide sufficient transparency through appropriate interfaces. Furthermore, when required, interfaces serve as a platform for responsibility negotiation. Image source: Krüger, Wiebel, and Wersing [1].

While cooperative systems can be a desirable way to create synergies without making available resources obsolete, they are also costly in the sense of their increased requirements when compared to substitutive automation. In the development of human-machine interaction scenarios it can hence be sensible to determine whether the cost of substituting a person's task outweighs the cost of additional requirements to achieve cooperative interaction and whether the capabilities gained from cooperation are required for achieving the desired goals.

3.4 Augmentation

Section 3.2 described how substitutive automation can lead to adverse effects and that these effects may partially be attributed to the disengagement of people from task-relevant feedback loops. With a subsequently introduced cooperative approach to human-machine interaction (3.3), human and machine still use separate feedback loops but facilitate an exchange of information and mutual interference or adaptation while striving for a common goal. This counteracts disengagement and maintains available resources but also increases complexity and requirements. The question arises whether out-of-the loop effects in HMI may also be avoided with lower interaction complexity.
A third type of human-machine interaction, further referred to as *augmentation* [153], is one approach to fulfilling that role. The idea behind augmentation is to utilize technology for providing additional capabilities to a person directly[3]. The added capabilities then serve an expansion of

[3]An alternate term that carries a similar meaning is *amplification*, coined by Schmidt [154]. The use of this

the scope of situations the augmented person can handle, or improve the probability of success in tasks, compared to performance without augmentation. Augmentation may occur at any processing level, i.e., during perception, comprehension, projection, or action. Augmentation at the perception level (augmented perception) then refers to cases where technology gives people a richer access to environmental information. Augmentation at the action level (augmented action) describes having additional means of acting in the world, e.g., in terms of mobility or manipulation. Augmentation at the comprehension and projection levels loosely indicates improved abilities in processing, comprehending, memorizing, relating, or extrapolating information. Nevertheless, following the argument outlined in Chapter 2, Sections 2.1.1 and 2.1.4.4, ultimately, performance on the different levels is interconnected.

In the case of driving, an example for perception augmentation would be a visual highlighter of low-visibility elements in the environment. For instance, at night or other low visibility scenarios it can be difficult to spot wildlife on or near the road. Technology that is available to a vehicle, such as radar, lidar, or infrared cameras, may still recognize animals with high accuracy and temporal resolution. Creating a high-contrast overlay in the driver's field of view through a head-up display (HUD) or augmented reality (AR) glasses can support the driver in also recognizing animals more easily. An example for additional augmentation on the comprehension level would then be to provide further information about the identified animal in order to speed up appropriate consideration of this animal in the planning of subsequent actions. For instance, if available, the animal's recent locations could be highlighted together with its current location to facilitate a driver's inferences about the scenario development. The addition may be categorized as an augmentation of the driver's short term memory to potentially even include information about events the driver has not directly perceived.

One characteristic that is central for a classification as augmentation within this thesis is that the added capabilities should integrate into an action-perception feedback loop of the augmented person. Figure 3.2d illustrates this characteristic. Through an interface between human and machine, the human operator can gain access to machine capabilities such as its sensing or actuation mechanisms. The recruitment of these mechanisms is controlled by the user and they serve their purpose only in active utilization, not by themselves[4]. In contrast, in the cases of substitution (3.2b) and cooperation (3.2c) the machine has a separate feedback loop. The inclusion of machine capabilities in the user's own action-perception loop counteracts negative out-of-the-loop effects by design. A user needs to be engaged in the task through the machine in order to make use of the machine's capabilities. In consequence, the utilization of augmentation is closely aligned with user demand. Augmentation further allows for the creation of synergies with fewer requirements than cooperation by leaving the responsibility for the integration of capabilities on the user side.

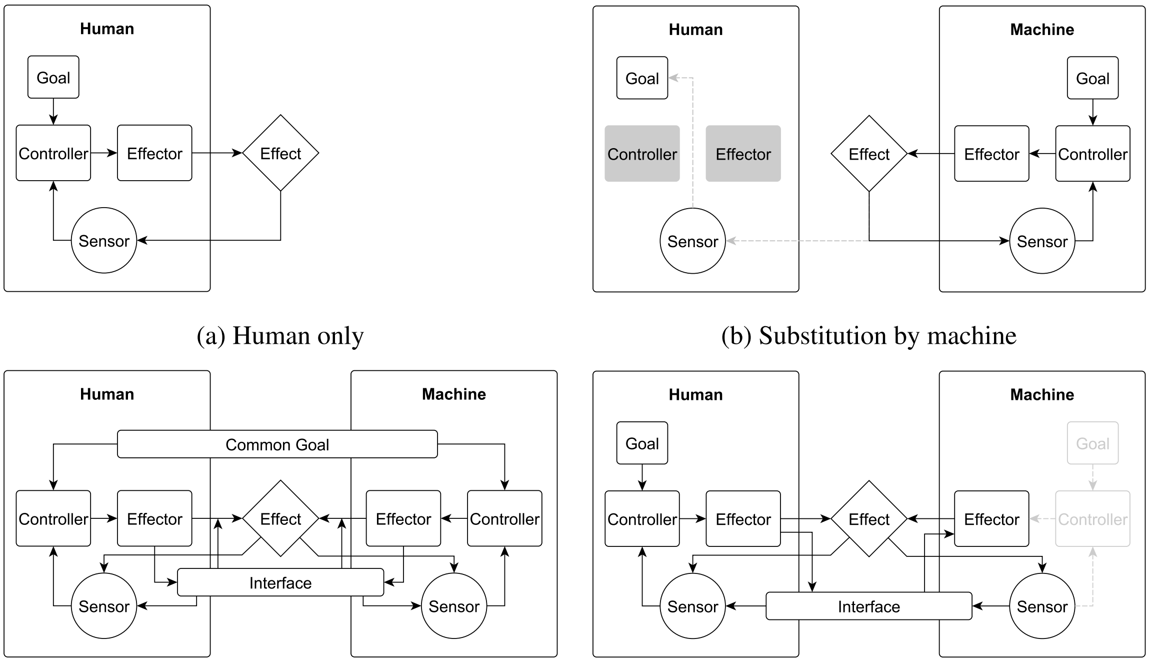
The need for user engagement is also a limiting factor for augmentation. When the human user is essential to carrying out a task, any interference, which the user is subjected to, can also interfere with the utility of the augmentation function. For instance, a tired driver will be

term carries the additional connotation that the technology should strengthen human abilities and not just add to them [154].

[4] There may still be internally controlled mechanisms maintained through separate feedback loops. However, such mechanisms would typically operate on parameters that are not necessarily accessible on the user level. An example would be automatic camera-sensor sensitivity adjustments based on illumination conditions.

impaired in his ability to process information about the environment irrespective of whether it originated in the driving scene or a visual overlay. Furthermore, a requirement for engagement also means that a user needs to have a correct understanding of the augmentation function. However, here it can be hypothesized that the inclusion in the user's feedback loop supports a quick development of an appropriate function understanding. For instance, errors or inaccuracies in augmented sensory data implicitly convey information about the quality of signals, which a user can use to calibrate trust.

In summary, augmentation can be a suitable approach to guide the development of human-machine interaction for scenarios in which active user engagement is required and where synergistic effects are targeted. Compared to a cooperative approach, its reduced complexity overhead is accompanied by a stronger dependency on user capabilities.



(a) Human only

(b) Substitution by machine

(c) Human-Machine cooperation

(d) Augmentation by machine

Figure 3.2: Differentiation of unassisted control (3.2a), machine substitution (3.2b), human-machine cooperation (3.2c), and human augmentation (3.2d) in terms of control- and feedback loops. Structures are abstracted and simplified for illustration purposes. Arrows indicate flow and direction of signals. Dashed arrows and grey outlines (3.2d) illustrate optional links and components. Boxes with a grey background (3.2b) indicate obsolete components. 3.2a: On their own, humans can attribute changes in the environment to their past actions and adapt their subsequent actions if necessary. 3.2b: When a function is substituted by machine automation, the machine establishes its own feedback loop for the substituted function. A human user is excluded from that feedback loop. 3.2c: In a cooperative scenario human and machine feedback loops are maintained and even expanded to also allow for a modeling of the cooperation partner. Actuation further includes the possibility of interference with the partner's actions to facilitate achievement of a common goal. 3.2d: In an augmentation scenario machine capabilities are incorporated into the human perception-action feedback loop through corresponding interfaces.

3.4.1 Augmentation in Driving

Driving a car could be a particularly suitable field of application for augmentation-based support. As described in Section 2.1, there are various challenges that can render a driver's existing capabilities insufficient to guarantee safety. Many of these challenges further relate to keeping track of agents in the environment. This would make simultaneous active coordination with and modeling of a cooperating assistance system an additional interfering burden for a driver, whereas an improved access to scenario information through augmentation could facilitate the formation of situation awareness and situation handling.
The following chapter connects the concept of augmentation to a selection of theories and findings about how humans form an understanding of their environment to further substantiate these claims and expound a theoretical foundation for the development of a specific form of mobility assistance.

4

Enacting a World of Anticipations

"We sample the world to ensure our predictions become a self-fulfilling prophecy and surprises are avoided."

Karl Friston, *[155, p. 295]*

The previous chapter discussed properties of three classes of human-machine interaction (HMI) and their consequences for driver assistance applications that incorporate their respective properties. Augmentation, one of these three classes, was identified as a particularly promising HMI principle for driver assistance. One perspective on augmentation is to see it as a quality that allows users to expand their capabilities by perceiving, acting, or reasoning *through* added technology. But how can this quality be achieved?

This chapter outlines a selection of theories and discoveries that can help in finding an answer to this question. As described in Section 2.1.1, one's understanding of the environment and the ability to act in it are ultimately informed by data gathered through sensory organs. Yet, various actions such as eye movements (see Section 2.1.2.1) and changes in head or body orientation often have the re-orientation of sensory organs and thereby selective data sampling from regions of interest as their main purpose. Action and perception thus appear to be closely linked: Perception informs action and action informs perception. This apparent link has lead to a variety of action-based theories of perception.

Contents

4.1 Reafference 48

4.1.1 Reafference Theory 49

4.2 Information 50

4.2.1 Multimodal Integration 50

4.3 Sensory Modalities 51

4.4 Enaction 52

4.5 Augmented Driving as a Sensorimotor Process 54

4.5.1 Sampling from the Future 55

4.1 Reafference

In 1823 and 1825, Bell [156] and Purkyně [157] [see 158] independently described a simple experiment that lead to an influential concept: When people move their eyes to shift the point of fixation, the world is perceived as stable and does not move together with the eyes. But when one eye is closed and the other (open) eye is slightly moved through a gentle push with a finger on the eyelid, the perceived image of the world is displaced. Bell and Purkyně suggested that there must be a signal generated by active eye movements that compensates for the motion of the retinal projection that it produces, resulting in the perception of a stable environment and that such a signal is missing when movement of the retinal projection is passive. Based on experiments with scene distorting prisms and patients who had damaged eye muscles, preventing them from certain eye movements, von Helmholtz [25] added that neither muscle proprioception, nor successful movement execution but rather the intentional effort ("Willensanstrengung") to perform a gaze change is central to perceiving retinal projections as stable or in motion [see 158].
Holst et al. [159] concluded from experiments with artificially handicapped flies that the oculomotor system creates *efference copies* of motor commands to eye muscles that are then subtracted from subsequent afferent retinal input in order to cancel out effects of self motion from motion perception. They called this principle *reafference* and proposed it as the basis for distinguishing between self-caused (*reafferent*) and externally caused (*exafferent*) sensory information. Based on this principle, only differences between sensory afferent signals and efference copies lead to the perception of motion. Figure 4.1 illustrates the reafference principle within an expanded diagram of a human sensorimotor feedback loop.

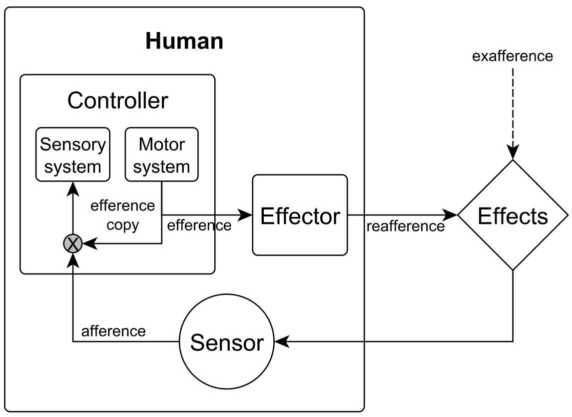


Figure 4.1: Illustration of the reafference principle within an expanded diagram for a human sensorimotor feedback loop (see Figure 3.2a).

In primates, a neural circuit for saccadic reafference or corollary discharge[1], involving superior colliculus, thalamus, and the frontal eye field (FEF), has since been identified [161, 162]. Physiological support for a link between reafferent signaling and perceptual stability in primates was discovered by Duhamel, Colby, and Goldberg [163]. They identified neurons in parietal cortex for which the receptive field (RF) shifts to a future gaze location prior to a corresponding saccade. Similar predictive responses have been identified in cells of the monkey FEF [165]. Sommer et al. [162] found that deactivation of the mentioned circuit for saccadic reafference indeed reduced such anticipatory activity in the frontal cortex, suggesting that signals from the medial dorsal nucleus of the thalamus to the FEF carry reafferent information that informs RF remapping.

4.1.1 Reafference Theory

The principle of reafference has been hypothesized to be an example for a more general mechanism of internal monitoring in order to anticipate what will happen as a consequence of one's own actions, not just on a motor level, but also for higher cognitive processing [e.g., 166] [see 167]. Similarly, Held and Hein [168, 169] proposed that reafference could be the basis of a general model of perception and perception-guided action in which movement information from efference copies is not the sole determinant but a contributor to a prediction about sensory consequences of movements. They further suggested that not only eye movements but any kind of movement may contribute to reafferent stimulation. This view, which is reminiscent of von Helmholtz's conclusions [25, p. 473], also finds support in theories about roles of other neural structures such as the cerebellum, which has been hypothesized to act as a predictive controller for the motor system [170]. Such theories are also compatible with a computationally guided interpretation of the cerebellum as a structure that implements supervised learning through error-based updating of event predictions (consistent with its largely feed-forward driven structure and *climbing fiber* error-encoding afferences) [171]. This link may be important because a structure that not only serves the creation of predictions but also learning of the models that produce these predictions is likely to also play a role in the acquisition of or adaptation to augmented capabilities. As pointed out by Doya [171], in contrast to invertebrates, whose neural circuits have evolved to carry out functions that are highly optimized for specific behaviors [172], evolutionary more recent structures of the mammalian brain, specifically cerebellum, basal ganglia, and cerebral cortex, have evolved for more flexible specialization through learning and adaptation.

This capability for adaptation even appears to persist for highly consistent perceptual regularities and extends into adulthood. For example, experiments with devices that change the relationship between the visual world and visual sensory input (e.g., through rotation, mirroring, distortion, displacement) [25, 173–175], labeled optical rearrangement devices (ORDs) by Briscoe and Grush [167] have revealed that after a brief initial period of visual confusion, the ability to fluently integrate ORD-modulated visual input is gradually established. Less extreme everyday examples are the adaptation to optical distortion created by spectacle lenses or under water [175, p. 263]. An example for a recalibration in the relationship between eye movements and the perception of external motion is an aftereffect of sea travel, which is characterized by

[1] The term *corollary discharge* (CD) coined by Sperry [160] refers to the same concept as reafference.

perceiving the world to be in swaying motion [see 176] due to a continued attempt to compensate for the disembarked vessel's motion in the waves.

4.2 Information

Held and Hein [168, 177] have suggested that active motion and the corresponding reafferent input would be required for sensory adaptation. However, experiments with altered passive sensory input have also revealed that adaptations to ORDs may take place in the absence of reafferent motor signals [178, 179] [175, p. 23]. As noted by Welch [175] and Briscoe et al. [167], multiple researchers [e.g., 180–182] have argued that it is not motion behavior itself, but the information it provides, which is important for adaptation. According to this *information hypothesis* [175], any sufficiently salient signal that contains the required information should enable sensory adaptation. Any qualitative advantages of motion-informed adaptation could still be accounted for by the inherent informative value, which active motion provides, but the generality of this view also allows for other sources of information.

4.2.1 Multimodal Integration

The information hypothesis is supported by findings about multimodal perception. Even though one might think of different sensory modalities as serving inherently distinct purposes, one's perception appears to be the result of information integrated from multiple senses. An example of this integration that demonstrates the multimodal nature of speech perception is the so called *McGurk effect* [183]. The McGurk effect describes an illusion that occurs when pairing the auditory component of a sound with the visual component of a different sound and a third, neither uttered nor visually displayed sound is perceived. When for instance dubbing a video of the lip movements for the sound /ˈga/ with the sound for /ˈba/, the sound /da/ is perceived. Here, both visual and auditory signals contribute to the perception, and the influence of the auditory signal on the perception appears to depend on its relative quality [184].

The rubber hand illusion (RHI) [185] is another demonstration of the multisensory nature of visual, tactile, and proprioceptive perception. To create this illusion a person's real hand is hidden from their view while a rubber hand is placed in a visible position that would be natural for the actual hand. When both the hidden hand and the rubber hand are then synchronously stroked with a brush, people feel the touch of their hand as coming from the rubber hand and even report that the rubber hand feels like belonging to them [185]. Illusions like those produced by the McGurk effect and the rubber hand illusion are just cases in which multimodal integration is exploited by injecting "false" information into the typically reliable visual data stream. A more common everyday example for the multisensory nature of perception is the sensation of the flavor of food. Flavor is not just determined by chemical reactions of taste receptors but also depends on food properties registered through other sensors capable of sensing smell, visual appearance, texture, temperature, and irritation [186], as well as internal states that affect hunger [187, 188].

From an information perspective it appears sensible to integrate all available evidence: A single source of information is often ambiguous but additional evidence from a second source can help to reduce such ambiguity. For example, Section 2.1.3.1 in Chapter 2 described how visual information helps in resolving ambiguity contained in vestibular signals and how the integration of vestibular and visual information is utilized for the creation of realistic movement simulators.

4.2.1.1 Multimodal Facilitation

In many cases a single sensory modality may be sufficient for disambiguating a signal for perception. But even in such cases multimodal perception can still be advantageous. Multimodal stimuli have been found to cause faster reactions than unimodal signals [189–193]. The temporal and spatial congruency of such multimodal stimuli seems to be a modulating factor for an effective integration such that a high congruency is more effective than low congruency [194–197]. Multimodal stimuli furthermore appear to reduce the risk of sensory overload in perceptually demanding scenarios [14, 198] by allowing an observer to divide a perceptual task among multiple modalities.

Interestingly, the magnitude of multimodal facilitation (also known as *redundancy gain*) seems to vary with the age of people in a manner that defies commonly reported [199–202], age related sensory and cognitive decline. Laurienti et al. [203] found that multisensory compared to unisensory stimuli resulted in a greater reaction time benefit in a two-choice audiovisual discrimination task for older than for younger adults. In the younger adult group (mean age 28.1 years) the average multisensory gain was 53.2 ms whereas in the older group (mean age 70.0 years) the average multisensory gain was 87.5 ms. This reaction time reduction in aged individuals was even strong enough to reduce response times to those seen in younger participants' unimodal cases. The authors relate this age-dependent difference to a phenomenon referred to as *inverse effectiveness*, according to which multisensory gain increases as the effectiveness of unisensory stimuli decreases [195, 204, 205]. As multiple individually ambiguous signals are more likely to complement each other than unambiguous signals, this inverse effectiveness appears logical. Age-related sensory declines are a possible cause of increased unimodal signal ambiguities, which could explain why older people seem to benefit more from multisensory integration. However, in addition to differences in multisensory gain, several studies [206, 207] report that older adults actually respond even faster than young adults in multisensory trials. This suggests a generally enhanced multisensory integration in older adults rather than just a greater benefit in using it to compensate for unisensory deficits [see 208].

In summary, there is ample evidence that people integrate information from multiple available sources for disambiguating and updating their understanding of events in the environment. Furthermore, this integration has beneficial effects for both perception speed and bandwidth, which, in agreement with evidence for continued sensory adaptivity in primates, not only appear to persist but potentially even improve with age. But how far does this adaptivity go?

4.3 Sensory Modalities

Our different sensory organs are all sensitive to different aspects of the world. For instance, the eyes respond to a bounded spectrum of electromagnetic radiation, the ears to changes in the pressure of a surrounding medium over time, the skin to heat and physical deformation, and the vestibular system to rotation and acceleration of the head in space. The senses also seem

to *feel* qualitatively different from one another[2], which may suggest that they are inherently specialized to the kind of subjectively relevant information, which the medium that they are sensitive to typically encodes. Yet, some experiences seem to depend on their joint stimulation with complementary information (in ways that go beyond representing specific physical dimensions): As described in Section 2.1.3.1 of Chapter 2, vestibular and visual signals have correlated features during motion that are used to distinguish between acceleration, gravity, and tilt and that determine the corresponding characteristic experiences. Even though gravity and acceleration are considered as indistinguishable on a physical level [209], in the context of our mobile existence they appear to carry sufficiently distinct meaning to create distinct qualitative experiences.
A coupling of qualitative experiences to specific physical metrics or even to specific sensory organs might thus not be strictly necessary. Experiments on what is known as *sensory substitution* support that view. *Sensory substitution* describes the replacement of one sense with another one by providing it sensory input that conveys signals collected through a different modality. A famous example for sensory substitution was the *tactile vision substitution system* (TVSS) developed by Bach-Y-Rita et al. [210]. The TVSS was a system, which translated image features recorded with a camera into vibrations of pins arranged in a grid-like manner on a person's back or belly to create a "display" of tactile pixels. Participants who practiced exploration of the surroundings through the TVSS reported vision-like experiences [210–212]. However, such experiences only occurred for participants who could actively move the camera that informed tactile stimulation. The concept has since been reproduced in different forms, involving, e.g., stimulation of the tongue [213] and the forehead [214]. Another example is the acquired ability of some, typically blind, people to sense objects in their environment through echolocation using actively generated sounds such as clicking noises [215]. The blood-oxygen-level-dependent (BOLD)[3] signal of human echolocators has revealed increased activity in primary visual cortex while listening to binaural click echoes [216], which even indicates a structural remapping of sound processing to a cortical area strongly associated with visual processing.

4.4 Enaction

The *sensorimotor theory of perceptual consciousness* [217] provides a framework that may account for such flexibility in the utilization of sensory organs and neural structures. This theory emphasizes identified dependencies between actions and resulting sensory changes of a perceiver, also labeled *sensorimotor contingencies* (SMC), as the basis for the *quality* of experiences and hence the distinction between sensory modalities. A *sensory modality* would thus not be bound to a particular sensory apparatus but represent a set of rules by which a signal changes in response to actions or events. A property of color perception may exemplify this principle: The colors of objects are often perceived as constant despite variations in illumination and the resulting vast changes in the spectral composition (i.e., the physical colors) of their reflections.

[2]With the notable exception of cases of *synesthesia*, which is a phenomenon characterized by having (involuntary) experiences associated with one sense caused by input from another sense.

[3]The *blood-oxygen-level-dependent* (BOLD) signal refers to measurable changes in blood oxygenation that are indicative of higher neuronal metabolic demand due to increased activity. In functional magnetic resonance imaging (fMRI) BOLD contrasts are therefore commonly used as a correlate for changes in neuronal activity.

According to sensorimotor theory, the perceived color of a surface should be constituted by "the laws that govern the way colored surfaces change the light reflected into the eyes as those surfaces are moved around under different illuminations - or as differently illuminated parts of a surface are sampled with the eyes" [218]. Put differently, the perceived color of a surface is not simply identical to the current spectral composition it reflects but also depends on the way this spectral composition changes under varying illumination. Philipona et al. [219] indeed found that, when considering humanly accessible information[4] available in light, surface reflection behavior contains asymmetries, which predict classifications of surface colors that are consistent across different cultures [see 218].

In many aspects, the sensorimotor theory of perceptual consciousness is reminiscent of the reafference theory described in Section 4.1.1. It puts a strong emphasis on the need for action as causal grounding for changes in sensory input, while recognizing that ultimately perception is guided by the task to extract subjective meaning from both efferent and afferent signals. Both are so-called *enactive* [220] approaches in the sense that organisms *enact* their individual environments by exercising sensorimotor processes, rather than by constructing internal representations of them[5]. But, in addition to reafference theory, the wider framing and sensor indifference of the sensorimotor theory opens up an exciting opportunity: If sensory experiences consist of the execution of SMCs and if SMC formation is an adaptive process, also an enaction of entirely new SMCs with corresponding idiosyncratic experiences should be possible.

Indications that this may indeed be the case are given by examples for *sensory augmentation* [224, 225]. Sensory augmentation refers to the concept of systematically remapping the input to a particular sensory organ to convey information acquired from a new, previously unavailable, sensor. It is thus a variant of sensory substitution in which the signal does not originate from a sensor typically available to people (e.g., vision to touch) but in which the sensor collects previously unavailable information. An example for sensory augmentation is the so-called *feelSpace* belt [224]. This belt consists of an array of equally spaced vibromotors worn around the core of the body, as well as a digital compass. Assuming a cylindrical placement of the actuator array, the vibromotor that best aligns with the direction towards the magnetic north is continuously activated. Self-rotation causes a corresponding shift in the activated vibromotor. This gives users information about their absolute orientation in space. In an investigation of effects of prolonged belt usage, Kaspar et al. [225] found that participants experienced substantial changes in their perception of space. The participants reported that the vibrating signal developed into a feeling of spatial information that enriched their spatial understanding and improved navigation skills. For some participants the absolute orientation became a new feature of known locations. Wahn et al. [14] investigated another variant of sensory augmentation in which a grid of vibromotors placed on the belly was used as a display of another person's current gaze location on a screen. In an experiment where two participants had to cooperatively complete a

[4]By accessible information Philipona et al. refer to the information about the spectral composition of light that trichromatic vision can theoretically extract.

[5]The shift from representation-centered frameworks for cognition towards an enactive view, in which action and perception are closely coupled in predictively sampling sensory input, is gaining support across disciplines [see 221, for a thorough discussion]. A well known example in the field of psychology is Gibson's *ecological approach to visual perception* [65], which also spawned the influential concept of *affordances*. More recently Friston's *free energy principle* [222], also known as *active inference*, offers a formal action-based account on not just cognition but supposedly all biological processes [223].

visual search task while having access to the partner's gaze location through such a tactile display, their performance increased substantially compared to unassisted joint search. Even with comparably short training periods, they reported a quick and intuitive feeling of the partner's current gaze location that even led to the unforeseen development of an implicit communication and efficient search strategies through the added channel. This suggests a potential for SMCs to develop across multiple individuals for whom stimulus-driving sensory changes are exafferent - albeit in a symmetric manner.

The examples for sensory substitution and sensory augmentation suggest that there is large potential for a remapping of at least tactile input to various spatial features. This apparent flexibility in interpreting sensory signals can help in the development of novel means of augmentation in the mobility context.

4.5 Augmented Driving as a Sensorimotor Process

This excursion into theories and findings about aspects of human perception lets us draw a variety of conclusions and hypotheses that will form the basis of approaches for augmenting driver capabilities introduced in subsequent chapters.

A first takeaway is the flexibility that our sensory organs seem to offer. Information itself is not bound to a particular medium and may in fact often be extracted from a combination of multiple channels. Conversely, the different sensory organs that are sensitive to aspects of specific physical media also appear capable of extracting "unconventional" information when available, as suggested, e.g., by cases of sensory substitution and augmentation. It can therefore make sense to view the sensory organs as interfaces that differ mainly in terms of communication media and spatial and temporal resolution.

An important role in perception processes is further being attributed to actions. On the one hand, they serve in the separation of the self and the environment through the distinction between reafferent and exafferent sensory input – they yield the information about "what happened because of me". On the other hand, they are thought of as a component of perception itself that actively shapes the information sampling process. Each action may be understood as an expression of a predictive process that serves both a more efficient acquisition of information and also an improvement of future predictions in case of discrepancies between anticipated and actual sensory input. Enabling drivers to actively sample information through their own actions can hence be a desirable property for driver assistance systems. As defined in Section 3.4, a central characteristic of augmentation in human machine interaction is that added capabilities should integrate into an action-perception feedback loop of the augmented person. SMC-guided sensory augmentation aligns well with that requirement.

One issue with learning from feedback and exploration is that it may take time and practice. When no or only little prior information is available, upon which sensorimotor coupling can be built, the relevant information needs to be acquired and consolidated from scratch and might thus lack intuition and practicality upon first exposure. In the previously mentioned TVSS-experiments by Bach-Y-Rita et al. [210] (see Section 4.3), congenitally blind people with no prior experience of visuo-spatial contingencies between visual angle, distance, and object appearance showed remarkable image and space perception capabilities after having used the TVSS between 15 and 40 hours [211]. However, they could already recognize simple edges and contrasts directly after first system exposure and some reached 100% recognition accuracy for a set of geometric shapes after only 10 minutes of exposure with active exploration [211]. In extrapolation, this suggests a logical relationship between practice and decoding ability, but it also indicates that only little practice may be required to decode simple messages. Similarly, for the augmentation of driver perception this can mean that it may take some practice for drivers to decode complex meaning from novel action-contingent signals but also that simple relationships may become apparent rather quickly.

To further accelerate understanding, another discussed aspect of perception may be utilized: Drivers are typically not congenitally blind but perceive aspects of the driving scene by, amongst others, visual, auditory, and vestibular means. Section 4.2.1 depicted how perception can often be regarded as a result of multimodal integration and that such an integration can create beneficial effects in terms of perception accuracy and speed. Building on such insights, it may also be feasible to facilitate the understanding of new sensorimotor contingencies through correlating contingencies from other sensory modalities that have likely already been internalized by drivers. For instance, Section 2.1.3.1 described how self-motion creates a characteristic radial expansion of visual elements known as optical flow (OF) and cited evidence for a multimodal integration of optical flow information with conditionally correlating vestibular signals that is thought to underlie the perception of motion, acceleration, and velocity in primates.

4.5.1 Sampling from the Future

Finally, it can be argued that an augmentation of driver perception should yield information that is relevant to the driver. Section 2.1.4.2 in Chapter 2, defined the *relevance* of an event in terms of its risks for a driver's goals[6]. Broadly speaking, in the driving context two primary goals are the reaching of a destination (mobility) and the avoidance of negative effects such as accidents (safety). An augmentation of driver perception may thus focus on informing about factors with an impact on these two goals.

An interesting characteristic of driving is that drivers primarily focus on their direction of movement [78]. This can be interpreted as sampling of information from their own future location, typically from about 2 seconds ahead [226]. Repeating glances to the periphery and rearview mirrors can be interpreted in a similar way: They provide information about possible co-determinants of future events. Consistent with a notion of relevance, scenery is only rarely fixated by drivers [78]. To support the goals of safety and mobility, visual sampling appears to serve a maximization of the prediction quality about future events (see Section 2.1.4.1). This seemingly predictive nature of driving, or self-directed mobility in general, aligns with the previously discussed view that each action is an expression of a predictive process.

Section 2.1.4 listed various challenges that drivers may face in forming projection-level situation awareness (SA), i.e., challenges for predicting the near future, and framed these in the context of narrowing down the set of possible relevant future states. A few aspects of this section should be revisited in light of the perspective gained within the current chapter: To begin with, temporal event predictions were discussed. In particular, the time-to-contact (TTC) and the time headway (THW) have been identified as predictors of human braking responses [86] and velocity-independent distances between vehicles [85, 226], respectively. Section 2.1.4.3

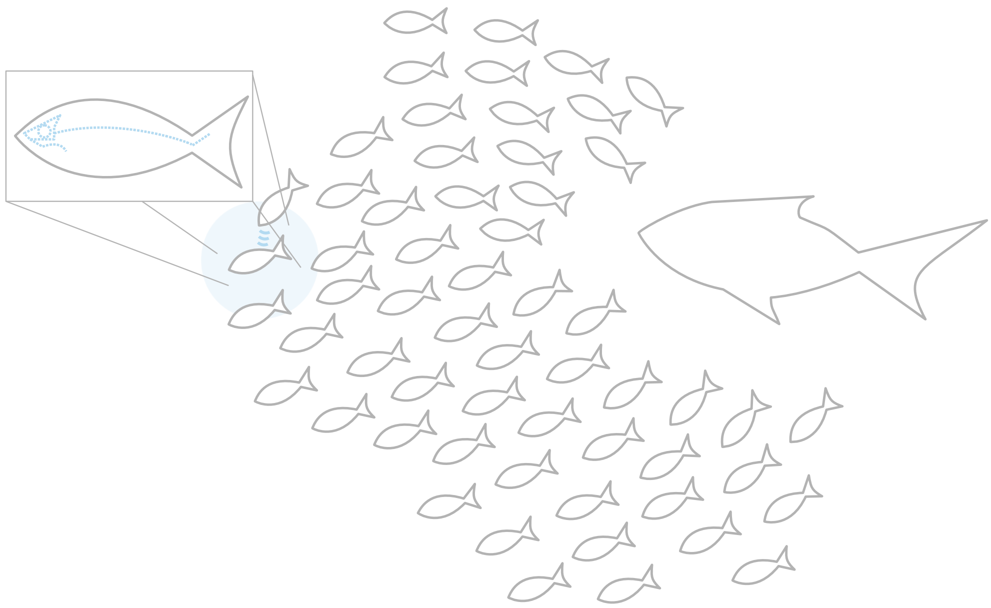
[6] For completeness, a relevance definition should further include goal-facilitating events.

further elaborated how OF appears to be used by drivers for making these temporal event predictions. Any added signals that are contingent on self-motion in a similar way but which would be provided through a different sensor might quickly be coupled with such existing contingencies while contributing to the disambiguation of evidence to enrich scene understanding.
Another striking link between predictions and actions can be found in Section 2.1.4.4. It explains the possibility to actively shape the future through one's own actions in order to favor the realization of a desired future. Predictions about the future can thus become self-fulfilled, a point that is also consistent with the concept of enaction in a very direct way. For the augmentation of driver capabilities it might hence be advantageous to also make the consequences of one's own actions more transparent and use this added "reafferent" input to also improve the ability to predict how future events may be shaped by one's own actions.
But at the same time the future cannot be assumed to be fully (self-)determined. Even with highly sophisticated models, wrong predictions can be made due to opaque exafferent factors such as the mental states of other traffic participants (see Section 2.1.3.5) or simply poor visibility conditions. An augmentation of driver perception, which also considers such sources of uncertainty, may help drivers in calibrating their trust in predictions to appropriate levels and plan for corresponding variability in exafferent input.

In summary, newly provided signals that encode information about the personal future are likely to be relevant to drivers and have an increased chance of being integrated with those signals that are already being sampled. To enable sensorimotor coupling, the signals should vary as a function of self-movement in a predictable manner and ideally be consistent with existing sensorimotor contingencies. However, also a signal variation in response to external events with potential influence on the own future situation can be desirable. Especially for such cases, a consideration of inherent uncertainties about externally determined events may be advantageous. The next chapters will introduce approaches to driver perception augmentation, which try to follow these derived guidelines, and present their investigation in a series of user studies.

Part II

The Lateral Line: Biomimetic Augmentation of Driver Awareness



5

Improving Driving Safety through Tactile Perception of Traffic Dynamics

"Time and space are modes by which we think and not conditions in which we live."

Albert Einstein

Having derived principles for an augmentation of driver capabilities (Section 4.5) based on existing awareness challenges (Section 2.1), theories, and findings about human perception and sensory integration (Chapter 4), this chapter introduces an approach for augmenting driver perception, which aims to implement these principles. In particular, the approach aims to leverage flexibility in the interpretation of sensory information to provide information about potential future safety hazards through tactile stimuli. This tactile encoding of information is not only selected to avoid interference with existing visual processing but also to integrate with existing means of information acquisition in movement for multimodal facilitation and accelerated understanding. Following the approach introduction, an evaluation of effects of a prototype that implements this approach as driver assistance in a driving simulator is presented and discussed. The evaluation targets the subjective understanding and utility of the assistance, as well as its effects on quantified driving performance. To refine the understanding of assistance effects, two scenarios that vary in criticality are compared.

Contents

5.1 Publication Disclosure . . . 60
5.1.1 Bibliographic Information . . . 61
5.1.2 Author's Contribution . . . 61
5.1.3 Copyright Notice . . . 61
5.2 Introduction . . . 62
5.2.1 The Lateral Line . . . 62
5.3 Concept . . . 63
5.3.1 Application Scenario . . . 64
5.3.2 Interface . . . 65
5.4 Methods . . . 67
5.4.1 Participants . . . 67
5.4.2 Experimental Setup . . . 67
5.4.3 Procedure . . . 69
5.4.4 Experimental Blocks and Trials . . . 69
5.4.5 System Exploration Block . . . 70
5.4.6 Independent Variables . . . 70
5.4.7 Dependent Measures . . . 71
5.4.8 Hypotheses . . . 71
5.5 Results . . . 72
5.5.1 Trial Validity . . . 72
5.5.2 Subjective Understanding and Utility . . . 73
5.5.3 Safety . . . 73
5.5.4 Velocity . . . 75
5.6 Discussion . . . 76
5.7 Chapter Summary . . . 78

5.1 Publication Disclosure

This chapter is based on the publication "The Lateral Line: Augmenting Spatiotemporal Perception with a Tactile Interface" by Krüger, Wiebel-Herboth, and Wersing [2], which was published at the Augmented Humans 2020 conference in Kaiserslautern, Germany where it was awarded with an honorable mentions award. The article introduces a concept for driver assistance and an evaluation of the effects of a functional prototype of this concept on safety in a driving simulator study. An evaluation of subjective questionnaire and interview data from the same study was published by Krüger, Wiebel-Herboth, and Wersing [3] under the title "Approach for Enhancing the Perception and Prediction of Traffic Dynamics with a Tactile Interface" as a work-in-progress article at the 10th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications (2018) in Toronto, Canada. Furthermore, the study and preliminary results were presented at the Doctoral Consortium of the same conference. To avoid repetition in the description of background and experiment, sections from Krüger et al. [3]

have been integrated into the version of Krüger et al. [2] contained in this chapter. Citations of Krüger et al. [3] mark corresponding additions. To improve integration into the dissertation, the first part of the introduction section (5.2) has been rewritten, the discussion has been shortened, and a chapter summary (5.7) has been added.

5.1.1 Bibliographic Information

[2] Matti Krüger, Christiane B. Wiebel-Herboth, and Heiko Wersing. "The Lateral Line: Augmenting Spatiotemporal Perception with a Tactile Interface". In: *Proceedings of the Augmented Humans International Conference*. AHs '20. ACM. Kaiserslautern, Germany: ACM Press, 2020. ISBN: 9781450376037. DOI: 10.1145/3384657.3384775.

[3] Matti Krüger, Christiane B. Wiebel-Herboth, and Heiko Wersing. "Approach for Enhancing the Perception and Prediction of Traffic Dynamics with a Tactile Interface". In: *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications - AutomotiveUI '18*. ACM. New York, New York, USA: ACM Press, 2018, pp. 164–169. ISBN: 9781450359474. DOI: 10.1145/3239092.3265961.

5.1.2 Author's Contribution

Personal contributions to publications Krüger, Wiebel-Herboth, and Wersing [2, 3] according to the Contributor Roles Taxonomy (CRediT) [24]:
Conceptualization, data curation, formal analysis, investigation, methodology, software, validation, visualization, writing - original draft, writing - review & editing.

5.1.3 Copyright Notice

5.2 Introduction

Chapter 2 discussed challenges for drivers to establish and maintain situation awareness (SA) on interdependent levels of perception, comprehension, and projection. Perception can, for instance, suffer from occlusion and the sequential nature of ocular vision (Section 2.1.2), i.e., limits to the sampling rate and quality in complex and dynamically changing environments. As the primary source of information during driving, vision serves the recognition of scene elements and is further linked to the formation of temporal distance and event predictions (see Section 2.1.4.3). A challenge in improving SA thus lies in circumventing the propagation of sensory bottlenecks in complex and fast-paced traffic situations. Chapter 4 pointed out the human flexibility in interpreting sensory stimuli, which, when consistently coupled to actions and events, may be integrated with congruent evidence from other sensors and thus augment perception.

Accordingly, here we introduce a concept aimed towards creating such an augmentation by utilizing tactile stimuli to encode relevant spatiotemporal information. To facilitate an understanding of its novelty and potential utility we introduce the concept with an analogy.

5.2.1 The Lateral Line

The following sections of this chapter are excerpts from the publication Krüger et al. [2], unless specified otherwise. For further publication details see Section 5.1.

While human senses may not have evolved for employment in the described kind of high velocity situations with multiple actors on intersecting trajectories, other members of the animal kingdom appear to have a stronger specialization in that niche:

Schooling, in the sense of a coordinated movement of a group in a common direction, is a remarkable ability of many aquatic vertebrates. Within a school, fish are able to adjust their position, acceleration and movement direction to that of multiple neighbors with such synchrony that they can appear to act as a common unit. In order to maintain the precise relative placement within a school during movement, its members need to be able to extract relevant information from their environment. One system of organs that is thought to play an important role in acquiring this information is known as the lateral line.

The lateral line describes a system of sensory organs that are sensitive to displacements of surrounding water and can thus be used to detect movements and vibrations. It converts local pressure changes into directional information and can be interpreted as a *remote sense of touch* or *sense of approach*. Fish appear to use the lateral line system for the formation of spatial awareness and for the ability to navigate. Predators have been found to employ their lateral line system to orient towards the source of vibrations such as those produced by fleeing prey [227]. Furthermore, fish with severed lateral lines seem unable to reintegrate themselves into a school [228]. Therefore, the use of the lateral line seems to be a crucial component for school formation. In relation to the perception of approaching objects, roughly speaking, the lateral line provides two measures:

1. Direction of approach and 2. strength of approach, which may be indicative of speed, size and proximity. Providing similar measures to humans could help to partially close the gaps left open by the existing sensory system and improve situation understanding and performance in complex dynamic situations. In the following section we introduce a concept that tries to transfer these properties.

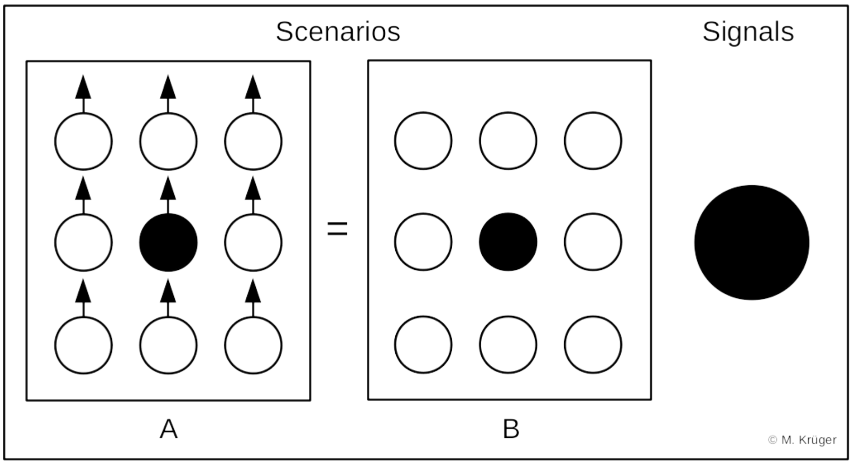
5.3 Concept

We propose to supplement a person's environment perception with two measures: The directions towards approaching objects that are on a collision trajectory with the user and the temporal proximities of each approaching object. The term *temporal proximity* is thereby to be taken as a variable that is (inversely) proportional to a time-to-contact (TTC)[1], which we here understand as a measure that depends on heading, distance, and momentary difference in velocity between two objects:
When assuming that an object b is moving behind an object a along the same path and trajectory with velocities V_a and V_b and a and b are distance D_{ab} apart, the TTC between a and b is given by:

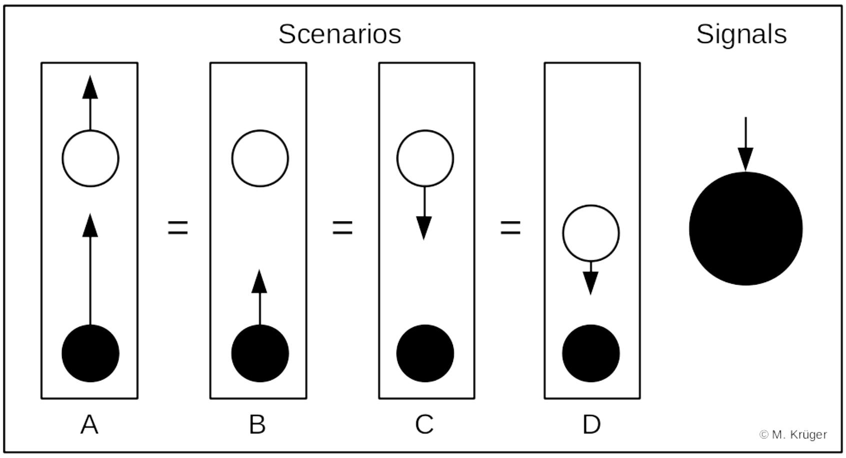
$$TTC = \begin{cases} \frac{D_{ab}}{V_b - V_a}, & \text{if } V_b > V_a \\ \infty, & \text{otherwise.} \end{cases} \tag{5.1}$$

In contrast to a purely spatial proximity measure we argue that a measure of temporal proximity can serve as a suitable expression of approach: The temporal proximity between two objects usually increases when one object approaches the other or vice versa, unless one object evades the other with sufficient speed. The same holds for the spatial proximity, which, however, does not take into account how fast that proximity increases or even whether it increases (i.e., the object approaches) at all. In contrast, a time-to-event measure or prediction implies an increase in proximity over time if trajectories and velocities should not change significantly.
Importantly, short spatial distances (= high spatial proximity) further do not necessarily entail short temporal distances as long as the respective objects do not approach each other. The temporal distance between spatially close objects with non-intersecting trajectories may in fact be infinite (see Figure 5.1a for an illustration of this property). Spatiotemporal measures or predictions therefore have a much wider applicability across different velocities and distances than purely spatial proximity measures (see Figure 5.1b for an illustration of this property) and yield higher relevance in informing about approaching objects and objects that are being approached.
We therefore assume that supplementing peoples' perception with the proposed spatiotemporal information allows them to develop a better understanding of the relevant dynamics in their surroundings and adapt their behavior accordingly. In addition to supporting the understanding of present situations, the predictive nature of the temporal proximity information provided to a user is further intended to facilitate the anticipation of future situations and the understanding of potential consequences of own action choices.

[1] More generally one may also define a time-to-event where the event could for instance already encompass reaching a specific distance threshold that is assumed to be relevant for the application task.



(a) When objects do not move relative to each other [A, B], the temporal distances between them are infinite regardless of the spatial distances and accordingly trigger no stimuli.



(b) Due to the dependence on both distance and relative velocity, the four scenarios [A, B, C, D] are identical with respect to the corresponding directed temporal proximity signals relative to an object represented by the dark circle. A, B, and C have equal distances and relative velocities. D presents a smaller distance but also a reduced relative velocity resulting in the same TTC as in A, B, and C.

Figure 5.1: Temporal equivalents: Because of the relative nature of the time-to-contact, scenarios that differ in absolute terms may yield identical temporal proximity signals. Outgoing arrows: length=velocity, direction=movement direction; Incoming arrow: length=temporal proximity, direction=approach target.

5.3.1 Application Scenario

In order to evaluate our approach for supplementing people's perception with directional and temporal information about approaching objects, we chose the task of driving a car on a highway as a plausible application scenario. This application domain has a number of advantages:

1. Variability: It naturally contains a high variability in distances and relative velocities. Speed differences between and within lanes allow for testing of safety-relevant scenarios in which the understanding and utility of directionality in the signals can be evaluated.

2. Simplicity: Lane-based navigation simplifies immediate trajectory- and thus TTC estimation as well as understanding of the same by drivers.
3. Utility: The information content of signals can be useful to drivers. The TTC can be argued to be proportional to the safety of a situation. When the TTC is falling, the risk of an accident increases because there is less time and thus opportunity to prevent the accident.

In this application we communicate directions and temporal proximities towards other traffic participants that are on a collision trajectory with the user's vehicle. The proximities are thereby not defined relative to the body of the driver but relative to the outer boundaries of the vehicle that the driver controls. Figure 5.2 illustrates the implementation of the approach in a driving situation.

5.3.2 Interface

As an interface for information transmission we chose to use vibrotactile actuators. Thereby the direction towards approaching vehicles relative to the driver's vehicle is encoded in the location of vibration and the temporal proximity is encoded in the intensity of vibration (pulse width modulated) such that stimulus intensity is inversely proportional to the TTC in a defined temporal range (e.g., highest at 0 seconds, lowest at 8 seconds, no stimulus above 8 seconds).
The vibrotactile interface consists of a belt with equally spaced vibromotors spanning the length of the belt such that the locations of individual vibromotors can be aligned with directions relative to the wearer's body and the controlled vehicle (see Figure 5.3b). This allows for an approximate matching between direction encoding and stimulus position, which should facilitate an intuitive understanding of the directional component in signals. Hereinafter we will refer to this interface as lateral line interface or *LLI*.
Using vibrotactile stimuli has multiple benefits ([see 3]): A driver's visual system is usually highly engaged and also auditory channels may be occupied by secondary tasks or other assistance functions. The tactile sense around the core of the body, on the other hand, is mainly idle while driving and thus likely available for novel input. Therefore no additional sensory load needs to be put on occupied modalities [see 14, 198, 229]. As tactile perception does not require active scanning [230] and is easily localizable [231], also the risk of creating stimuli that cannot be perceived is low. In contrast, visual stimuli need to be presented in the visual field with sufficient salience to draw a driver's attention. Furthermore, in combination with the visual modality, multisensory facilitation, which is characterized by faster reaction times [189–193] and a reduced cognitive load [14, 198], may take place. To our knowledge, the coupling of directional and temporal information encoding in tactile stimuli has not been investigated before.

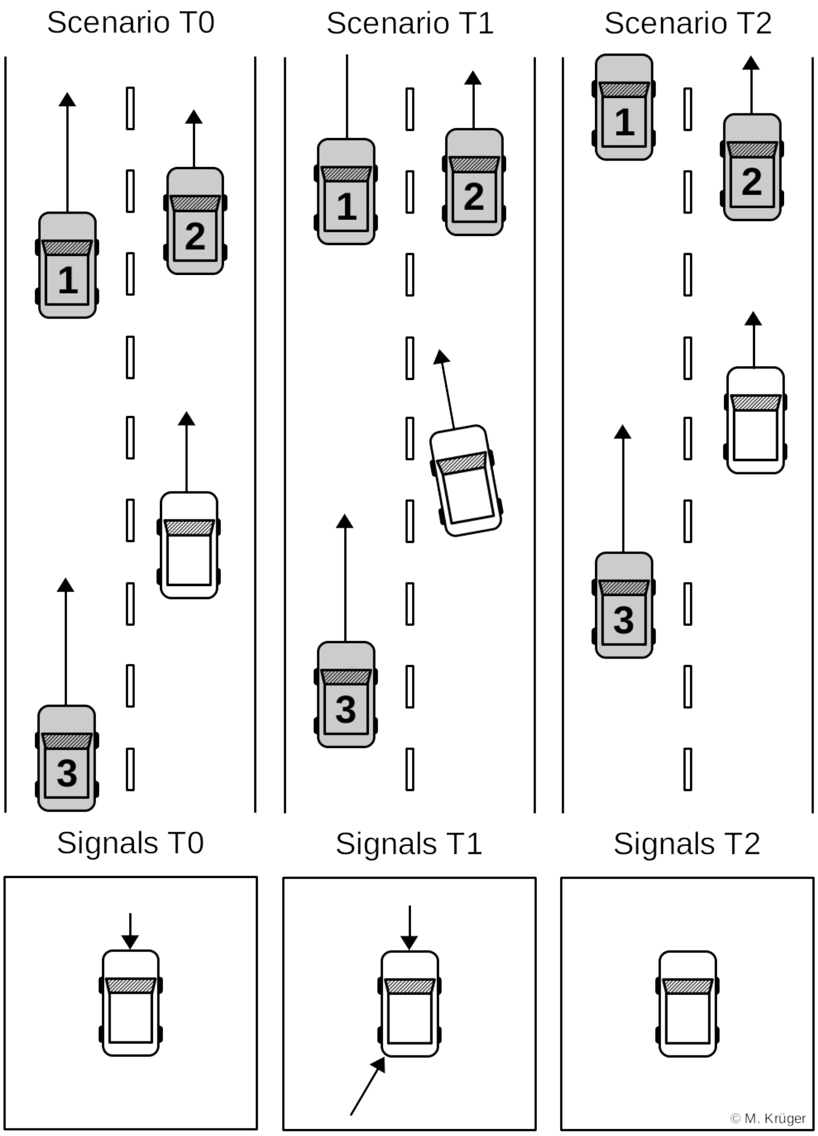


Figure 5.2: Traffic scenario and temporal proximity signals. Scenario: Outgoing arrows display the direction (heading) and velocity (length) of corresponding vehicles. Signals: Arrows represent the directions and associated temporal proximity or urgency (length) encoded in the signals. At time T0 the ego-vehicle (white) is faster than vehicle 2, leading to a TTC reduction in the front direction. As a consequence the TTC is translated into a corresponding directed proximity signal. In response to the situation at T0, the driver decides to overtake vehicle 2 at T1 and initiates a lane change. This maneuver puts the ego vehicle on a second collision trajectory with vehicle 3, leading to a second directed temporal proximity signal. In the described implementation of the system, proximities are signaled relative to the current lane of the ego vehicle. Because the ego-vehicle is still on the same lane as vehicle 2 at T1, the front signal is still active and slightly stronger than before because the ego-vehicle has come closer to vehicle 2 compared to T0. The combination of the two proximity signals might prompt the driver to abort the overtaking maneuver until another gap becomes available (T2).

Beyond vehicles, related approaches have mainly investigated spatial distance encodings for sensory support [232–236]. For example the "haptic radar" [232] introduced whisker-like properties, which push the spatial range of touch perception beyond the boundaries of the body.

In contrast, the LLI specifically targets dynamic situations by providing temporal information about approaching objects. The LLI can be "blind" to spatially nearby objects when they are not moving relative to the user (see Figure 5.1a) but sensitive to even very distant objects that approach with sufficient speed. Thus, systems like the "haptic radar" and the LLI can be seen as complementary. To evaluate the described approach and its effects on driver perception and performance we conducted a driving simulation study with a prototype of the system (see Figure 5.3a).

5.4 Methods

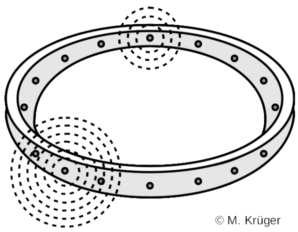
5.4.1 Participants

Data from 13 participants (12 male, mean age 33, [24-43]) were recorded. Participants were required to have a valid driving license and corrected-to-normal vision. All participants gave written informed consent before taking part in the study.

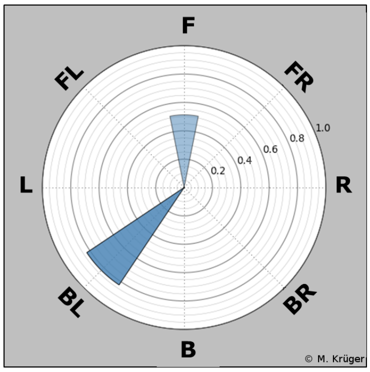
5.4.2 Experimental Setup

A static driving simulator running *SILAB 5.1* (WIVW GmbH) with real vehicle controls for steering, braking and accelerating was used for the experiments. Three display panels (50 inch diagonal, resolution: 3 x 1080p, updated at 60 Hz) were arranged to provide approximately 160° field of view and showed the front, side- and rear-view mirror views of the driving scene. A wearable 120 Hz monocular eye-tracker (Pupil Labs GmbH, see [237]) was used for gaze recording. Tactile stimuli were delivered via a belt that contains 16 equally spaced vibromotors (feelspace GmbH, see [224]) and a firmware customized for the purpose of the experiment.
The belt uses eccentric rotation mass motors with a maximum amplitude of 2.2 g and a frequency spectrum of 50-240 Hz (0.45 - 3.3 V) triggered with a 50 ms latency. Frequency and amplitude scale almost linearly with voltage. We used four different belt sizes to ensure a good fit for all participants because firm contact is critical for intensity perception and localization. In a pre-test we determined a joint smallest noticeable intensity across 12 people as a lower bound for stimuli at the temporal stimulus threshold.
The perceived stimulus magnitude has been found to scale logarithmically with physical stimulus magnitude for various senses [238]. Expressed in a power law relation, exponent values can thereby differ between senses and stimulus sites [239]. Reference (Stephens's [239]) exponents for vibrations in the sub-240 Hz range on the body have been found to range from 0.75 to 0.97 [240], which approximates linear scaling. We tested mappings with exponents 0.75, 0.83 and 1.0 but found scaling with the smaller exponents to feel more irregular and thus decided to scale intensity with an exponent of 1.0.

(a) Setup showing the driving simulator, eye-tracker (A), vibrotactile belt as LLI (B), and the driving scene from Figure 5.2 (T1).



(b) Sketch of the tactile interface with two active vibromotors (out of 16).



(c) Screenshot of a visualization of directional *temporal proximity* values that serve as LLI input.

Figure 5.3: Picture of the experimental setup (5.3a) containing the scenario illustrated in Figure 5.2 (T1). A sketch of the LLI (5.3b) and a live visualization (5.3c) show the associated vibromotor activations and directional urgency values, respectively.

Out of the 16 available vibromotors we only used 8, spaced 9.8 to 13 cm apart (depending on belt size) for the following reasons: Simultaneously signaling multiple directions requires sufficiently large distances between tactors to avoid interference by the funneling effect [241] or an illusion of apparent motion [242]. The eight directions map nicely to environment structures (three lanes, front, mid, back) and vibromotors partially align with anatomical reference points, which may support intuitive direction mapping [243]. Note that Van Erp et al. [244] successfully used the same number and distribution of tactors for signaling directions in navigation tasks.

Description	Duration
Simulator familiarization	15 min
Block 1 (Baseline 1)	8 min
System exploration (LLI)	4 min
Questionnaire 1	4 min
Block 2 (LLI)	8 min
Block 3 (Baseline 2)	8 min
Questionnaire 2	4 min

Table 5.1: Experiment components and durations.

5.4.3 Procedure

The study was structured into three experimental blocks and one system exploration block. Table 5.1 lists the different experiment components. Before the start of the experiment, all participants had to complete a driving simulation familiarization procedure according to guidelines specified by Hoffmann and Buld [245]. By gradually increasing exposure to longitudinal and lateral accelerations and introducing a variety of driving tasks, this familiarization procedure simultaneously served the two objectives of reducing the probability of simulator sickness and introducing participants to virtual vehicle control and behavior.

5.4.4 Experimental Blocks and Trials

In the three experimental blocks participants were given the two tasks of a) driving accident-free and b) trying to maintain a velocity of 120 km/h when possible. The driving course was a straight two-lane highway with vehicles on the fast (left) lane driving noticeably above the 120 km/h target speed and vehicles on the right lane driving at exactly 120 km/h. Therefore the speed maintenance task could best be satisfied by staying on the right lane at most times.
However, sometimes a vehicle on the right lane would slow down, forcing the driver to react. The braking of a front vehicle puts both tasks of accident-free driving and velocity maintenance at risk: slowing down to avoid crashing into the front vehicle violates the velocity task while staying on the lane at the target velocity would result in an accident. This made an overtaking maneuver the only sustainable solution. Doing so was, however, complicated by the traffic on the fast lane and thus additionally required the identification of feasible gaps (see Figure 5.2).
We regarded successful overtaking maneuvers in such situations as valid trials. Thereby the onset of a trial is marked by the time at which the front vehicle on the right lane starts to decelerate. The end of a trial is defined by the time at which the longitudinal coordinate of the ego-vehicle equals that of the slowing front vehicle, i.e., the time at which the slow vehicle is overtaken correctly. Due to this event-based definition, individual trial durations are dependent on driver behavior and situation difficulty and can therefore vary. Invalid trials were defined by a failure to respond appropriately to such events: breaking to an extent that overtaking became unfeasible and the target velocity was significantly reduced, overtaking on the emergency lane, or creating an accident. Furthermore, a trial was considered to be invalid if the spatial distance between front- and ego-vehicle at trial onset violated the realization of the respective trial difficulty setting defined by Equation 5.2. A total of 12 trials were realized in each experimental block for

each participant. Between trials, periods of varying length without task-affecting events were inserted to reduce trial onset predictability. In Blocks 1 and 3 (Baseline) participants had to complete the task without the LLI. In Block 2 the LLI was active.

5.4.5 System Exploration Block

The system exploration block served the purpose of allowing the participants to familiarize themselves with the LLI. Here they could freely explore the functionality of the interface while driving through a prepared two-lane course with a variety of traffic situations. No information about the function or meaning of the LLI stimuli were given until after the free exploration phase. After finishing exploration, participants filled in a questionnaire and were interviewed about their perception and understanding of the LLI stimuli (see Krüger et al. [3]). The experimenter then introduced the participants to the concept of the LLI before continuing the experiment.

5.4.6 Independent Variables

Two independent variables were varied throughout the experiment: The availability of the assistance function (Block 1 and 3 vs. Block 2) and the task difficulty (*difficult* vs. *easy*). We defined task difficulty in terms of the available time for a driver to react once a front vehicle started to decelerate, assuming that this manipulation would also affect how demanding a situation would be experienced. This was realized by a) manipulating the available time-to-contact to the front vehicle and b) the number of feasible gaps available on the fast lane, which would allow for successful overtaking. Thereby, the available time is computed as a time-to-contact that takes the deceleration of the front vehicle into account and assumes that the ego vehicle maintains its speed:

$$t = -\frac{\sqrt{(v_{\text{ego}} - v_{\text{front}})^2 - 2a_{\text{front}}d} - v_{\text{ego}} + v_{\text{front}}}{a_{\text{front}}} \qquad \text{and} \quad a_{\text{front}} < 0. \tag{5.2}$$

Here t stands for the available time, v_{ego} and v_{front} for the start velocity of the ego- and the front vehicle respectively, a_{front} for the acceleration of the front vehicle and d for the initial distance between the two vehicles. We set t for trials labeled as *easy* to 7.4 seconds and for trials labeled as *difficult* to 5.4 seconds. In addition to the quantitative difference, *easy* and *difficult* trials also differed on a qualitative level: This difference consisted of the number of available gaps on the fast lane that the drivers could enter when assuming that they would keep the target velocity after trial onset. While in the difficult cases the first available gap would need to be taken, in easy cases also entering the second gap was still possible without causing an accident[2].

[2]Besides the time-to-contact, in the experimental scenario the time available for a driver to react is additionally constrained by the availability of feasible gaps on the passing lane. The size and frequency of these time windows depend on the velocity difference between the ego vehicle and passing vehicles as well as on the distance between individual vehicles on the passing lane. For the experiment we kept these two variables roughly constant, which allowed us to vary difficulty only with the time variable described by Equation 5.2.

5.4.7 Dependent Measures

In correspondence to the two primary tasks for the participants, we evaluated performance in terms of the two dependent measures driving safety and velocity as functions of two independent variables: LLI availability and task difficulty (*difficult* vs. *easy*). We operationalized safety at any point in time as the minimum time-to-contact across all directions at that moment. For each trial we use the minimum of all TTCs (mTTC) measured in that trial[3] as a summary statistic. The mTTC measure therefore expresses how dangerous a trial got at most (smaller value = higher danger) rather than how dangerous it was on average. To assess driving velocity we used the arithmetic mean over a trial as our dependent measure.

In mobile systems a tradeoff between velocity and safety may be seen as an inherent property. Such a tradeoff between safety and velocity is not by itself problematic but it could be argued that any measurable safety benefit in terms of mTTC may be fully accounted for by a corresponding decrease in driving velocity[4]. We were therefore not only interested in whether the LLI condition would yield higher safety but also whether a potential safety improvement would be accompanied by a corresponding change in average velocity or whether safety could be improved independently of the average velocity.

5.4.7.1 Questionnaires and Interviews

This section is an excerpt from Krüger et al. [3]. For further publication details see Section 5.1.

Participants were given questionnaires with seven point Likert scales after the system exploration phase and after the third experimental block. The first questionnaire was primarily designed to asses the intuitive understanding of the system and its subjective utility. In total, nine questions were asked, targeting function understanding (5), subjective comfort (2) and signal perception (2). In the second questionnaire, four questions concerning function understanding and comfort were repeated to assess potential changes after further exposure to the assistance function. In addition, ten questions were designed to mainly tackle the subjective experience of the scenario and the utility of the assistance function as a function of task difficulty. Interviews were further used to gain insights about the participants' perception and understanding of the assistance function.

5.4.8 Hypotheses

If people should be able to purposefully integrate the spatiotemporal information provided by the LLI into their environment perception, we hypothesize that they should also be able to carry

[3]See , e.g., Eggert [246] for an account on the link between risk and time-to-event measures and Eggert and Puphal [84] for a proposed probabilistic extension of time-to-event based risk estimates that may be well suited for potential future real-world scenario evaluations of our concept.

[4]Note that this effect is partially prevented by experimental design. Vehicles on the passing lane are driving at a velocity slightly above target velocity. The slower the ego-vehicle is, the more difficult a lane change becomes. Therefore participants should additionally be motivated not to slow down too much in order to still be able to do a successful (safe) lane change.

out driving tasks more safely without affecting average velocity compared to driving without an LLI. Furthermore, for particularly demanding situation we would assume such a benefit to be even more pronounced due to the alleged sensory support and circumvention of visual limitations. This results in the following hypotheses:

H1: Participants adapt their driving behavior in LLI trials such that safety is improved compared to the baseline conditions.

H2: If present, such an improvement in safety would not be explained by a lower average velocity.

H3: Task difficulty affects driving behavior such that safety and average velocity decrease in difficult trials compared to easy trials.

H4: If present, effects of LLI usage on the driving behavior are moderated by task difficulty such that positive safety effects are more pronounced in difficult trials compared to easy trials.

5.5 Results

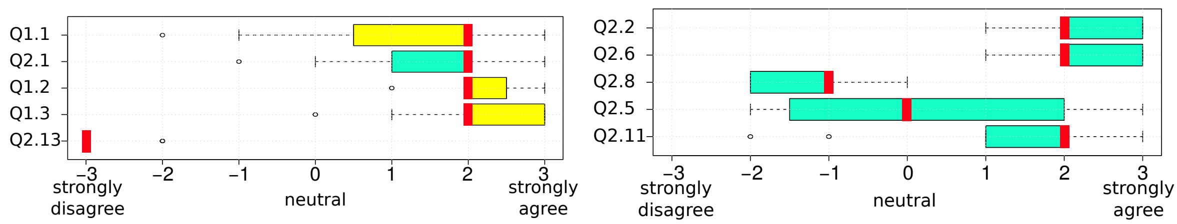
5.5.1 Trial Validity

Prior to investigating performance, we evaluated the number of valid trials for each condition. Trial validity was defined as a filter criterion to ensure that all data entering further analysis would be comparable and to exclude trials in which the task was not achieved.
In the first baseline condition, 21% of all trials across participants were classified as invalid. In the LLI condition, the percentage of invalid trials was reduced to 7.7%. In the second baseline block, 7.1% of all trials across participants were excluded as invalid trials. These results show that overall the driving task was feasible but not trivial. However, the increasing success rate suggests that a substantial improvement took place between the first experimental block (baseline) and the second experimental block (LLI). No difference in failure count was observed between the second and the third experimental block. However, the results on trial validity do not convey information about the quality of task performance in each trial. This will be further analyzed in the following.

5.5.2 Subjective Understanding and Utility

This section is an excerpt from Krüger et al. [3]. For further publication details see Section 5.1.

Data from the first questionnaire show that the initial understanding of the assistance function and its perceived utility was high (see Figure 5.4a, Q1.2, Q1.3). Participants were able to develop an intuitive understanding of the function without any prior explanation within only four minutes of system exposure. A comparison with the data from Questionnaire 2 shows that the certainty on the function understanding increased further over time (Figure 5.4a, Q2.13). Comfort of the interface was rated as almost equally high in both questionnaires (Figure 5.4a, Q1.1, Q2.1), indicating that prolonged use does not lead to annoyance. All participants indicated making use of the signals (Figure 5.4b, Q2.2, Q2.6) and the driving task was overall rated as easier when driving with the system (Figure 5.4b, Q2.8). Data from the second questionnaire indicate that the perceived utility of the assistance function increased with task difficulty (Figure 5.4b, Q2.5, Q2.11). However, the variance in the responses suggests that some participants could subjectively benefit more from it than others. A first subsequent inspection of the metadata indicates that individual driving experience might be a moderating factor and should be considered in future analyses. Overall, the subjective data suggest that the assistance function can support a driver's understanding of dynamic traffic situations. Interview responses confirm these indications. Many participants reported having more freedom in monitoring their environment and being able to better assess situations with the system, resulting in an elevated sense of safety.



(a) Subjective LLI understanding (b) Subjective LLI utility

Figure 5.4: **5.4a**: Boxplots for a subset of responses about interface understanding. Yellow: Questionnaire 1; Turquoise: Questionnaire 2; Red: Median response; Q1.1: *The belt signals felt comfortable to me*; Q2.1: *The belt signals felt comfortable to me during the driving task*; Q1.2: *I understand the belt signals*; Q1.3: *I felt that I could change the belt signals with my own behavior*; Q2.13: *The meaning of the belt signals remained obscure to me*. **5.4b**: Boxplots for a subset of responses about system utility. Q2.2: *I made use of the belt signals for my driving behavior*; Q2.6: *I felt supported by the belt signals in the driving task*; Q2.8: *The driving task was easier without the belt signals*; Q2.5: *Easy situations became easier with the belt signals*; Q2.11: *Difficult situations became easier with the belt signals.*

5.5.3 Safety

To analyze the effects on driving safety in each valid trial (see Figure 5.5), we first conducted a two-way repeated measures ANOVA to compare the main effects of condition and trial difficulty

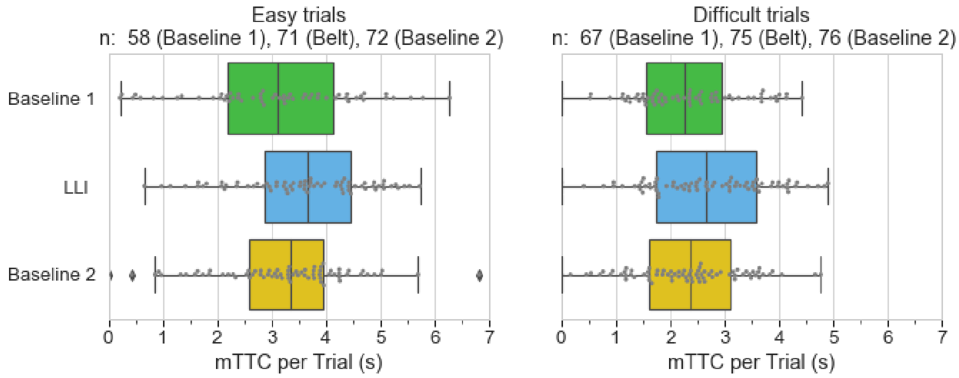
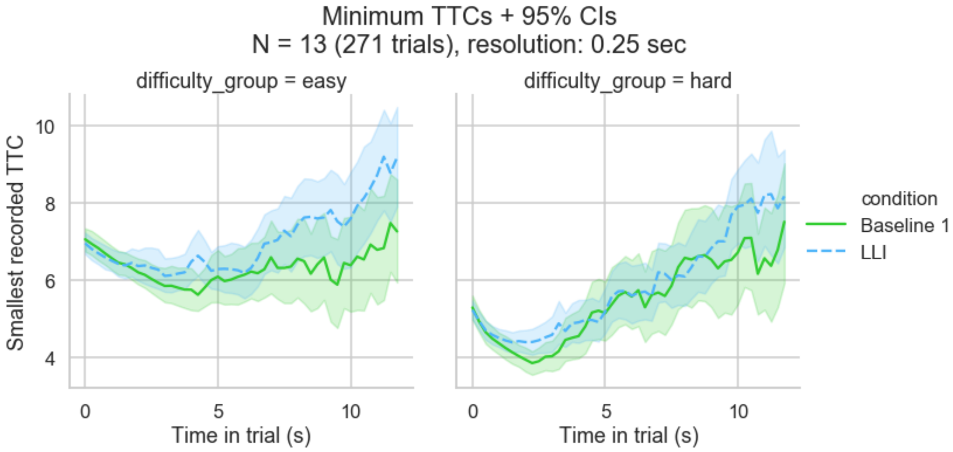


Figure 5.5: Distributions of mTTC values for all trials as an indicator for *trial safety*, ordered by conditions. Boxplots show minimum and maximum values (whiskers), and the first, second (= median), and third quartiles (box). Overlayed grey dots show mTTC values of individual trials.

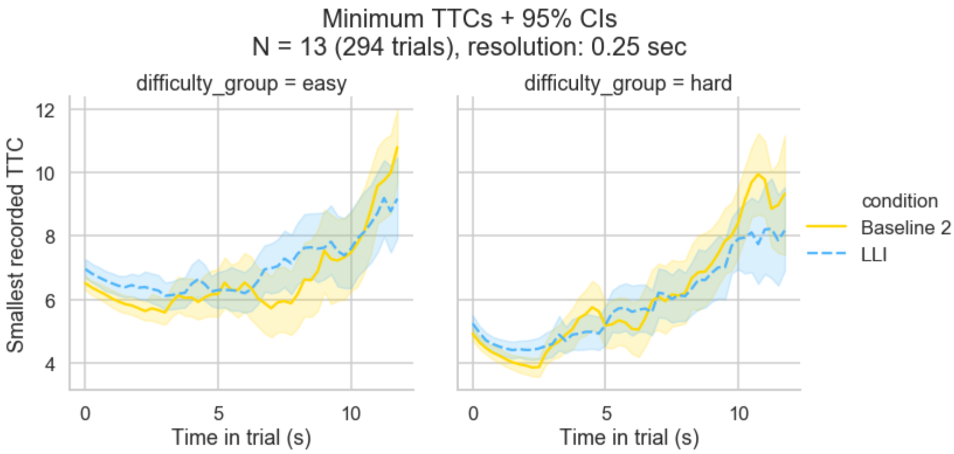
and their interaction on the minimum time-to-contact (mTTC). *Condition* included three levels (Baseline 1, LLI, Baseline 2) and trial difficulty consisted of two levels (easy and difficult). The effects of condition and trial difficulty were statistically significant at the 0.05 significance level. The main effect for condition yielded an F ratio of $F(2.0, 16.72) = 5.917$, $p < 0.01$. A post-hoc Tukey test showed that the mTTC differed significantly at $p < 0.05$ between Baseline 1 (M = 2.64 s, SD = 1.319) and LLI condition (M = 3.127 s, SD = 1.265) and between the LLI condition and Baseline 2 (M = 2.767 s, SD = 1.219). There was no significant difference in mTTC between Baseline 1 and Baseline 2. This safety benefit observed in the LLI condition compared to the baseline condition suggests that a purposeful use of the provided information has taken place. Because a safety benefit of the LLI usage compared to the baseline condition persisted also for trials in the second baseline condition (after the introduction of the LLI), we can exclude the possibility that the described benefit can be solely explained by learning effects. These results support our first hypothesis.

The main effect for trial difficulty yielded an F ratio of $F(1.0, 80.297) = 56.577$, $p < 0.001$, indicating a significant difference in mTTC between easy (M = 3.313 s, SD = 1.303) and difficult (M = 2.432 s, SD = 1.101) trials. With an average temporal *safety difference* of 0.88 seconds, which approximately equals a distance of 29 meters when driving at 120 km/h, the difficulty manipulation thus appears to have been successful, which supports our hypothesis 3. There was no significant interaction between condition and trial difficulty, $F(2.0, 0.293) = 0.103$, $p = 0.901$. Therefore, contrary to hypothesis 4, no evidence for a modulation of LLI effects by task difficulty was found.

Figure 5.6 additionally shows the average temporal development of minimum TTCs across conditions. Upon trial onset, the safety initially decreased in all conditions due to the deceleration of the front vehicle. In easy trials this decrease continued for 4.5 seconds and 3.8 seconds in Baseline 1 and 2, respectively. In the LLI condition recovery appeared already around 2 seconds and the resulting safety advantage remained for most of the trial. In *difficult* trials the overall initial safety was, by definition, much lower in all conditions. Also here the recovery in the LLI condition was much faster than in the baseline conditions. Later during trials the condition differences diminished while *safety* reached non-critical levels.



(a) Average minimum TTC over time as an indicator for temporal safety development + 95% confidence intervals (CIs) for trials from the first baseline block (green) and the LLI block (blue).



(b) Average minimum TTC over time + 95% CIs for trials from the second baseline block (yellow) and the LLI block (blue).

Figure 5.6: Average minimum TTC over time as an indicator for temporal safety development.

5.5.4 Velocity

As a second performance measure we inspected driving velocity in the different experimental conditions (see Figure 5.7). To test whether a difference between driving velocities exists when driving with the LLI compared to driving without the LLI, we conducted a two-way repeated measures ANOVA, comparing the main effects of condition and trial difficulty and the interaction effect between the two on the average velocity during a valid trial.
Condition included three levels (Baseline 1, LLI, Baseline 2) and trial difficulty consisted of two levels (easy and difficult). There was no significant main effect of condition, $F(2.0, 136.73) = 2.004$, $p = 0.136$. This result indicates that, on average, participants did not differ in their driving velocities depending on the LLI availability. Furthermore, in support of Hypothesis 2, it excludes the possibility that the temporal safety benefit reported for the LLI condition compared to the baseline conditions can be accounted for by a velocity-reduction alone. The effect for trial

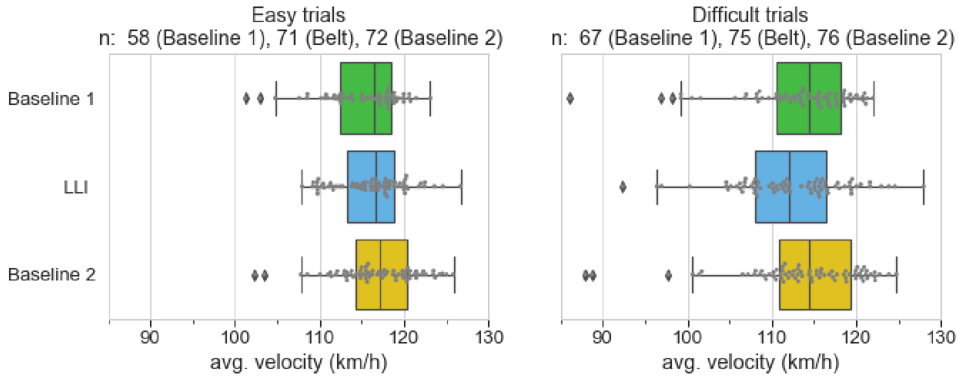


Figure 5.7: Distributions of average velocity measures for all trials, ordered by conditions. Boxplots show minimum and maximum values (whiskers), and the first, second (=median) and third quartiles (box). Overlayed grey dots show average velocity values of individual trials.

difficulty was statistically significant, yielding an F ratio of $F(1, 946.95) = 27.762$, $p < 0.001$ and indicating a significant difference in average velocity between easy ($M = 116.18$ km/h, $SD = 4.53$) and difficult ($M = 113.16$ km/h, $SD = 6.84$) trials. As observed for the mTTC measure, this result further supports the claim of a successful difficulty manipulation (Hypothesis 3), which appears to have caused participants to slow down more in trials classified as difficult. There was no significant interaction between condition and trial difficulty, $F(2.0, 47.93) = 0.701$, $p = 0.496$.

5.6 Discussion

We introduced a concept for supplementing people's spatiotemporal perception using tactile stimuli, which are informative of directions and temporal proximities towards approaching objects. Inspired by sensory capabilities of many aquatic vertebrates that enable coordinated movements in dynamic multi-agent environments, we applied this concept in a driving simulation scenario as a first approach to evaluate whether the signal content can be understood and used to improve performance in traffic situations.

In the automotive [247–251] and navigation domains [224, 244, 252–258], vibrotactile displays have previously been proposed as promising interfaces for various functions. Related work thereby focused on the encoding of direction [e.g., 244, 259–265] and spatial distances [e.g., 232–236, 266] in signal components. However, the use of spatial encodings limits the utility of such systems to specific movement velocities. At a velocity of 100 km/h, a distance of 20 meters in the movement direction is usually much more critical than the same distance would be at a velocity of 30 km/h. Nevertheless, a spatial distance encoding would signal both cases in the same manner. In contrast, a spatiotemporal encoding, as introduced here, is a function of both relative velocity and distance and thus naturally applicable across a wide range of velocities and distances. Spatiotemporal information, in this case a directed time-to-contact, can also be seen as more relevant and less disturbing than a simple distance metric because only objects that signal a potential collision danger induce a stimulus. By making the stimulus-salience inversely proportional to the time-to-contact, the spatiotemporal encoding has the added theoretical advantage of naturally facilitating prioritization in cases of multiple simultaneously communicated items. To our knowledge, a simultaneous encoding of directions and a TTC-contingent measure for one or more events has not been described or investigated before.

We conducted a user study with a prototype that implements the proposed concept in a driving simulator and found that driving safety, quantified as mTTC, was significantly higher with the supplementary spatiotemporal information provided via the lateral line interface (LLI) than without it. This safety benefit, compared to baseline conditions, suggests that participants were able to understand and utilize the provided information and that the purposeful use of this information was beneficial for task performance. For the second performance measure of average velocity there was no evidence for a difference between baseline and LLI conditions. The independence between trial safety and average velocity is particularly interesting because it means that the safety benefit in LLI trials cannot be accounted for by an average velocity reduction alone. This suggests that LLI usage does not simply shift participants to a different portion of a safety-velocity Pareto front but that it may in fact elevate it and therefore improve overall driving performance.

As illustrated in Section 5.3.1, both stimulus direction and salience, i.e., directional and temporal information, can play a role in supporting safety maintenance. Due to the dynamic encoding of this information we argue that the suggested concept is not just a warning device but constitutes an example for sensory augmentation that, for instance, allows a user to plan and prioritize actions according to the salience of individual stimuli. However, the reported improvements in safety might also be explained by less information. Using, e.g., only the tactile stimulus onset as an alerting signal might be sufficient to achieve similar safety benefits by shortening reaction times to potential dangers. Questionnaire and interview responses reported by Krüger et al. [3] indicated an understanding and subjective utility of both stimulus direction and time-contingent stimulus salience, suggesting a use of the full information provided by the system. In the future this question should be explicitly addressed by testing and comparing a variant of the system without (continuous) time encoding. Conversely, investigating possible extensions such as a LLI-based system with adaptive or cooperative assistance [1], by, e.g., considering a user's current situation awareness, might provide insights about peoples' ability to utilize more complex and adaptive sensory support systems.

Besides addressing the above points, future studies could target a better understanding of the role of long-term system exposure. In the present study, the exposure to the LLI was rather short and may not yet have reached its full potential in terms of the emergence of new perceptual and behavioral qualities. Long-term exposure may lead to a manifestation of systematic relations between actions and associated sensory changes, so called sensorimotor contingencies [217], which have been hypothesized as the basis for sensory modality formation [176, 217, 267] (see Chapter 4). Some subjective accounts from interviews and questionnaires reported by Krüger et al. [3] already described stimuli as being perceived in terms of the communicated information rather than the tactile stimulation. Studies on long-term usage could help to identify whether such qualitative shifts develop universally and what amount of exposure would be required.

One factor that may have substantially facilitated stimulus understanding and utility is a potential cross-modal facilitation [268] through the relationship between the TTC and optical flow (see Section 2.1.4.3). [...] An expansion of measures to include more direct physiological correlates of sensory integration and potential perceptual alterations [e.g., 269] should be a valuable

addition. This might also help to identify the underlying cognitive mechanisms that mediate the effects of the proposed system.
To conclude, we proposed a novel approach for supplementing peoples' spatiotemporal perception in dynamic situations using tactile stimuli. We implemented a first prototype - the lateral line interface (LLI) - and evaluated it in the context of a driving simulation study. Results show that participants could understand and use the provided information by adapting their driving behavior to improve safety. We suggest that the LLI denotes a system with applicability beyond that of basic warning systems.

5.7 Chapter Summary

This chapter introduced a concept for augmenting peoples' spatiotemporal perception in driving, labeled the lateral line interface (LLI). As an exemplary research platform, a functional prototype was realized in a driving simulation environment. The prototype utilizes an array of vibrotactile actuators, distributed horizontally around the core of the driver's body, to dynamically communicate directions and temporal proximities to approaching objects. The temporal proximity was defined as the complement of the time-to-contact (TTC) below an upper time bound and served as a measure of collision risk and urgency. A driving simulator study revealed a fast and intuitive understanding of tactile stimuli by participants, as well as a positive rating of its utility in the simulated highway scenarios. These subjective ratings are in agreement with measured effects on driving performance: In trials with active tactile assistance, participants presented higher driving safety than in unassisted trials. Two levels of scenario difficulty were included in the study. While participants reported that the LLI supported them more in the more difficult scenarios, the relative objective safety gain through the LLI did not significantly differ between difficulty levels.
The LLI was designed to follow the *enactive approach to perceptual augmentation in mobility* described in Chapter 4. It establishes a consistent mapping between a temporal hazard vector and tactile sensory input. However, this consistency only emerges when considering the inherent relativity of collision hazards in mobility. One's own movement but also the movement of another traffic participant can alter the situation and thereby affect tactile sensory input. The quick understanding and utilization of the LLI by participants is thus not necessarily self-evident and might have depended on an integration with congruent sensory evidence from other modalities, such as the optical flow (OF) around the signaled hazard direction.
This raises multiple questions: Do people utilize the temporal information encoded by LLI stimuli on top of the direction information or does the LLI rather serve as a pointer to guide visual attention and hazard estimation? Does the LLI retain its utility in conditions with poor visibility or occlusion? Conversely, rather than reducing the feature scope of the LLI, also an expansion of its information encoding can be considered to further enrich hazard perception. In the following two chapters, these topics will be addressed in more detail.

6

Direction and Temporal Distance Encoding

"The only constant is change."

Heraclitus of Ephesus

Participant reports and quantified driving safety in the first study suggest an intuitive understanding and utilization of the lateral line interface (LLI) by drivers in critical highway scenarios. Yet various questions concerning the LLI remain open. For instance, although a safety benefit was present, this benefit might, in theory, also be accounted for by tactile signal onset without subsequent TTC-dependent stimulus intensity scaling. Another open question is, how well LLI effects generalize, e.g., whether they transfer from highway scenarios with relatively high criticality to other situations such as road intersections with lateral traffic. This chapter describes an investigation of these questions by expanding LLI prototype functionality in two spatial dimensions, introducing a binary variant of the LLI prototype and evaluating effects of both prototype variants in a dynamic driving simulator study with highway and intersection scenarios.

Contents

6.1 Publication Disclosure . . . **81**
6.1.1 Bibliographic Information . . . 81
6.1.2 Author’s Contribution . . . 81
6.1.3 Copyright Notice . . . 81
6.2 Introduction . . . **82**
6.2.1 Open Questions . . . 82
6.2.2 Research Hypotheses . . . 83
6.3 Materials and Methods . . . **84**
6.3.1 Tactile Interface . . . 84
6.3.2 Stimulus Encoding . . . 85
6.3.3 Driving Simulator . . . 87
6.3.4 Data Acquisition . . . 88
6.3.5 Data Analysis . . . 92
6.4 Results . . . **94**
6.4.1 Subjective Reports . . . 94
6.4.2 Driver Behavior . . . 99
6.5 Discussion . . . **102**
6.5.1 Subjective Effects . . . 102
6.5.2 Objective Effects . . . 103
6.5.3 Binary and Continuous Stimuli . . . 104
6.5.4 Long-Term Exposure . . . 106
6.5.5 LLI Function Expansion . . . 107
6.6 Chapter Summary . . . **108**

6.1 Publication Disclosure

This chapter is based on the publication "Tactile encoding of directions and temporal distances to safety hazards supports drivers in overtaking and intersection scenarios" by Krüger, Wiebel-Herboth, and Wersing [4], which was published in Volume 81 of the journal *Transportation Research Part F: Traffic Psychology and Behaviour*. To improve integration into the dissertation, the first part of the introduction section (6.2) has been rewritten, the discussion has been shortened, and a chapter summary (6.6) has been added.

6.1.1 Bibliographic Information

[4] Matti Krüger, Christiane B. Wiebel-Herboth, and Heiko Wersing. "Tactile encoding of directions and temporal distances to safety hazards supports drivers in overtaking and intersection scenarios". In: *Transportation Research Part F: Traffic Psychology and Behaviour* 81 (2021), pp. 201–222. ISSN: 1369-8478. DOI: `10.1016/j.trf.2021.05.014`.

6.1.2 Author's Contribution

Personal contributions to publication Krüger, Wiebel-Herboth, and Wersing [4] according to the Contributor Roles Taxonomy (CRediT) [24]:
Conceptualization, data curation, formal analysis, methodology, project administration, resources, software, supervision, visualization, writing - original draft, writing - review & editing.

6.1.3 Copyright Notice

6.2 Introduction

The lateral line interface (LLI) introduced in the previous chapter utilizes tactile stimuli to convey both *direction* and *temporal proximity* to an approaching object on a collision trajectory. Such a tactile encoding of dynamic temporal and spatial features has received only little attention (see, e.g., [271]) despite being a promising research direction for driver assistance due to beneficial properties of the sense of touch, including intuitive localizability [231] and a capability to notice new tactile input without prior attention [230].
Results of the first user study, in which the LLI was available to participants during simulated highway traffic scenarios, suggest that the LLI could exploit these properties. Study participants felt supported and drove safer than without LLI assistance after only a few minutes of LLI exposure. However, different aspects of the LLI could theoretically account for the measured safety benefits: The lowest stimulus intensity level of the LLI was chosen to be just above people's perceptual threshold. The transition from receiving no stimulus to the first stimulus at the signaling threshold is thus a noticeable event, which already signals that a safety hazard approaches from the given direction (binary presence information). Furthermore, the stimulus intensity level conveys how close the respective hazard is temporally (continuous urgency information). Decoding the intensity level would allow people to better plan and prioritize their actions, especially when multiple objects need to be tracked.

6.2.1 Open Questions

The following sections of this chapter are excerpts from the publication Krüger et al. [4], unless specified otherwise. For further publication disclosure details see Section 6.1.

Although questionnaire and interview responses reported by Krüger et al. [3] indicated that participants understood and utilized the stimulus intensity, the practical contribution of the time-contingent stimulus intensity has not yet been addressed. With the present work we investigate the role of the time-contingent stimulus intensity explicitly by a comparison of binary and continuous signal variants. Such a comparison can be particularly insightful in situations in which the time information gives the driver a theoretical advantage. An example for such a situation is a scenario in which multiple vehicles are simultaneously approaching the ego-vehicle but are predicted to collide with it at different times. In this scenario a variable intensity could help a driver to prioritize the most urgent of multiple concurrent stimulus sources. Scenarios with laterally crossing traffic such as intersections can provide an appropriate basis for addressing the value of a continuous encoding.
Another open question is whether the reported safety advantages generalize to scenarios that differ from the tested highway overtaking scenarios. Krüger et al. [5] found that, on average, LLI-usage increased the safety by more than 2 seconds in highway scenarios with strongly limited visibility and thus even higher inherent criticality. An investigation of cases with reduced criticality, in which the LLI may be utilized outside the scope of a warning device, has not yet been reported and constitutes another contribution of the present work. The earlier drivers

become aware of potential upcoming hazards, the more foresighted their driving behavior can be. Assistance utility in situations of reduced criticality could thus even have the potential to reduce the occurrence of more critical situations. In the context of the LLI, we define scenarios of reduced initial criticality as scenarios in which a driver can manage to avert a collision already near the edge of the stimulus onset threshold of 5 seconds without falling into a 0-3 seconds TTC range.

With the information provided by an LLI, drivers should be able to more accurately assess the safety of situations and adjust their behavior accordingly. By basing predictions on present conditions, the LLI assumes a function within a feedback loop [272, 273] that tells a driver whether the last action leading to the current state was safety-reducing or safety-increasing. The safety increase in critical situations reported by Krüger, Wiebel-Herboth, and Wersing [2] supports this perspective. Additionally, driving adjustments may be efficiency-driven [274].

Typically, a driver implicitly balances a safety and an efficiency objective on the way to a destination. An example in which the two objectives are weighted against each other is a situation on a multi-lane road with a decelerating vehicle in the front. Maintaining the own speed, with an intention to overtake once a gap opens on the fast lane, temporarily reduces the safety but not the efficiency. Matching the velocity of the slow front vehicle improves the safety but reduces efficiency due to braking (energy loss) and slowing down (time loss), which in turn reduces the chance of overtaking successfully. For many drivers, decisions might additionally be influenced by a *fairness objective*. In traffic, each action can have consequences for other traffic participants' set of operational possibilities. Selecting actions that maximize this set for all affected traffic participants aids the promotion of safety and efficiency on a wider scope and can hence be a worthwhile objective in foresighted driving [275]. We hypothesize that the choice to act one way or another depends on how the driver judges it to affect individual objectives. Thus, the driver's ability to correctly assess the consequences of possible actions would be a determining factor. The purpose of the LLI is to support the driver in this assessment. Here we aim to extend the understanding of the effects of LLI-usage on driving experience, driver behavior, and safety.

6.2.2 Research Hypotheses

Based on the above reasoning about the utilization of encoded time information and behavioral effects of system utilization under reduced criticality, we propose the following research hypotheses:

H1 (subjective benefit): Drivers benefit subjectively from direction and TTC-based urgency information encoded in tactile stimuli to improve safety in

- **a:** highway overtaking scenarios with low criticality
- **b:** intersection scenarios with lateral traffic

H2 (objective benefit): Drivers present higher driving safety levels when assisted by direction and TTC-based urgency information encoded in tactile stimuli in

- **a:** highway overtaking scenarios with low criticality
- **b:** intersection scenarios with lateral traffic

H3 (advantage of time encoding): Continuous tactile TTC-based urgency signaling provides a larger subjective and objective benefit than binary signaling that does not differentiate between different levels of sub-threshold urgency.

To investigate these hypotheses we present a new driving simulator study in which we tested the effects of binary and continuous LLI variants in two classes of driving scenarios.
The remaining chapter is divided into three parts: *Materials and Methods*, *Results*, and *Discussion*. The *Materials and Methods* section starts with a description of the interface and stimuli of the investigated assistance. This is followed by descriptions of the data acquisition processes, including participant selection, experimental design, and procedure description. The final part of the *Materials and Methods* section describes the methods of data analysis. The *Results* section contains results descriptions according to the data analysis methods illustrated previously. The section separates results based on subjective reports such as questionnaires and results that refer to driver behavior and performance. Results are interpreted in terms of the research hypotheses specified above this paragraph. Finally, in the *Discussion* section we summarize, critically discuss, and interpret the results. Furthermore, proposals for future work are derived from the discussion.

6.3 Materials and Methods

This section describes the individual components of the study. First, we introduce the tactile interface and stimuli that were utilized to realize two variants of the previously mentioned lateral line interface (LLI). Next we describe the driving simulator setup and the different scenarios in which these interfaces were employed, followed by a description of the data acquisition process. The section concludes with our data analysis procedure.

6.3.1 Tactile Interface

To generate tactile stimuli we used belt-like interfaces containing 16 equally spaced eccentric rotation mass motors that are triggered with 50 ms latency (feelSpace GmbH, [224]). These actuators can vibrate with a maximum amplitude of 2.2 g and have a frequency spectrum of 50-240 Hz (0.45-3.3 V). Frequency and amplitude scale almost linearly with voltage. However, this physical stimulus magnitude does not necessarily map linearly to a perceived magnitude. For various senses the relationship between physical and perceived stimulus magnitude can be more accurately expressed in a power law [239, 276] where exponent values vary across sensory modalities and stimulus sites [239]. As described by Krüger et al. [2, 3, 5] who used the same actuators and stimulus locations, the perceived stimulus magnitude for vibrations in the sub 250 Hz range on the body has been found to scale approximately linearly with reference exponents ranging from 0.75 to 0.97 [240]. For stimulus intensity scaling, we decided to use an exponent of 0.83, which is the reference value obtained by Merchel, Altinsoy, and Schwendicke [240].
Because firm contact with the actuators is critical for intensity perception, we used five different belt sizes that can accommodate different body shapes. Depending on the size, the actuators are

spaced between 4.9 and 6.5 cm apart. With this setup it is theoretically possible to produce a so-called funneling illusion [241, 277], which describes a perception of one stimulus that appears to be located between two neighboring actuators that are simultaneously active. However, the design of our scenarios contained no instances of simultaneously signaled objects that were located close enough to each other to induce such an illusion. Therefore, we were able to take advantage of the high spatial resolution of the interface without having to fear a confound from funneling effects. The spacing of actuators also allows for an illusion of apparent motion [242] when neighboring actuators are subsequently triggered. In our setup, this case could occur whenever the angle between the ego-vehicle and a signaled object changes. We argue that such a perception of movement is likely to help drivers to correctly attribute stimuli to a moving object in the environment and thus facilitate scene understanding.

6.3.2 Stimulus Encoding

We mapped two types of information about approaching objects to tactile stimuli. First, the direction of any approaching object relative to the ego-vehicle was mapped to a stimulus location on the belt. To do so, the angle between the ego-vehicle and an approaching object was calculated in ego-centered coordinates and mapped to one of sixteen ranges of 22.5° that were associated with individual vibromotors. The angle γ between the ego-vehicle a and an approaching object b was obtained by taking the $arctan2$ function of the difference $\vec{d}$ between their position coordinates $\vec{a}$ and $\vec{b}$ (see Equation 6.1).

$$\begin{aligned} \vec{d} &= \vec{b} - \vec{a} \\ \gamma &= \arctan2(d_x, d_y). \end{aligned} \tag{6.1}$$

Second, a bound temporal proximity between ego-vehicle and the approaching object was mapped to the intensity of tactile stimuli. Here we define the bound temporal proximity as the complement of the time-to-contact (TTC) between the ego-vehicle and another object that is on a collision track with the ego-vehicle within a limited time range. As TTC we understand the time it would take two objects to collide when assuming that they maintain their current velocities and movement directions [278]. Accelerations are not taken into account.

For two vehicles a and b, driving behind each other on the same lane, the TTC between them consists of the distance d_{ab} divided by the relative velocity $v_b - v_a$.

$$TTC_{1D} = \begin{cases} \frac{d_{ab}}{v_b - v_a}, & \text{if } v_b > v_a \\ \infty, & \text{otherwise.} \end{cases} \tag{6.2}$$

However, the LLI does not just require TTC information for the front or back directions but for arbitrary directions in the horizontal 2D plane. Here we therefore implemented a different approach that predicts the TTC based on individual extents and estimated trajectories of objects in the environment.

6.3.2.1 TTC-2D

In a first step, the positions, orientations, velocities and extents of movable objects in the environment are obtained. Based on these, the future trajectories of the objects are calculated and spatially expanded according to individual object extents, resulting in a set of trajectory polygons. To limit the need of computational resources, trajectories are only estimated up until a specified future point in time t_{max}.
The program then checks for a spatial and temporal overlap between the trajectory polygons of ambient objects and the ego-vehicle. In case of a detected spatiotemporal overlap, the time of the first predicted overlap is taken as the TTC towards that object[1]. Otherwise the TTC for that object is considered to be infinite.

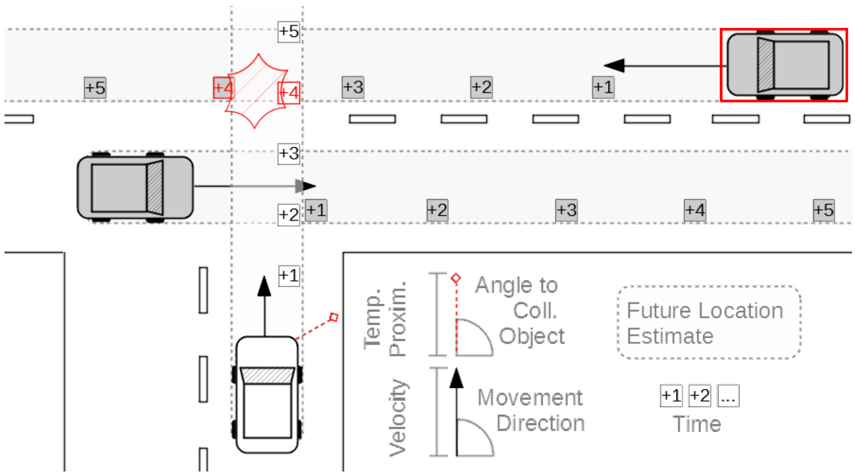


Figure 6.1: Illustration of the TTC estimation procedure with two spatial dimensions. Predicted trajectories are annotated with time markers that indicate the predicted vehicle's front position at the respective time. Arrows represent the moving direction (angle) and velocity (length). Vehicles with a predicted collision (spatial and temporal overlap) are highlighted.

[1]Our method for collision prediction relies on momentary trajectories and relative velocities to create one predicted path for each vehicle at a time. It does not consider any uncertainty about the future behavior of each vehicle, which could result in alternative predictions with varying probabilities for each vehicle. Our method may thus be classified as deterministic. For a probabilistic approach that aims to incorporate some of this uncertainty to derive a broader prediction of a collision risk than the TTC, see Eggert & Puphal [83].

Algorithm 1: TTC_{2D} computation in pseudocode.

for *each object* **do**
  Compute future trajectory from location, orientation and velocity;
  $\forall t \in \{t_0 < t \le t_{max}\}, pos_t = \begin{pmatrix} x + d_t\cos(\alpha) \\ y + d_t\sin(\alpha) \end{pmatrix};$
  Create space-time polygon from trajectory and extents;
  if *object == ego vehicle* **then**
    Store *ego-polygon*;
  else
    if *intersects with ego-polygon (in space and time)* **then**
      TTC = time of first intersection;
    else
      TTC = ∞;
    end
  end
end

6.3.2.2 Intensity

We created two LLI variants, which differed in how the stimulus intensity was utilized to encode information. For objects with a TTC above the threshold θ of five seconds, no stimulus was generated (intensity = 0). We chose this threshold because it approximates the limit at which present-day systems can make event predictions [129, 279] and because prior research on driver behavior [280] suggests a TTC of 4.5 to 5 seconds as an appropriate activation threshold for collision avoidance systems. For the first LLI variant the stimulus intensity I was set to increase with falling TTC according to Equation 6.3. Here s stands for the chosen Stephens' exponent of 0.83. Due to this continuous mapping from TTC to intensity, we term this LLI variant *continuous LLI*.

$$I_{continuous} = max\left(\frac{\theta - TTC}{\theta}, 0\right)^{\frac{1}{s}}. \tag{6.3}$$

For the second LLI variant, the intensity was not varied for any TTC below that threshold but kept at a constant level μ corresponding to the continuous intensity level at $TTC = 0.5 \cdot \theta$. Due to this binary mapping from TTC to intensity, we term this LLI variant *binary LLI*.

$$I_{binary} = \begin{cases} \mu, & \text{if } TTC < \theta \\ 0, & \text{otherwise.} \end{cases} \tag{6.4}$$

6.3.3 Driving Simulator

The study took place in the dynamic driving simulator of the Würzburg Institute for Traffic Science (WIVW). The integrated vehicle's console contains commonly available instrumentation with automatic transmission. The simulator's motion system uses six degrees of freedom and can briefly realize a linear acceleration up to 5 m/s^2 or $100°/s^2$ on a rotary scale. It consists of 6 electropneumatic actuators (stroke +/- 60 cm; inclination +/- 10°). Three LCD projectors (1920 x 1200 px) are installed in the dome of the simulator and provide the driving scene projection with 240° field-of-view. Exterior and interior mirrors are replaced by LCD displays. The test driver can be observed via a video system and communicate to a system operator via an intercom system. System operation is controlled from a separate operating room. SILAB (WIVW GmbH) was used as driving simulation software.

6.3.4 Data Acquisition

6.3.4.1 Participants

The study included 33 participants, selected from a panel of trained test drivers maintained by the WIVW GmbH. All drivers were trained in simulator driving according to a training procedure specified by Hoffmann & Buld [281] and had experience with participating in traffic research. All participants were naive to the LLI. Eighteen drivers were female (9 experienced, 9 inexperienced) and 17 drivers were male (9 experienced, 8 inexperienced). Drivers were categorized as *experienced* if they reported to have driven more than 100000 km in their life and more than 10000 km per year. Drivers who did not meet these criteria where categorized as *inexperienced*. These definitions are in line with previous studies that used similar driving experience classification criteria [282, 283].

6.3.4.2 Experimental Design

We carried out a mixed design study with two independent groups of participants, where members of the first group would be driving with the binary LLI and members of the second group with the continuous LLI. Within each group we carried out a repeated measures experiment with the independent variables *assistance* (baseline, assisted) and *scenario* (longitudinal, lateral). In the lateral condition we further distinguished between two scenario variants as described in Section 6.3.4.3, resulting in the addition of the independent variable *scenario variant* (unidirectional, bi-directional) for trials with lateral traffic.
Figure 6.2 illustrates the experimental procedure. One experimental session consisted of four blocks. The first block consisted of unassisted drives in highway (longitudinal) and intersection (lateral) scenarios, which are further specified in Section 6.3.4.3. The purpose of this block was to obtain baseline driving data prior to any LLI exposure for each participant. In the second block, the LLI was introduced to the participants and they were given the opportunity to freely explore its functionality in a set of subsequent exploration scenarios, which are further specified in Section 6.3.4.3. Accordingly, the purpose of this second block was the introduction and first familiarization with the LLI.
In the third block, participants had to drive again through either the same highway- or the same intersection scenarios as in block one. However, in this block the LLI was enabled for the first 12 trials (assisted) and then disabled again for 12 trials (baseline) in order to also obtain secondary baseline data after LLI exposure for each participant and scenario. For half of the participants within a group, block three consisted of intersection trials (lateral). For the other half it consisted of highway trials (longitudinal).

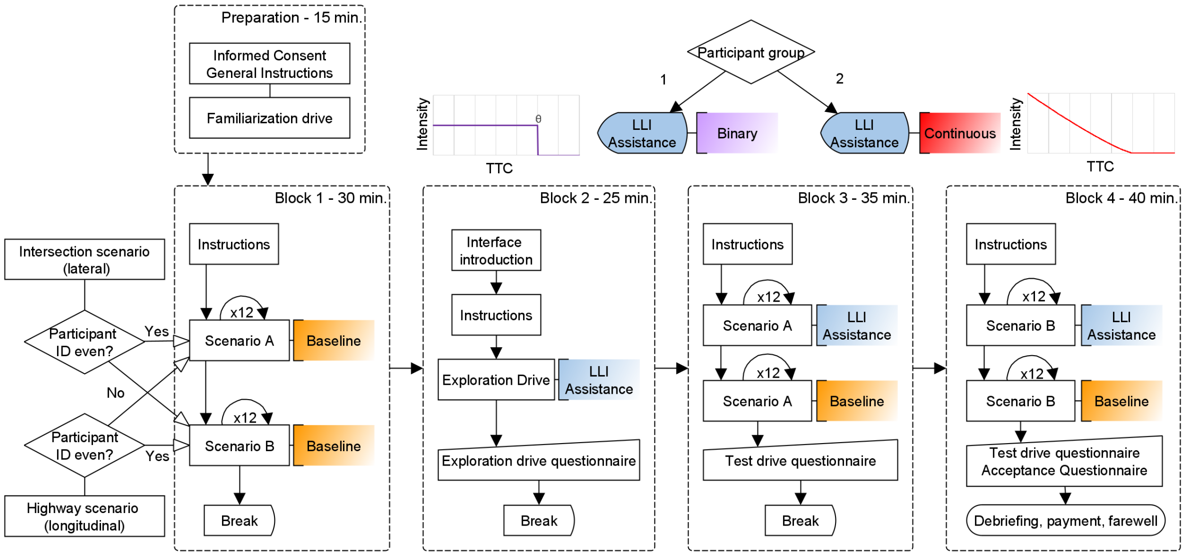


Figure 6.2: Experimental procedure with approximate durations for each block. Participants were assigned to one of two groups that differed in the type of LLI assistance (binary or continuous). Within each participant group, for half of the participants Scenario A was the longitudinal scenario and Scenario B was the lateral scenario. For the other half this assignment was inverted to counter any potential ordering effects. The complete experimental procedure took about 145 minutes.

In terms of driving, block four had the same conditions as block three with the only difference that different driving scenarios were used. Participants who drove through intersection scenarios in block three now had to drive in highway scenarios in block four and vice versa. Through this last block, assisted and secondary baseline data for each experimental scenario and participant could be acquired. For each of the blocks two, three, and four, participants also had to complete a selection of questionnaires further specified in Section 6.3.5.1. The first three blocks concluded with a five minute break.

6.3.4.3 Driving Scenarios

6.3.4.3.1 Exploration Track

An exploration track was included to give participants the opportunity to explore the functionality of the assistance system on their own without prior explanations. It consisted of multiple scenarios, which served to gradually familiarize the driver with different aspects of the LLI. Table 6.1 lists the individual scenarios and corresponding objectives.

Part	Description	Objective
Car following	Two lead vehicles which decelerate. One following vehicle	Perceive front and rear activity (longitudinal)
Intersection	Two intersections: 1. vehicle approach from left side 2. vehicle approach from right side	Perceive lateral LLI activity
Gap merge	Driver must enter the motorway and find a gap for merging into traffic	Infer best gap through stimulus intensity
Motorway	Scenario with varying vehicle platoons: 1. cars on right lane 2. cars on both lanes (displaced) 3. bikes on right lane 4. bikes on both lanes	Experience possibility for active manipulation of signals through action

Table 6.1: Scenarios and objectives of the exploration track

Participants were instructed to determine under which circumstances the LLI would be activated and what meaning the stimuli could have.

6.3.4.3.2 Longitudinal Scenario

The longitudinal scenario was realized on a two-lane motorway track and consisted of a curved approach section (right-hand bend) and a straight test section. The drivers approached a slightly slower moving front vehicle on the right lane while the left lane was occupied by multiple fast moving vehicles.

The main task for participants was to maintain a target speed (120 to 125 km/h) by overtaking slower moving vehicles when necessary. When the driver reached a time headway (THW) of 2 seconds the front vehicle decelerated to provoke a faster approach and thereby an activation of the assistance system. When approaching at target speed the corresponding TTC was approximately 7 seconds at deceleration onset. This gave participants who drove at target speed about 2 seconds to react prior to stimulus onset in LLI conditions. In the approach phase, the traffic on the left lane developed in a way that either a gap for lane change opened up (4 out of 12 trials) or an existing gap was closed by a rear vehicle (4 out of 12 trials) to avoid scene predictability from experience. Traffic on the left lane was realized as a platoon with an infinite amount of cars. In order to maintain the target speed, participants had to overtake the slowing front vehicle in most trials. The period between the moment of front vehicle brake onset and the moment of successful overtaking defined a valid trial. However, in 4 out of 12 trials the front vehicle would not decelerate and, accordingly, require no overtaking maneuver. These trials were included as distractor trials and were not considered in the data analysis. During periods between trials the vehicles on the right lane allowed for undisturbed driving at target speed.

6.3.4.3.3 Lateral Scenario

The lateral scenario consisted of an inner-city intersection situation. The main task was to cross the stream of vehicles that approached from either the left or right intersection arm. Situation predictability was counteracted through a combination of different gap sizes with different approach speeds (first scenario: v = 8.4 m/s, gap size / THW = 4.5 s, second scenario: 13.8 m/s, gap size / THW = 3.0 s). In order to encourage the participants to cross the stream of other road users, the secondary task of the participants was to follow a guidance vehicle driving at 50 km/h, which acted as a navigator and crossed the intersection already before the participants. We opted for car-following as an implicit, yet effective method of navigation [see, e.g., 284], which we estimated to interfere less with driver perception than explicit navigation instructions. In addition, the participants were informed that the traffic routing had been changed and therefore the traffic rules at the intersection would be ambiguous for both the participants and the other road users. This instruction offered an explanation for why other road users would not comply with the right-of-way rule or "expect" the participant to do so either.
In addition to situations in which vehicles approached from only one of the intersection arms, for a subset of 4 out of 12 situations per block the scenario was altered to include approaching vehicles from both sides. In these situations, two vehicles would initially approach the intersection with the same velocity (v = 13.8 m/s) from opposing directions. However, one of the vehicles would decelerate before reaching the intersection and come to a halt in order to yield to the ego vehicle while the other vehicle would continue crossing the intersection at constant velocity. A driver would need to notice which of the vehicles remains a collision risk and adjust the vehicle speed accordingly during approach and intersection crossing. For both scenario variants we defined a trial as the period during which the vehicle was driving in the region starting 70 meters in front of the intersection and ending at the opposite site of the intersection.

6.3.4.4 Experiment Procedure

Upon arrival, participants were welcomed and asked to read and fill out an informed consent form, a privacy statement and a short questionnaire for demographic data. The experimenter then explained that the study is concerned with the evaluation of a new type of driver assistance that utilizes vibrations. These vibrations are transmitted by means of a waist belt that is equipped with vibromotors.
Participants were then instructed to do a familiarization drive for a few minutes before starting the actual experiment according to a procedure specified by Hoffmann et al. [245]. Next, the experimenter explained that multiple driving blocks in and out of town would follow and that participants would need to complete these blocks with and without the tactile assistance while complying with the local road traffic regulations. The blocks were structured according to Section 6.3.4.2. Between blocks, participants could take a break if desired. After completion of all experimental blocks and questionnaires, participants were debriefed, compensated, and dismissed. One session took about 145 minutes. Figure 6.2 illustrates the complete experimental procedure.

6.3.5 Data Analysis

We used a variety of measures to assess both the subjective experience with the system and the objective driving performance. Here we describe these measures.

6.3.5.1 Subjective Measures

6.3.5.1.1 Exploration and Test Drive Questionnaires

For the exploration block and the two test drive blocks (longitudinal and lateral) we used custom questionnaires to assess the participants' experience with the LLI. These questionnaires contained statements for which participants could indicate their agreement on a 7 point Likert scale ranging from *strongly disagree* to *strongly agree*. See Figures 6.3 and 6.5 on page 95 for a list of items and response distributions. Following the questionnaire after the exploration drive, participants were asked the following three interview questions targeting aspects that were difficult to capture using Likert-style items: "What do you think does the belt signal mean?", "What did different signals strengths mean?", "What does the signal location indicate?". Because custom questionnaire items only related to assisted drives and not to baseline drives, we analyzed data for custom questionnaire items descriptively based on median responses and interquartile ranges. For interview questions we categorized individual responses based on semantic similarity and used category counts for a descriptive analysis.

6.3.5.1.2 Perceived Helpfulness

After each trial with an active LLI, participants were asked to verbally confirm whether or not they had noticed the assistance in the preceding situation and to rate its helpfulness on a 7 point ordinal scale ranging from -3 (*not helpful at all*) to 3 (*quite helpful*). Thus, the helpfulness ratings provide a close to real-time subjective evaluation. We tested the effects of stimulus mode and scenario variant (lateral) on helpfulness ratings using two proportional odds logistic regression models, also known as cumulative link model, which are regarded as an appropriate method for the analysis of ordinal data by correctly treating observations as categorical [285, 286] – one for longitudinal and one for lateral scenarios. To test if ratings were positive we used one-sided one-sample t-tests with Bonferroni adjusted alpha levels for repeated testing.

6.3.5.1.3 Acceptance

At the end of the experiment participants completed the Van der Laan acceptance questionnaire [287]. This questionnaire utilizes nine items to assess the *acceptance* of the LLI on two dimensions termed *usefulness* and *satisfaction*, both of which range from -2 (worst) to 2 (best). We compared these scores between stimulus modes using Mann-Whitney-U-tests because usefulness and satisfaction scores are derived from ordinal Likert items. To test whether acceptance was positive we used additional one-sample Wilcoxon signed rank tests with Bonferroni adjusted alpha levels. Because this questionnaire was only used at the end of the experiment, no differentiation between scenarios was possible.

6.3.5.2 Objective Measures

We were interested in how LLI usage would affect driver behavior and, in particular, whether and how it affects driving safety. The following measures were used to assess these aspects:

6.3.5.2.1 Minimum Time-to-Contact

The minimum time-to-contact (mTTC) is a continuous measure that describes the smallest value in a given set of TTC estimates. In our case this set contains TTC values for all recording steps within a trial and across all directions on a 2D plane. The mTTC is thus an expression for how dangerous a trial got at most, with low values indicating high levels of imminence and vice versa. Fluctuations in TTC levels are natural in traffic and dynamic scenarios with moving agents in general [86]. However, as the TTC falls, opportunities to avert a collision are increasingly constrained. Below 3 seconds the TTC approaches dangerous levels, which should be avoided for safe driving.
We tested the effects of assistance and stimulus mode on mTTC scores using linear regression models due to their flexibility in terms of predictor types. For the lateral scenario we included additional predictor terms for scenario variant and the interaction between scenario variant and stimulus mode. Because we only used categorical predictors, the regression analysis can also be interpreted as an analysis of variance (ANOVA).

6.3.5.2.2 Critical Situations

The mTTC also served as the basis for our second objective measure, the occurrence of safety-critical situations. We defined such situations as trials in which the mTTC fell below a threshold of one second. While falling below this threshold does not necessarily entail that a collision occurred, doing so is at least a near-miss case and sufficiently critical [86, 278] to be avoided whenever possible. Due to the binary classification of criticality we tested the effects of assistance and stimulus mode on the occurrence of critical situations using binomial logistic regression models. For the lateral condition we added predictor terms for scenario variant and the interaction between scenario variant and stimulus mode.

6.3.5.2.3 LLI Activation

The longitudinal condition was designed to contain an evolving hazard in the form of a braking front vehicle but should nevertheless give the driver sufficient time and opportunity to resolve the situation safely. However, this also had the effect that it was not guaranteed that the vehicle would necessarily enter a state that would trigger LLI activation despite a deceleration of a front vehicle. This property of the scenario allowed us to additionally investigate, whether the availability of the LLI would have an effect on the probability to enter a state of system activation. An increase in such cases could be interpreted as an indication for a utilization of the LLI for information sampling whereas a decrease could indicate an increased aversion of either stimulus-triggering conditions or of the stimuli themselves. We tested the effects of assistance and stimulus mode on the occurrence of LLI relevant trials using binomial logistic regression due to the binary nature of LLI presence. For the lateral condition we added predictor terms for scenario variant and the interaction between scenario variant and stimulus mode.

6.3.5.3 Postprocessing

Because we are interested in the effects of LLI usage, we had to ensure that data entering the analysis were accompanied by sufficient participant exposure to the LLI. After all, if a participant should drive so carefully that the LLI signaling range of 5-0 seconds mTTC is never reached, there would be little grounds for any effect by LLI activation on driver behavior or experience. We therefore applied a filter criterion to exclude blocks in which LLI signaling ranges have not been reached in at least 4 out of 12 trials. Distractor trials were excluded from all analysis by default. This resulted in an exclusion of 167 trials (=49%) in the longitudinal condition and 0 trials in the lateral condition. We applied the exposure criterion to all test drive block measures except for the occurrences of critical situations and LLI activation because these two quantities are by definition only meaningful with a full availability of opposing data.
In the exploration block the scenario design and experimenter instructions ensured sufficient LLI exposure so that no data filtering criterion had to be applied for exploration data. Data from baseline blocks before and after LLI exposure were merged for each scenario to counteract potential learning effects. All data were processed with *Python* 3.8 using *pandas* data structures for statistical computing [288]. Subsequent statistical analysis was carried out using *R* [289].

6.4 Results

This section contains study results and their consequences for our research hypotheses stated in the introduction. Detailed interpretations and discussions of the results can be found in the discussion section (6.5).

6.4.1 Subjective Reports

6.4.1.1 LLI Perception after Exploration

Figure 6.3 shows the distribution of responses to custom questionnaire items that followed the exploration drive (exploration drive questionnaire). Overall, participants strongly agreed that they perceived stimuli at different belt locations. They agreed that they had noticed signal changes and varying intensities, and that they perceived the influence of their own behavior on the signals. They also agreed with the statement of having understood the meaning of the signals before the exploration period was over. There was slight agreement about the ability to use signals without conscious thought. Participants did not consider the signals as useless or disturbing. These ratings indicate a quick understanding and subjective utility after the free exploration drive.
While a subjective confirmation of understanding reveals that participants may have found a potential explanation for the meaning of LLI signals, it does not confirm that this explanation corresponds to the true meaning. For this reason participants were asked to comment on their understanding of the LLI in their own words. Figure 6.4 shows the distribution of responses after

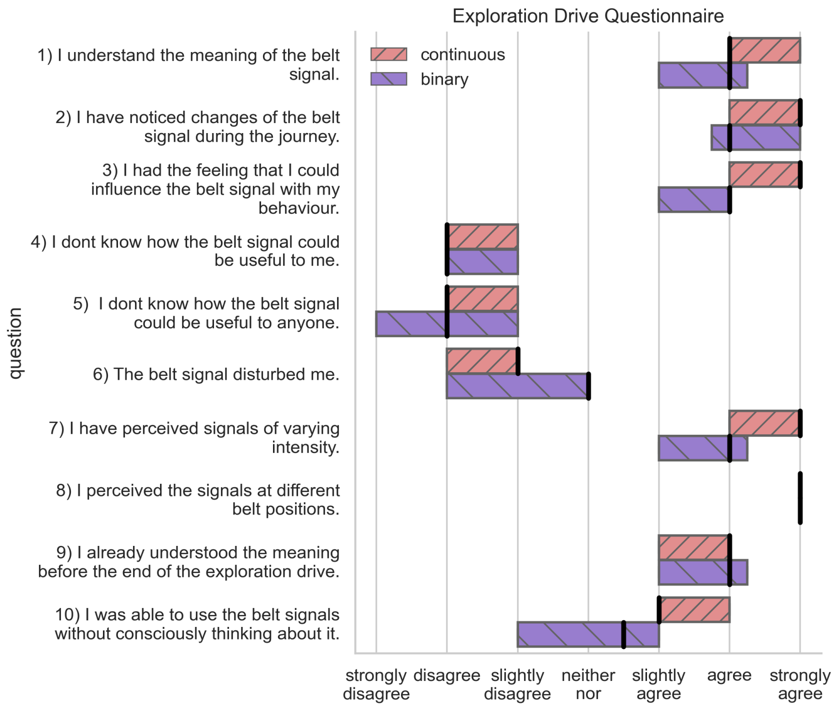


Figure 6.3: Exploration drive questionnaire responses (median and interquartile ranges), separated by stimulus mode (binary and continuous LLI).

a conversion from individual statements into categories that can describe multiple responses. When asked about their understanding of the meaning of signals, participants either attributed the meaning to other vehicles or a risk in the environment. In accordance, stimulus location was linked to the direction of the respective vehicle or danger. Interpretations were similar between the binary and continuous conditions. Signal strength was mainly linked to proximity (mainly continuous LLI) or danger (binary and continuous). One participant thought that it would represent vehicle size and another one understood it as "speed of approach". Only one participant in the binary LLI condition reported not perceiving any changes in signal strength. This outcome is in agreement with responses to the corresponding Likert item "I have perceived signals of varying intensity". Only one out of 16 participants in the binary LLI group disagreed with this statement, two were neutral, and 13 participants reported having perceived signals of varying intensity. However, this outcome is also surprising as it stands in contrast to the single physical intensity level utilized for the binary LLI.

In summary, the subjective reports after the LLI exploration drive indicate that participants were able to perceive stimuli generated by the LLI and quickly form an understanding about the meaning and utility of these stimuli. Their interpretations largely captured important aspects of the underlying information, suggesting that an uninstructed intuitive utilization can be possible.

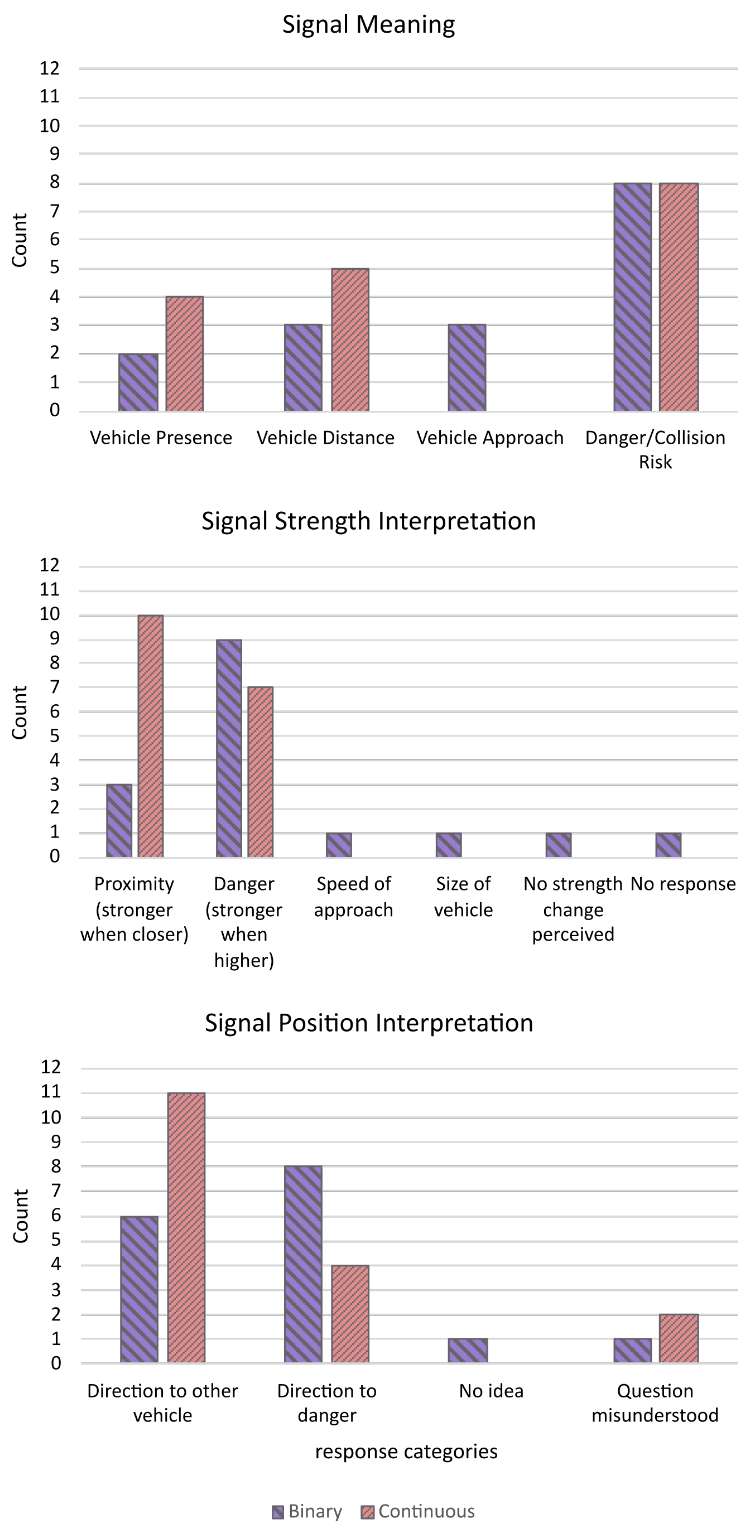


Figure 6.4: Counts of categorized responses to three interview questions concerning a) Interpretation of signal meaning, b) Interpretation of signal strength, and c) Interpretation of signal position.

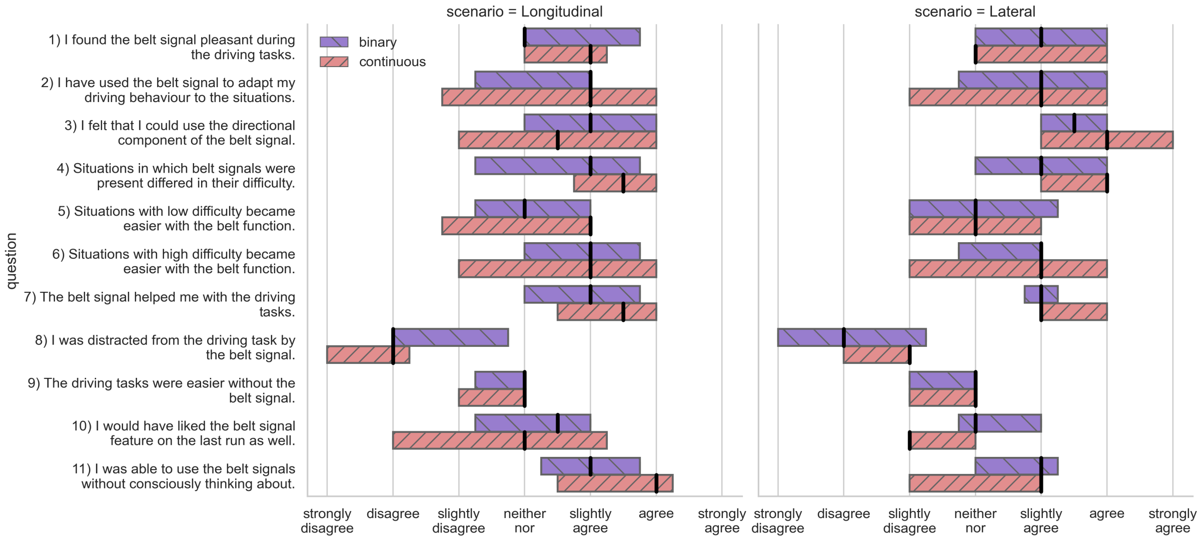


Figure 6.5: Test drive questionnaire responses (median and interquartile ranges) for longitudinal (left) and lateral (right) scenarios and separated by stimulus mode (binary and continuous LLI).

6.4.1.2 LLI Perception after Testing Blocks

Figure 6.5 shows the distributions of responses (median and interquartile ranges) to custom questionnaire items that followed test driving blocks in longitudinal and lateral scenarios (test drive questionnaire). For both scenarios and stimulus modes the participants agreed that LLI signals were pleasant, were helpful in the driving task, and made difficult situations easier to resolve. Most participants indicated having used belt signals to adapt their driving behavior to the situations, especially in lateral scenarios for which also the perceived usefulness of the directional signal component was higher. These ratings provide first support for our hypothesis H1 (subjective benefit), according to which drivers benefit subjectively from LLI signaling in a) highway overtaking scenarios with low criticality and b) intersection scenarios with lateral traffic.

Participants did not perceive the LLI as distracting or as a negative influence on driving task performance. On average, participants were neutral with respect to having liked to drive with the LLI during the last baseline condition. This may indicate that even though participants recognized the utility of the LLI, in their eyes the longitudinal and lateral scenarios did not necessitate LLI use for safe performance. For most items there were only small differences between ratings for binary and continuous LLI variants. In the longitudinal scenarios the binary LLI may have higher relative distraction potential than the continuous variant. There was further more agreement about the continuous LLI being usable without conscious thought than the binary variant, albeit only for longitudinal scenarios.

6.4.1.3 Perceived Helpfulness

Based on our hypothesis H1 (subjective benefit), we would expect helpfulness ratings to be positive in both scenarios. Hypothesis H3 (advantage of time encoding) would further predict an effect of stimulus mode that indicates higher ratings for the continuous LLI than the binary LLI. Figure 6.6 shows the distributions of helpfulness ratings for longitudinal and lateral trials. Table 6.2 shows the output of the cumulative link models for the longitudinal and lateral conditions ($helpfulness \sim stimulus mode$ and $helpfulness \sim stimulus mode * scenario\ variant$, respectively). For both longitudinal and lateral trials, we found no significant effect for stimulus mode (binary, continuous). For lateral trials we further tested for scenario variants (unidirectional, bi-directional) and variant-stimulus mode interaction but found no significant effects for either. However, ratings were significantly above 0 (neutral) and thus positive in both longitudinal $t(96) = 10.106, p < 0.001$ and lateral scenarios $t(341) = 26.463, p < 0.001$. These results support our hypothesis H1 (subjective benefit) a) and b). Drivers did benefit subjectively from LLI signaling in both highway and intersection scenarios. Due to the absence of an effect of stimulus mode, the helpfulness ratings provide no support for our hypothesis H3 (advantage of time encoding).

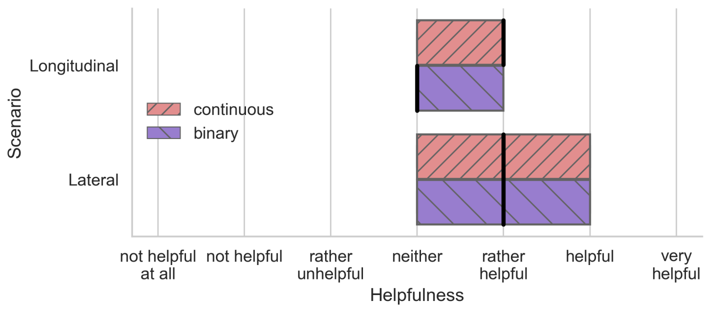


Figure 6.6: Helpfulness ratings (median and interquartile ranges) for longitudinal and lateral trials with both binary and continuous LLI stimulus modes.

	Dependent variable:	
	Helpfulness	
	(Long.)	(Lat.)
Stimulus mode	−0.235	0.058
	(1.045)	(0.647)
Scenario variant		−0.197
		(0.617)
Interaction		0.490
		(0.922)
Observations	14	60
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table 6.2: Helpfulness rating regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

6.4.1.4 Acceptance

Based on our hypothesis H1 (subjective benefit), we would expect usefulness and satisfaction scores to be above 0 in both scenarios. Hypothesis H3 (advantage of time encoding) would further predict an effect of stimulus mode that indicates higher ratings for the continuous than the binary LLI. Figure 6.7 shows mean usefulness and satisfaction scores. Neither usefulness ($w = 141.5, p = 0.6$) nor satisfaction scores ($w = 90.5, p = 0.9$) differed significantly between stimulus modes. Therefore our hypothesis H3 (advantage of time encoding) is not supported by acceptance scores. The acceptance ratings do not indicate that continuous signaling provided a larger subjective benefit than binary signaling. However, both usefulness ($v = 418.5, p < 0.001$) and satisfaction ($v = 328, p < 0.01$) are significantly above 0 (neutral) and thus positive. This supports our hypothesis H1 (subjective benefit). In terms of acceptance ratings, drivers benefited subjectively from direction and TTC-based urgency information encoded in tactile stimuli. However, a distinction between longitudinal and lateral trials is not possible because participants only received the acceptance questionnaire at the end of the experiment.

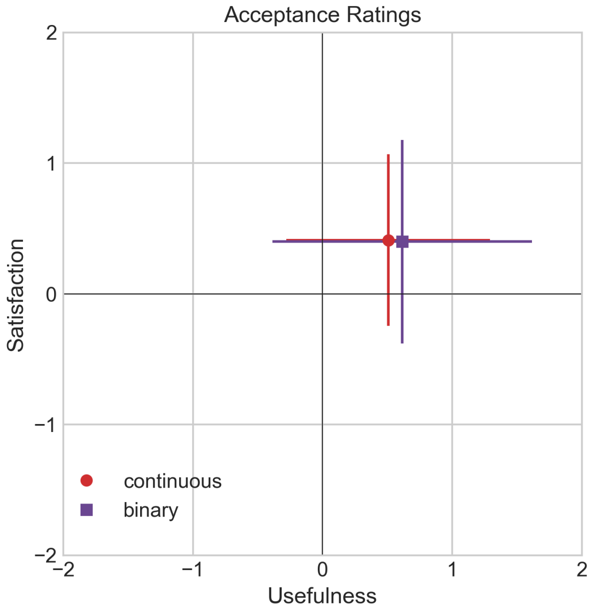


Figure 6.7: Mean acceptance ratings (+ standard deviations) in terms of the dimensions *usefulness* and *satisfaction* for both LLI variants (continuous, binary).

6.4.2 Driver Behavior

6.4.2.1 Minimal Time-To-Contact

Based on our hypotheses we would expect the mTTC to be higher in LLI trials than in baseline trials (H2 - objective benefit) and to be higher with the continuous LLI than with the binary LLI (H3 - advantage of time encoding). Figure 6.8 shows the distributions of mTTC scores with and without an active LLI. In the longitudinal condition mTTC values were distributed near the 5 second LLI activation threshold and only rarely fell below 3.5 seconds with and without LLI activation (assistance on and off). For lateral trials the mTTC values were distributed around 3 seconds, regardless of whether a trial was assisted (on) or not (off = baseline).

Table 6.3 contains the output of the linear regression models of the mTTC for the longitudinal and lateral scenarios ($mTTC \sim stimulus\,mode$ and $mTTC \sim stimulus\,mode * scenario\,variant$, respectively). For both longitudinal and lateral trials there was no significant effect for assistance (LLI on, off). This stands in disagreement with our hypothesis H2 (objective benefit). The mTTC data does not indicate higher safety levels when assisted by the LLI for either a) highway scenarios or b) intersection scenarios. There was no effect for stimulus mode (binary, continuous) in longitudinal trials but a significant effect in lateral trials. In contrast to our hypothesis H3 (advantage of time encoding), according to which the continuous encoding should provide a larger benefit than binary signaling, mTTC values were on average 0.24 seconds lower with continuous than binary assistance. However, also in baseline trials this difference between groups was 0.26 seconds, suggesting the presence of an LLI-independent contribution. For lateral trials neither scenario variant nor the interaction between stimulus mode and scenario variant showed significant effects. The mTTC data therefore do not support hypothesis H3 (advantage of time encoding).

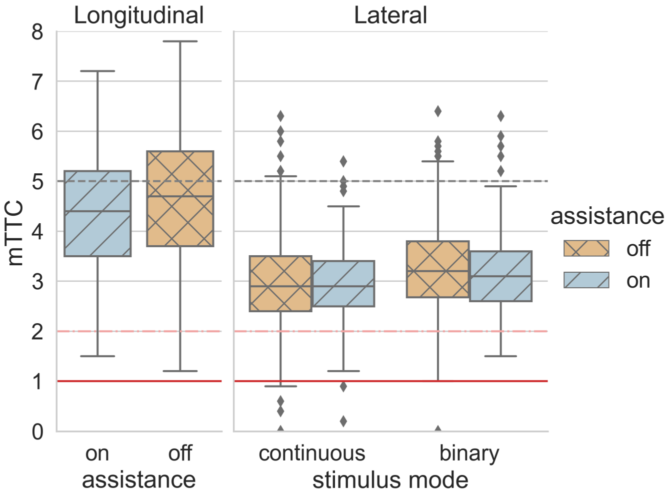


Figure 6.8: Minimum Time-to-Contact measures from trials with (on) and without (off) enabled LLI assistance in longitudinal and lateral scenarios. For trials from lateral scenarios an additional distinction between different LLI variants (binary, continuous) is made.

	Dependent variable:	
	mTTC	
	(Long.)	(Lat.)
Assistance	−0.279	0.002
	(0.169)	(0.061)
Stimulus mode	0.209	-0.183^{**}
	(0.172)	(0.072)
Scenario variant		−0.066
		(0.084)
Interaction mode:variant		−0.185
		(0.118)
Intercept	4.572^{***}	3.234^{***}
	(0.137)	(0.054)
Observations	276	1,042
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table 6.3: mTTC regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

6.4.2.2 Critical Situations

If any critical situations should occur, we would expect their rate to be lower in LLI trials than in baseline trials (H2 - objective benefit) and further to be lower with the continuous LLI than with the binary LLI (H3 - advantage of time encoding). Figure 6.9 shows the percentage of critical situations for longitudinal and lateral scenarios with and without LLI assistance. Trials in longitudinal scenarios did not reach critical levels regardless of whether the LLI was active or not. In lateral scenarios critical situations were rare but nevertheless appear to have occurred more frequently without than with LLI assistance.
Table 6.4 shows the output of the logistic regression models for the occurrence of critical situations in the longitudinal and lateral scenarios ($critical \sim assistance + stimulus\,mode$ and $critical \sim assistance + stimulus\,mode * scenario\,variant$, respectively). For trials in longitudinal scenarios there was no significant effect of assistance. However, in lateral trials there was a significant effect of assistance suggesting that the occurrence of critical situations was reduced in LLI assisted trials. This supports part b of hypothesis H2 (objective benefit). There were no significant effects of stimulus mode, lateral scenario variant (lateral) or the interaction between stimulus mode and scenario variant (lateral) and thus no support for hypothesis H3 (advantage of time encoding). Data on the occurrence of critical situations therefore suggest that drivers presented higher driving safety with LLI assistance in intersection scenarios with lateral traffic but do not indicate an advantage of continuous over binary tactile encoding.

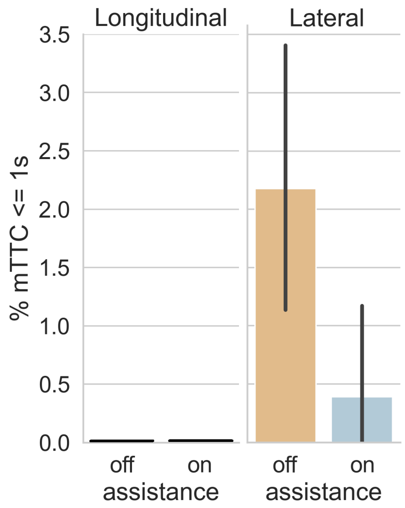


Figure 6.9: Percentage of critical trials (mTTC <= 1 second) in longitudinal and lateral scenarios for trials with (on) and without (off) enabled LLI assistance.

	Dependent variable:	
	Critical Situations	
	(Long.)	(Lat.)
Assistance	18.374	-1.620^{**}
	(2,418.685)	(0.745)
Stimulus mode	-0.621	0.728
	(1.233)	(0.500)
Scenario variant		-16.405
		(1,265.327)
Interaction mode:variant		15.609
		(1,265.327)
Intercept	-22.296	-3.822^{***}
	(2,418.684)	(0.418)
Observations	591	1,176
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table 6.4: Critical trial rate regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

6.4.2.3 LLI Activation

Figure 6.10 shows the percentage of trials that met the LLI activation criteria for longitudinal and lateral trials with and without LLI assistance. For longitudinal trials LLI activation criteria appear to have been met more frequently with the binary than the continuous LLI and further more frequently when the LLI was enabled (assistance on) than when it was disabled (assistance off). In lateral trials LLI activation criteria were met much more often than in longitudinal trials, especially for scenarios with two approaching vehicles for which almost all trials reached mTTC values below 5 seconds. For trials with vehicles approaching only from one side, LLI activation criteria appear to have been met less frequently in the continuous LLI group than for participants with the binary LLI. Table 6.5 contains the output of the logistic regression models for the occurrence of situations that would have triggered LLI activation in the longitudinal and lateral scenarios ($activation \sim assistance + stimulus\,mode$ and $activation \sim assistance + stimulus\,mode * scenario\,variant$, respectively). For longitudinal trials there were significant effects of assistance and stimulus mode. The percentage of trials that reached system activation thresholds was on average 10% higher with than without an active LLI. However, in the continuous LLI group the percentage of such trials was on average 10% lower than for drivers with a binary LLI. For lateral trials there was no significant effect of assistance. However, there were significant effects of stimulus mode, scenario variant, and the interaction between the two on LLI activation. The percentage of trials that reached system activation thresholds was lower with continuous than with binary signaling and lower in scenarios with vehicles approaching from one side than from both sides.

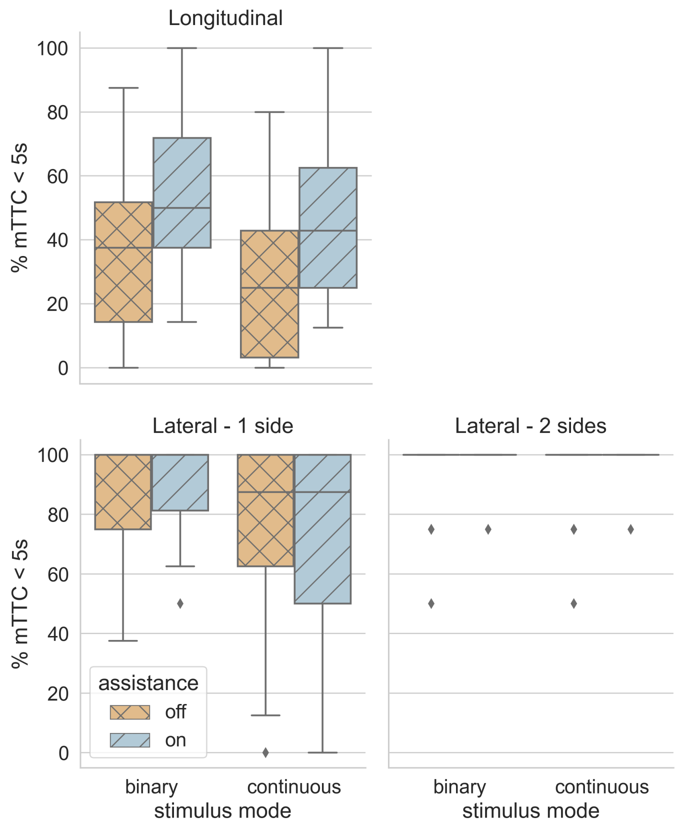


Figure 6.10: Percentage of trials that met the LLI activation criteria (mTTC $\leq$ 5 seconds) in longitudinal (top) and lateral (bottom) scenarios with (on) and without (off) LLI assistance for each LLI variant (binary, continuous). For lateral scenarios we further distinguish between two scenario variants (left: vehicles approach from one side, right: vehicles approach from both sides)

	Dependent variable:	
	LLI Activation	
	(Long.)	(Lat.)
Assistance	0.804***	−0.038
	(0.179)	(0.183)
Stimulus mode	−0.363**	−0.873***
	(0.173)	(0.193)
Scenario variant		1.168***
		(0.393)
Interaction mode:variant		0.958*
		(0.546)
Intercept	−0.590***	1.958***
	(0.135)	(0.167)
Observations	591	1,176
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table 6.5: LLI activation regression coefficients with standard errors in parentheses. Asterisks indicate statistical significance.

6.5 Discussion

In this section we critically discuss and interpret the results of the presented driving simulator study in reference to existing literature. Based on this discussion, we outline proposals for potential follow-up research.

6.5.1 Subjective Effects

Participants were able to perceive intensity and direction components in stimuli and attribute them to nearby vehicles that may pose a collision risk. These findings agree with prior research on peoples' ability to attribute risk [290, 291], distance [235], and direction [247, 292] information to properties of tactile stimuli. This suggests that an employment of tactile stimuli with location- and intensity-based information encoding could be suitable for interfaces that should intuitively convey direction and danger information in the automotive context. In terms of trial-level helpfulness ratings and post hoc usefulness and satisfaction scores, participants rated both LLI variants positively in longitudinal and lateral driving scenarios. Responses to custom questionnaire items further illustrate that participants felt supported by the LLI. These findings support our hypothesis H1 (subjective benefit) for both a) highway overtaking scenarios with low criticality and b) intersection scenarios with lateral traffic.

6.5.2 Objective Effects

We measured objective safety effects in terms of the mTTC and the occurrence of critical events. In contrast to our hypothesis H2 (objective benefit), there was no significant difference in mTTC between trials in which the LLI was active and baseline trials without LLI activation for both longitudinal and lateral trials. Notably, in the longitudinal condition mTTC values were distributed around the 5 second LLI activation threshold and only rarely fell below 3.5 seconds. This stands in contrast to our previous experiments [2, 3] where mTTC values usually reached the range between 1 and 4 seconds, especially during baseline trials. Arguably, this means that the trials in the present study were easy enough for participants to be resolved as well with their basic capabilities as with the additional assistance by the LLI.

For the lateral trials the situation is different: Here the mTTC values were mainly distributed around 3 seconds regardless of whether a trial was assisted (LLI) or not (baseline). This indicates that the scenario affected the mTTC but the LLI did not. The overall smaller and more narrowly distributed mTTC values can be explained largely by the nature of the scenario: While approaching an intersection, the time for reaching that intersection naturally drops. This time coincides with a TTC whenever one of the crossing vehicles would reach the intersection at the same time. Therefore, the mTTC is very likely to keep dropping as the driver approaches an intersection with crossing traffic until the point where the vehicle would come to a stop in front of it. Only few possibilities exist to avoid such a drop in mTTC: 1) maintaining a constant velocity while approaching the intersection once a non-colliding (= no feedback) trajectory has been determined, 2) approaching the intersection at a very low velocity and optionally stopping at an early point. For this reason the direct mTTC is only of limited value for evaluating the safety in lateral trials.

For our second safety measure, the proportion of critical trials, the applicability for longitudinal and lateral trials is reversed. Although classified by the TTC [86, 278], an occurrence of a critical situation was not predetermined by design and may hence be attributed to driver capabilities. Our finding that the rate of critical situations was significantly higher without than with LLI assistance in lateral trials therefore suggests that the LLI helped drivers in avoiding critical situations. This supports part b) of our hypothesis H2 (objective benefit). For longitudinal trials where critical situations did not occur, a measure of their occurrence does not yield information about the LLI's impact on safety.

Besides the rate of critical situations we also investigated the occurrence of LLI-relevant situations, i.e., situations with a TTC below five seconds, as an additional indicator for how the LLI might affect driving behavior. We found that in the longitudinal condition the percentage of trials that met the LLI activation criterion was on average 10% higher with an activated LLI than in baseline trials. In terms of safety this may appear to be a contradiction to our hypothesis H2 (objective benefits). However, because mTTC values were distributed near the activation

threshold and only rarely reached safety-critical levels, we argue that such an interpretation would be misguided. Instead we would like to discuss potential explanations that could be subject to future investigations.
A first explanation might lie in the novelty of the experience of the LLI. If the initial exploration drive should not have sufficed, the participants may have taken the trials with an active LLI as an additional opportunity to explore its functionality. Such a wish for exploration could have let them purposefully surpass the activation threshold also in cases where they could have avoided it. However, if the novelty should be the driving factor, one could argue to expect further exploratory behavior expressed through smaller mTTCs below the activation threshold as well. This does not appear to be the case.
Another explanation could be that participants may have utilized the LLI to sample information. A substantial portion of the signaling range, especially around the onset threshold, does not yet signify danger. In such a range it merely informs the driver about directions from which a dangerous situation could develop in the future if the present trajectory would be maintained and, in the case of the continuous LLI, also how imminent such a danger is. This informative value could serve as an incentive for using the LLI to sample safety-relevant information about the environment in order to improve one's situation awareness and driving competence. Such an explanation would be in line with an ecological approach to perception [65] as well as related frameworks that emphasize the role of actions for sampling and understanding sensory input [217, 222, 293, 294] (see Chapter 4). In Gibson's terms, the LLI may provide an *affordance* that can make some driving maneuvers more informative. When taking a more passive stance, the LLI could also enable drivers to rely on its input as a trigger for a needed correction. Such a reliance might in turn cause drivers to become less attentive outside the signaling range and ,accordingly, increase their likelihood of entering the signaling range. While this third explanation may only find partial support in *active perception* frameworks, it would conform with the theory of risk homeostasis [295].
Presently, we cannot answer whether the increase in the percentage of trials that met the LLI activation criterion was due to novelty, active/passive information sampling or another unspecified reason. A study on long-term effects could aid in confirming or ruling out novelty as an explanation. Active and passive utilization could be contrasted by targeting their respective consequences, i.e., a participants awareness of relevant events that are not communicated by the LLI.

6.5.3 Binary and Continuous Stimuli

In addition to the extended investigation of the original LLI with a continuous encoding of the temporal proximity in the stimulus intensity, here we have introduced a binary LLI variant that is only capable of providing stimuli at a constant intensity whenever the TTC falls below a set threshold. By comparing effects of this binary LLI to the continuous LLI we aimed at learning about the subjective and practical value of the temporal information conveyed through a continuous encoding in the tested scenarios. In contrast to our third hypothesis H3 (advantage of time encoding), we found no significant differences between subjective ratings of helpfulness, usefulness, and satisfaction. Both variants were regarded as equally positive. In terms of trial safety, quantified as the mTTC, we found no difference between the LLI variants in longitudinal trials and lateral scenarios, even with traffic crossing from both sides. However, the average rate of trials in which participants entered a function-relevant TTC range was 10 percent higher with the binary LLI than with the continuous LLI in both longitudinal and lateral scenarios. This suggests that drivers behaved more cautiously when assisted by the continuous LLI than the binary LLI. One possible explanation for this difference could be that a binary signal is easier to interpret as a situation classification criterion than a continuously changing signal. Besides communicating that another object is in a TTC range between 5 and 0 seconds, the binary LLI expresses that a safety-relevant threshold has been crossed. Only the onset of the stimulus is thus informative with respect to the available time and can be learned to mean that any object in the signaled direction can develop into a risk within the foreseeable future. This warning property in turn may have led participants to reduce their caution above the signaling threshold and use any signal onset as a trigger to adapt their driving. In contrast, the gradual development of any continuous LLI stimulus essentially expresses a degree of danger attributed to the signal direction. It may thus be treated less as the crossing of a specific safety-relevant threshold and, accordingly, be less likely to reduce a driver's caution outside its activation range. Taken together these subjective and objective results provide only partial support for our third hypothesis, which predicted larger subjective and objective benefits of the continuous over the binary LLI.

A reason for the lack of subjective differences might have been that the situations were not challenging enough to reveal the informative advantage of the continuous LLI. Indeed, driving data show that in longitudinal trials with system activation the mTTC seldom dropped below 4 seconds for both stimulus variants, which means that only a narrow portion of the continuous signaling range was actually expressed. This makes the realized informative value of both variants more similar and could account for the similarities in the subjective evaluations. However, in the lateral condition mTTCs below 3 seconds were frequently reached, which means that a larger range of continuous stimuli must have been expressed. Accordingly, participants could have taken better advantage of continuous LLI properties, especially in trials where vehicles approached from two sides. Participant accounts on their perception of the stimuli may offer an explanation for why this was not the case: After the exploration drive, thirteen out of sixteen participants in the binary LLI condition stated that they have perceived signals of varying intensity. Additionally, when asked for their understanding of signal intensity only two of these participants mentioned that they either did not perceive a change in intensity or gave no response. The remaining participants linked the intensity to danger, proximity, speed of approach or vehicle size. This outcome surprised us. After all, the binary LLI utilized a single intensity level when active and, accordingly, should not have caused a perception of varying intensity levels, let alone a coupling of a perceived intensity to events in the simulated environment. Also a thorough check of individual log-files confirmed that participants in the binary group have indeed only been exposed to the binary LLI.

This outcome challenges the assumption that tactile intensity perception is determined entirely by the physical stimulus intensity. Research on multimodal perception [183–185, 296, 297] indeed provides grounds for doubting this assumption (see Section 4.2.1). [...]

Another link to our findings presents itself in research on *peripersonal space* (PpS), a representation of the space surrounding an agent's body that is thought to originate in the binding of information from proximal and distal sensory modalities such as vision and touch [298, 299]. Studies on cross-modal extinction [300, 301] suggest the presence of PpS representations in humans, which have been linked to the coordination of defensive behavior and also purposeful actions towards nearby objects [302, 303]. Similar experimental paradigms have revealed a modulation of tactile perception by visual stimuli close to anticipated future hand positions [304, 305]. A utilization of such crossmodal features while driving might offer an explanation for why participants reported perceiving varying stimulus intensities in the binary condition. If a contextual and distance-dependent modulation of tactile intensity perception should indeed be taking place, this would not only mean that a (perceptually) binary LLI would need to include a distance-dependent weakening of stimulus intensities to be perceived as constant but also that the slope of perceived intensity scaling for our continuous LLI could deviate from the linear relationship we were targeting to implement through our scaling function (see page 87). When we tested stimuli and system configurations prior to the experiment we did not notice any effects of this kind. However, our own prior knowledge about the system as well as an available comparison between binary and continuous stimulus variants may have masked such effects during pretests. Future work should investigate such multimodal and context-dependent effects on tactile intensity perception in the driving context more directly. Additionally it could be beneficial to investigate effects of the LLI on driving performance after longer exposure.

6.5.4 Long-Term Exposure

In the present study each participant only had about 40 minutes of LLI exposure. Considering the adaptive nature of human perception and sensory integration, any effects we observe may be dependent on the amount of experience participants had with the LLI. On the other hand, an adaptation in terms of an increase in perceptual thresholds or habituation effects (i.e., a loss of attention due to constant stimulation [306]), may already be counteracted by the relative rarity, short-lived nature and attention relevance of individual stimuli. For studies on effects of prolonged LLI exposure we propose to move from driving simulation to a real vehicle implementation. This would not only increase scenario variability but also introduce factors not considered in controlled simulation such as vehicle vibrations, visibility, and road conditions, some of which may be difficult to observe. When such unobserved factors have an influence on the response variables without being accounted for, this can lead to erroneous inferences. While this so called *unobserved heterogeneity* [307] may already occur to a some extent in our driving simulator setting, it is likely to be amplified in real driving and should thus be addressed explicitly by appropriate statistical models [see, e.g., 308–310].

Real-vehicle implementation would also entail a substantially expanded set of objects the assistance would need to be able to identify and model as potential hazards. For instance, in addition to vehicles also pedestrians can be at the risk of colliding but appropriate risk estimates for pedestrians in real-life may require more than a velocity-based trajectory extrapolation [see, e.g., 311]. Expanding LLI functionality accordingly may be particularly valuable because, amongst others, pedestrians are much easier to miss by visual perception due to their relatively small size.

Real-vehicle employment could also face non-technical challenges that are presently not considered such as driver distraction. While the LLI has the potential to support distracted drivers to quickly focus on identified hazards, its availability as an additional safety layer may also affect

the drivers' susceptibility for distraction [312]. If confirmed, such a property could reduce LLI applicability in manual driving. However, for the same reasons the LLI application scope could be shifted towards shared control and automated driving settings, in which driver distraction is to be expected. Here the LLI's contribution to scene understanding and system transparency might have a positive impact on user acceptance of vehicle automation [313].
Another issue that relates to the proposed interface would be a defiance of seatbelt use that is still present in some regions and demographics [314] and which would compromise any seatbelt-based communication. However, giving the seatbelt additional informative value through LLI functionality could also help in reducing such bad habits as it would provide one additional reason for seatbelt use.

6.5.5 LLI Function Expansion

Our method for deriving the TTC in two dimensions, as introduced on page 86, can also be understood as a deterministic heuristic for predicting the collision risk (see Eggert [246] for a discussion on the link between risk and time-to-event estimates). Despite conveying information about a predicted future, the TTC-dependent signal maintains a direct causal link between current states and actions, and future event predictions: Steering into a collision trajectory activates a stimulus whereas steering away from a collision trajectory deactivates the stimulus. Maintaining or increasing a relative velocity that reduces the gap between vehicles increases stimulus intensity while actions that decrease it will trigger stimuli of stable or reduced intensity. A downside of such a direct correspondence between the future impact of current events and generated stimuli is that the potential impact of future situation-altering actions by other agents is not considered. Information about a collision-relevant action by another agent is only obtained and communicated at the time of the action, regardless of its prior probability. A system that would take the uncertainties associated with the future behavior of other drivers or other second order predictions into account [see, e.g., 83], could provide safety-relevant information for a larger set of situations and at an earlier point in time. However, such a system would carry the risk of making the causes of stimuli more difficult to infer for a driver. It could therefore also be necessary to find an appropriate way of encoding uncertainty in tactile stimuli and investigate whether such an added interface dimension can be understood and utilized by drivers.

6.6 Chapter Summary

This chapter presented an investigation of the roles of hazard criticality and the continuous urgency encoding of tactile stimuli on the perceived support and driving safety influence of the lateral line interface (LLI) introduced in Chapter 5.
While scenarios in the previous study [2] (Chapter 5) were characterized by urgent and largely externally determined events, for the driving simulator study presented in this chapter, the scenarios were designed to be less urgent and give participants more opportunity to handle events according to their preferences. In addition to longitudinal highway scenarios, also intersection scenarios with laterally crossing traffic were included. This required an extension of LLI functionality to be driven by lane-independent trajectory predictions in two spatial dimensions. To investigate the extent by which the continuous urgency encoding of LLI stimulus intensity affects perceived utility and driving safety, a binary variant of the LLI with a single intensity level beyond the activation threshold was contrasted with the continuous version.
Driving safety, quantified as the minimum time-to-contact (mTTC) and rate of critical situations, as well as the participants' understanding, acceptance, and perceived helpfulness of the two LLI variants were measured. In agreement with the previous study by Krüger et al. [2], participants presented an intuitive understanding of LLI functionality after brief exposure and rated the LLI favorably in terms of helpfulness and acceptance. In contrast, for mTTC values no differences between unassisted and LLI-assisted drives were found in the tested low urgency scenarios. Nevertheless, LLI-assisted trials in intersection scenarios had a lower occurrence of safety-critical situations. In highway scenarios critical situations did not occur. However, here LLI availability increased the likelihood for entering system-relevant signaling ranges, suggesting that the LLI may have been utilized as a response trigger by participants. While this interpretation gives a large weight to the binary presence information conveyed by the LLI, subjective reports of LLI understanding emphasize the perception of continuous urgency information. Surprisingly, a perception of continuous danger-dependent intensity variation was even reported by most participants who were only exposed to the binary variant of the LLI (binary LLI), i.e., an LLI variant in which no continuous intensity scaling was present. This raises questions about the stability of tactile psychophysics in light of variable driving context.
In summary, the findings suggest that the LLI supports drivers in avoiding critical situations in intersection scenarios but also that drivers achieve similar safety levels in low urgency situations with and without the LLI in terms of the mTTC. Nevertheless, participants felt supported and showed signs of reliance on binary presence information. Such effects have to be considered when planning a utilization of LLI-like systems in real world mobility. Reliance might partially be an effect of perceived reliability. So how do drivers utilize the LLI when assistance stimuli start to convey uncertainty? This question will be addressed in the next chapter.

7
Spatial Ambiguity

"I think people get it upside down when they say the unambiguous is the reality and the ambiguous is merely uncertainty about what is really unambiguous. Let's turn it around the other way: the ambiguous is the reality and the unambiguous is merely a special case of it, where we finally manage to pin down some very special aspect."

David Bohm, [315, p.25]

One way to interpret the lateral line interface (LLI) is as a form of what Sorkin et al. ([126]) refer to as *likelihood alarm systems*. A likelihood alarm system produces graded alerts that become more prominent as the likelihood of the event, which it signals, increases. The scaling of LLI stimuli is dependent on the time-to-contact (TTC), i.e., a temporal distance to an event. TTC and collision probability are linked: as the TTC falls, the number of ways in which a collision may be averted decreases. As there is less time to react, reactions must further become increasingly fast, which eventually becomes difficult to accomplish due to inherent physical constraints for interference with vehicles that are in motion. While a trajectory-, distance-, and velocity-dependent TTC is not necessarily the only factor that affects collision probability, it is at least an approximation. For a driver, it might thus be equally valid or useful to think about LLI signals as indicators for hazard directions together with the corresponding collision probabilities expressed in stimulus salience. Conversely, the less definite or more uncertain a risk is, the less salient the corresponding stimulus appears. However, uncertainty can also exist on other dimensions. For instance, in some situations it might not only be unclear whether an element in the environment is a hazard but also where exactly this hazard will appear.
This chapter explores the possibility of encoding uncertainty about hazard directions in LLI stimuli on top of encoding the TTC. It introduces a novel approach for implementing that target and presents an investigation of the effects of a corresponding prototype on drivers in a driving simulator study. Of particular interest are the questions whether stimuli with the added spatial uncertainty can still be understood and, if so, whether they are utilized to achieve a safety benefit.

Contents

7.1 Publication Disclosure **111**
7.1.1 Bibliographic Information 111
7.1.2 Author’s Contribution 111
7.1.3 Copyright Notice 111
7.2 Introduction **112**
7.2.1 Related Work 112
7.2.2 Current Study 114
7.3 Materials and Methods **115**
7.3.1 Participants 115
7.3.2 Experimental Setup 115
7.3.3 Stimuli 116
7.3.4 Experimental Design 118
7.3.5 Procedure 119
7.3.6 Analysis 123
7.4 Results **126**
7.4.1 Subjective Reports 126
7.4.2 Gaze Distribution - H2 (Subjective Benefit) and H4 (Safety) 130
7.4.3 Trial Safety - H4 (Safety) 131
7.5 Discussion **132**
7.5.1 Signal Understanding and Experiment Validation 132
7.5.2 Uncertainty Signaling in Human Uncertain Conditions 133
7.5.3 Uncertainty Signaling in Human Certain Conditions 134
7.5.4 Limitations 134
7.6 Chapter Summary **135**

7.1 Publication Disclosure

This chapter is based on the publication "Feeling Uncertain - Effects of a Vibrotactile Belt that Communicates Vehicle Sensor Uncertainty" by Krüger et al. [5], which was published in the special issue "Test and Evaluation Methods for Human-Machine Interfaces of Automated Vehicles" [316] of the journal *Information*. To improve integration into the dissertation, a chapter summary (7.6) has been added. Some of the research that underlies this chapter was carried out within the Master's thesis project of Tom Driessen, whom I supervised during his time at HRI-EU.

7.1.1 Bibliographic Information

[5] Matti Krüger, Tom Driessen, Christiane B. Wiebel-Herboth, Joost CF de Winter, and Heiko Wersing. "Feeling Uncertain - Effects of a Vibrotactile Belt that Communicates Vehicle Sensor Uncertainty". In: *Information* 11.7 (2020). ISSN: 2078-2489. DOI: 10.3390/info11070353.

7.1.2 Author's Contribution

Personal contributions to publication Krüger et al. [5] according to the Contributor Roles Taxonomy (CRediT) [24]:
Conceptualization, data curation, formal analysis, methodology, project administration, software, supervision, validation, visualization, writing - original draft, writing - review & editing.

7.1.3 Copyright Notice

7.2 Introduction

The following sections of this chapter are excerpts from the publication Krüger et al. [5], unless specified otherwise. For further publication disclosure details see Section 7.1.

Modern cars are equipped with sensor systems that surpass human perception in various ways. For example, camera systems may offer continuous 360-degree vision and Lidar can provide vision in the dark. Advanced driver assistance systems use these sensor capabilities by providing the driver with supportive information (e.g., lane departure warning, blind spot detection, navigation) or by taking over control (e.g., adaptive cruise control, automated lane keeping). However, the reliability of sensory systems may degrade due to changes in the environment. For example, the accuracy of Lidar measurements tends to decrease in the rain [317], and car manufacturers warn about reduced reliability of sensors in tunnels [e.g., 318, p.96]. Since drivers cannot be expected to have an understanding of the functioning or the mere existence of these sensor systems, they may benefit from the availability of information on sensor reliability. An assistance system could assess such measures of uncertainty by itself, where the level of uncertainty may be based on signal variance or the disagreement between different sensor signals. A system that would share information on sensor uncertainty could help drivers adjust their level of trust in the automation to appropriate levels [127]. This approach is in line with a cooperative automation framework, which challenges designers to regard assistance functions as cooperative partners or team agents, rather than as tools, for example, [1, 151, 319–321]. Among ten challenges to make automation a team player, Klein et al. [320, p.93] listed the team agent's ability to "make pertinent aspects of their status and intentions obvious to their teammates". Communicating system uncertainty might be one step in this direction.

7.2.1 Related Work

Drivers have been found to show safer behavior when being given appropriate supplementary information about the traffic environment [see, e.g., 322–324] [but cf. 325, for potential adverse effects]. Several studies in the automotive context have further investigated the potential of reliability displays, especially for automated driving. Most attempts to communicate system uncertainty have focused on visual displays [326–331]. Variants of such displays include function-specific versus function-unspecific uncertainty encodings or different types of implicit and explicit visualization. Qualitative displays, for example, have illustrated uncertainty through icons, while quantitative displays have incorporated multiple levels or continuous measures of uncertainty using graphs and scales. Beller et al. [326] used an emoji-like icon showing a confused face reaching out with open palms to indicate system uncertainty in a driving simulator experiment. Helldin et al. [328] investigated the impact of visualizing assistance uncertainty on drivers' trust by displaying a visualization of assistance competence (*SAE* level 2 [132]) in a driving simulation with varying weather conditions. The amount of machine confidence was displayed by means of seven empty bars that filled up as confidence increased, in a similar way to mobile phone status bars displaying signal quality. Kunze et al. [329] designed an anthropomorphic reliability display for a simulated *SAE* level 3 automated vehicle.

They made a visual display showing a peak from a heartbeat graph that lit up according to a simulated heartbeat frequency between 50 bpm (high reliability) and 140 bpm (low reliability). In addition to the graph, a numeric value of the current machine heart rate was visible.
Uncertainty communication has been shown to be beneficial. Previous work has found improved safety measures [326], faster take-over times [328, 329, 332], and accompanying changes in gaze behavior [328, 329, 332]. Furthermore, it was found that drivers showed a more appropriate trust calibration [326, 328, 331] and gave higher acceptance ratings for such systems [326] compared to baseline conditions without uncertainty. Also, system comprehension [326] and situation awareness [326] were shown to be improved due to uncertainty communication. However, the deployment of the visual modality as a feedback channel has also been subject to criticism. One disadvantage of visual uncertainty communication is that the driver's visual modality might not be continuously available for input as other activities compete for visual attention. When observing the road or engaging in non-driving tasks, drivers may neglect continuous visual displays [333]. This might become especially problematic in automated driving, where the driver is likely to be engaged in a non-driving task. Thus, the use of visual displays for communicating uncertainty carries the risk of disuse or an increase in perceptual workload [329, 332].
Recent studies have investigated the use of touch [334], olfaction [335], as well as peripheral vision to share measures of system uncertainty with the driver. In particular, a driving simulator study by Kunze et al. [334] investigated different variants of vibrotactile feedback in a car seat to communicate increases or decreases in the global uncertainty of an automated vehicle for initiating a takeover by the driver. They showed that encodings of uncertainty increase were more intuitive to users than encodings of uncertainty decrease. Moreover, changes in amplitude and rhythm of the vibrotactile feedback were rated highest. The authors did not investigate the effect of the tactile uncertainty feedback on objective measures and recommended that it should still be examined whether people can make use of the feedback and respond to it appropriately. In another study, Kunze et al. [332] coupled a peripheral awareness display with vibrotactile feedback in order to communicate different levels of global system uncertainty in an automated driving simulator experiment. However, they only used the vibrotactile feedback to communicate the highest level of system uncertainty. Results showed that driver workload was significantly lower compared to a visual display condition that needed focal visual attention for the uncertainty communication to be perceived. In addition, they found that users had a more appropriate attention distribution and showed better take-over performance.
Apart from its potential for reliability communication, vibrotactile interfaces have been identified as promising elements of user interfaces [336] and as particularly applicable in the context of driver assistance [337] such as for driving [247–251] or navigation support [224, 244, 252–258]. In addition, also advanced tactile encodings of relevant information such as spatial distances [232–236, 266, 338], directions [244, 259–264] and spatiotemporal measures [2, 3] have been investigated. Auspicious reports from these studies let us conclude that vibrotactile feedback is a promising candidate for uncertainty communication in the automotive context and should be investigated in greater detail. To our knowledge, no study so far has investigated tactile communication of system uncertainty relating to individual sensing and signaling about other traffic participants. Here we extend previous research by investigating a previously presented vibrotactile driving assistance system [2, 3] that is extended with an uncertainty com-

munication functionality.

7.2.2 Current Study

The main goal of this study was to evaluate driving experience and performance with a driver assistance system that communicates safety-relevant information and additionally conveys its uncertainty about this information. Using a driving simulation environment, we tested how the tactile encoding of one dimension of system uncertainty would affect the driver's perception of the system in terms of its usefulness, satisfaction, and the perceived workload. In addition, we explored whether such a signal influences measures of driving safety and gaze-based attention. We introduce an extension of a vibrotactile driving assistance interface that has been shown before to successfully support a driver in gaining a better understanding of the environment through sensory augmentation [2, 3]. The tactile assistance provides two types of information – temporal distances and the directions of objects that are on a collision trajectory with the ego-vehicle. The extension introduced here consists of further encoding uncertainty in the tactile stimuli about the directions of objects that are directly approaching. We refer to this uncertainty as directional or spatial uncertainty. Because the underlying assistance system provides information about both direction and temporal distance, also temporal uncertainty, that is, uncertainty about temporal distances, can exist. This dimension of uncertainty is not investigated here and the system is marginalized to have full temporal certainty in this study.
We expect that the effect of directional uncertainty communication are moderated by the driver's own certainty about the directions of potential collision objects. More specifically, we propose the following hypotheses:

H1 (Understanding). Drivers perceive and understand directional uncertainty encoded in tactile stimuli that communicate spatiotemporal distances of approaching vehicles.

H2 (Subjective Benefit): Drivers utilize complementary uncertainty information in tactile stimuli for their subjective benefit.

H3 (Disturbance). Drivers are not disturbed by receiving redundant uncertainty information.

H4 (Safety). Signaling complementary uncertainty information leads to higher objective safety.

We here understand *subjective benefit* as a term that subsumes impressions of usefulness, satisfaction and reduced workload and *objective safety* as an expression of safety derived from driving data such as the the smallest predicted time-to-contact to any vehicle that is on a collision trajectory with the ego-vehicle (i.e., the minimum time-to-contact, see Sections 7.3.3 and 7.3.5.5.4). *Complementary uncertainty* information is here defined as information that augments uncertain human perception. *Redundant uncertainty* information is defined as information that is already fully covered by more certain human perception. *Disturbance* should be understood as the opposite of benefit and would be expressed in lower scores on the subjective measures and lower performance on the objective measures. For this study, we created conditions that enable us to induce both machine and human sensory uncertainty and thereby determine how complementary or how redundant the encoded uncertainty information becomes.

7.3 Materials and Methods

7.3.1 Participants

Fourteen drivers (1 female) between 21 and 41 years old (*M* = 29.1, *SD* = 5.4) participated in the study. All participants reported that they had (corrected-to) normal vision and held a valid driving license for an average of 11 years. All participants gave their written informed consent before taking part in the study.

7.3.2 Experimental Setup

The experiment was conducted in a static driving simulator (Figure 7.1) with controls for steering, braking, and accelerating. Transmission was set to automatic mode. Three display panels (50 inch diagonal, 1080p each, 60 Hz) presented the driving scenario and the remaining parts of the interior (dashboard, instrument cluster, mirrors), using the SILAB 5.1 driving simulation software developed by the WIVW GmbH (Würzburg Institute for Traffic Sciences). Participants wore a 120 Hz monocular eye-tracker (Pupil Labs GmbH [237]). In addition, participants wore a waist belt (feelSpace GmbH [292]) containing 16 equally spaced vibromotors (between 4.9 and 7.5 cm depending on the size of the belt). In particular, the belt contains eccentric rotation mass motors that can have a maximum amplitude of 2.2 g and a frequency spectrum of 50–240 Hz (0.45–3.3 V) triggered with a 50 ms latency. Frequency and amplitude were set to scale approximately linearly with voltage. Four belt sizes were used in the experiment to ensure a good fit for all participants. The firmware of the belt interface was customized for the experiment.

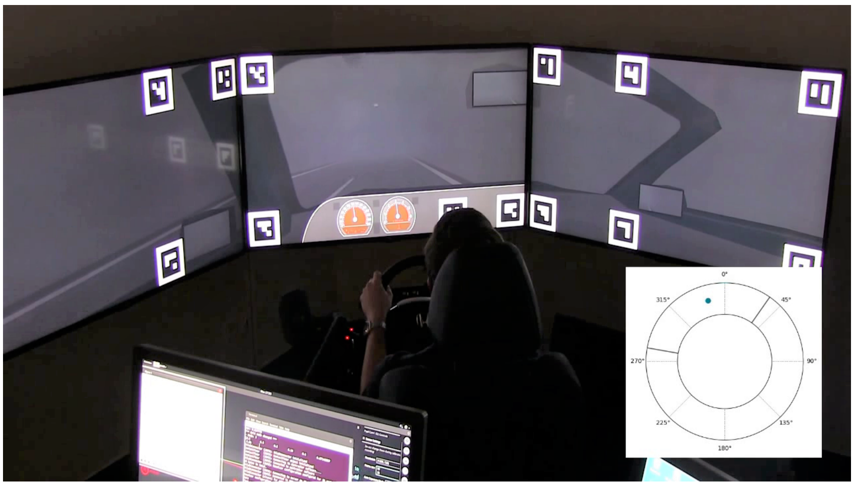


Figure 7.1: Driving simulator setup in the foggy tunnel scenario. The experimenter screen (bottom left) shows a visualization of the tactile stimuli. In this visualization (magnified in the white box on the right side) the location of a dark dot corresponds to the current direction communicated via a tactile stimulus and the size of the dot indicates the intensity of the respective stimulus. Black bars mark the boundaries between which stimuli oscillate dependent on the current range of spatial uncertainty. This visualization was not available to participants.

7.3.3 Stimuli

The tactile communication was implemented with a signaling mode similar to the interface used in the experiments by Krüger et al. [2, 3]. Two information dimensions about approaching objects were encoded in the tactile stimuli. First, the direction of approaching objects relative to the ego-vehicle was encoded in a mapping of stimulus location on the belt. That is, stimulus location signaled from which lane(s) and lane segments (i.e., center front/back, left front/back, right front/back) vehicles were approaching by activating pre-defined vibromotors that were corresponding to the direction of the lane and segment. In previous studies [2, 3], we have found a circular arrangement of actuators, as provided by the feelSpace belt, to be suitable for intuitive signaling of direction information. Nevertheless, other arrangements may also be suitable and could be preferred when working with specific design constraints. Six out of the 16 vibromotors were chosen to realize such mapping (Figure 7.2). The vibromotors for directional lane encoding were distributed according to the schematic shown in Figure 7.2. Thereby we chose to set distances between dorsal actuators to be larger than those for the front direction due to differences in spatial discriminability between dorsal and ventral regions [339, 340]. A similar direction encoding with eight actuators but no varied treatment of ventral and dorsal regions has, for instance, been successfully employed before by Van Erp et al. [244].
Second, the temporal proximity to the approaching object was encoded in the stimulus intensity. We defined the temporal proximity as the complement of the time-to-contact/time-to-collision (TTC) towards a surrounding object that is on a collision track with the ego-vehicle within a fixed temporal range. Assuming that an object b is moving behind an object a along the same path and trajectory with velocities V_a and V_b and a and b are distance D_{ab} apart, the TTC between a and b is given by:

$$TTC = \begin{cases} \frac{D_{ab}}{V_b - V_a}, & \text{if } V_b > V_a \\ \infty, & \text{otherwise.} \end{cases} \tag{7.1}$$

For the left and right lanes, we simplified TTC computation by calculating the L^2 norm of a vector consisting of the respective hypothetical (i.e., assuming already being on the respective lane) longitudinal TTC (TTC_{Long}) and the time to lane crossing (TLC) for the respective lane according to Equation (7.2). The TLC is derived as a TTC that is based on the lateral velocity relative to the lane and the distance to the lane boundary.

$$TTC_{L/R} = \left(TTC_{Long}^2 + TLC_{L/R}^2\right)^{\frac{1}{2}}. \tag{7.2}$$

The TTC defines the time it would take until a collision occurred if two objects maintained their current velocities and direction of travel. In the present experiment, we decided to make the stimulus intensity correspond to the complement of the TTC for a temporal range between zero and nine seconds. Stimulus onset occurred whenever the TTC between the ego-vehicle and a surrounding object dropped below a threshold (θ) of nine seconds. This value was chosen as a compromise between the goal of maximizing the range of intensity coding and the need to keep stimuli in a range that can still be perceived by the participants as relevant. Stimulus intensity at onset was set to the smallest perceivable intensity identified by the experimenter, and increased linearly as the TTC dropped. If the TTC was zero (a collision), stimulus intensity reached its maximum, which was equal to the maximum intensity provided by tactile interface. Accordingly, close temporal proximities were signaled with more intense vibration and vice versa.

$$\text{Intensity} = max\left(\frac{\theta - TTC}{\theta}, 0\right). \tag{7.3}$$

The tactile interface can give exact signals about the location and temporal proximity of an approaching object as long as the vehicle has precise knowledge about the location and velocity of this object. We refer to this signal as the precise signal and use it as a baseline.

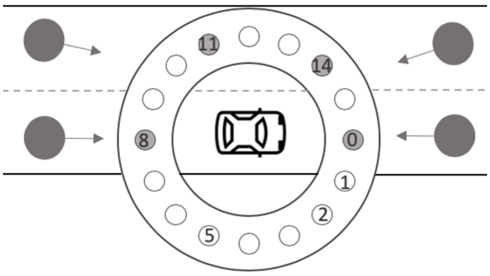


Figure 7.2: Schematic of the belt in an example situation where from every left and center lane direction an object (large gray dot) is approaching with a time-to-collision (TTC) value under nine seconds. Vibromotors no. 0, 14, 8 and 11 (small grey dots) would activate in this case. If the ego-vehicle drove on the left lane, the activations would occur at vibromotor 0, 2, 5 and 8. Note that the selected vibromotors on the rear were spaced two instead of one gap apart to account for differences in spatial discriminability between dorsal and ventral regions [339, 340].

7.3.3.1 Uncertainty Communication

In addition to the precise signal, a second signaling mode was realized to communicate the machine's uncertainty about an exact object direction to the user. We refer to this signal as the uncertainty communication. For the uncertainty communication, the encoding of temporal proximity was identical to the precise signal; only the location encoding was varied. The rationale behind the uncertainty communication was that, due to the environmental changes, the vehicle's sensory system may be unable to measure precise object locations (the exact lane), but could still signal the *presence* of an approaching object from either front or back, without specifying the ego- or a neighboring lane. In order to convey this information to the user, the direction of approach for a vehicle was no longer signaled by one unique stimulus location, but through a dynamic vibration pattern traveling over a specific range that represented the overlap between the two lanes on which a vehicle might appear. Upon stimulus onset, neighboring vibromotors were successively activated in the clock- or counter-clockwise direction, creating a tactile illusion of *apparent motion* [336]. The initial vibromotor position and direction was chosen randomly from the available vibromotors within the respective uncertainty range.
Figure 7.3A shows a schematic of the uncertainty signal. The stimulus development is illustrated by the pointer oscillating between the two borders with a constant frequency (1.0 Hz, from start-to-start point). The next vibromotor activated at the same instance that its predeces-

sor switched off (Figure 7.3B). The pointer continued to bounce between these borders until either one of two events occurred: (1) the TTC became greater than nine seconds, in which case the signal disappeared, or (2) a reliable estimate of the current lane of the approaching vehicle became available. In the latter case, the width of the range converged to zero, conveying the same unique direction as in the precise signal condition. We also experimented with other representations of uncertainty, such as synchronously activating multiple actuators in the uncertainty range. However, such variants, which employ co-activation of nearby actuators, can produce side effects like the funneling illusion [241] and a perceived stimulus intensity increase [341]. Because such effects would interfere with the encoding of information in stimulus direction and intensity, we favored the described method of sequential activation.

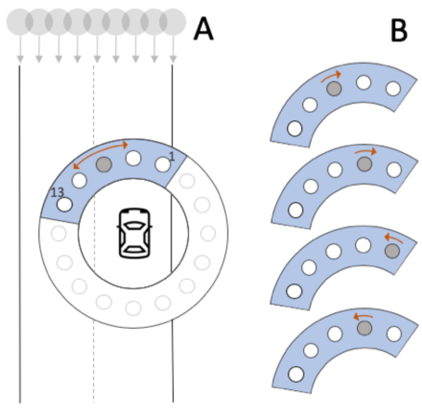


Figure 7.3: Uncertainty signal for an object approaching from the front on a two-lane road (**A**). Grey dots indicate possible locations of the approaching vehicle as signaled by the system. The stimulus *traveled* between the borders and bounced back in the other direction as it hit one of the borders (**B**). The width of the range was chosen to be between the vibromotors that were allocated for the static signal (Figure 7.2) plus one extra vibromotor on each side. Thus, in the example shown in this figure, the signal bounced between vibromotors 13 and 1.

7.3.4 Experimental Design

7.3.4.1 Independent Variables

Two factors were systematically varied in the experiment in order to evaluate the proposed uncertainty communication system. First, we varied the availability of uncertainty communication (on vs. off). Second, we varied the perceptual uncertainty in the different scenarios between human and machine (machine certain-human uncertain (MC-HU), machine uncertain-human certain (MU-HC), both uncertain (MU-HU)). The uncertainty manipulation was realized through contextual conditions in the driving scenarios that aimed at independently modulating the uncertainty of the vehicle's observations and the uncertainty of the human's observations. Machine uncertainty was introduced by means of driving through a) a foggy tunnel and b) rain. Both situations would decrease sensor reliability and increase machine uncertainty. Human uncertainty was provoked by driving through a) a foggy tunnel and b) a foggy road. The foggy tunnel thus served as the joint uncertainty condition, in which both the human and the machine suffered from limited sensory input. Since the goal of this study was to examine the effects of uncertainty communication in human-machine interaction, we decided to omit a condition in which both the human and the machine would be certain. In the foggy road scenario, the machine had an accurate estimate of the position of vehicles at any distance away from it, and it could always communicate the precise signal. Therefore, uncertainty communication (uc) was only available in the foggy tunnel and rain scenarios. Participants drove through these scenarios twice: once without (MU-HU, MU-HC) and once with the uncertainty communication functionality enabled (MU-HU-uc, MU-HC-uc). In case the uncertainty communication was disabled, the vibrotactile interface provided a precise signal only as soon as the approaching car entered a visible range (see Section 7.3.5 for details). In case the uncertainty communication was enabled, the vibrotactile interface communicated the uncertain signal whenever the defined threshold of a TTC lower than nine seconds to an approaching object was reached. This resulted in five experimental conditions in total. Their characteristics are summarized in Figure 7.4.

	Human Uncertain: **HU**			Human Certain: **HC**		
	Scene	Sensor Range	Human Vision	*Scene*	Sensor Range	Human Vision
Machine Certain: **MC**	*foggy road*	inf.	33m			
Machine Uncertain + Unc. Comm.: **MU-uc**	*foggy tunnel*	Unc. > 33 m	33m	*rainy road*	Unc. > 33 m	inf.
Machine Uncertain: **MU**	*foggy tunnel*	33m	33m	*rainy road*	33 m	inf.

Figure 7.4: Overview of five experimental conditions with corresponding ranges for human vision and machine sensors. Colors are assigned to individual conditions to facilitate condition mapping of the results. For machine uncertain conditions (blue and green), the light colors mark conditions without uncertainty communication while their dark counterparts indicate uncertainty communication.

7.3.5 Procedure

The study was structured into five experimental and two familiarization blocks. The two familiarization blocks had the purpose of introducing the participants to the driving simulator and the tactile interface. The first familiarization procedure was carried out according to guidelines specified by Hoffmann and Buld [342]. This procedure is aimed at reducing the probability of causing simulator sickness by gradually increasing exposure to virtual accelerations. The second familiarization scenario allowed the driver to explore the direction and temporal proximity encoding provided by the tactile interface in a scenario where the machine was certain (precise signal). In the five experimental blocks the participant's task was to maintain a speed of 120 km/h when possible and avoid collisions with other vehicles. All scenarios consisted of a straight two-lane highway. To rule out potential learning effects, the order in which experimental conditions were conducted varied between participants. Half of the participants started with the two uncertainty communication conditions and half without it. Foggy scenarios and rain scenarios were alternated. Before the uncertainty communication conditions, participants were verbally instructed by the experimenter about the machine limitations as follows: “In this section, you will drive through rain/a tunnel. Therefore, the vehicle is less certain about the locations of vehicles that are farther away”. The following sections further detail the design of the scenarios. Conceptually each scenario followed the same structure: To maintain an objective speed of 120 km/h the driver had to detect and overtake slower cars on the left or right lane from the front, and avoid faster cars that approached at 160 km/h from the rear and which might potentially change lanes for overtaking.

7.3.5.1 Familiarization - System Exploration Scenario

The scenario consisted of a two-lane highway on a sunny day. Participants were not informed about the functionality of the tactile interface and were asked to maintain a speed of 120 km/h where possible. Since vehicles on the passing lane were designed to drive faster than the target speed, the task was most easily fulfilled by driving on the rightmost lane. However, vehicles on the right lane that were trailed by the ego-vehicle would occasionally slow down, forcing the participant to either overtake via the left lane or brake to avoid a collision. These instances ensured that the time-to-collision between the ego-vehicle and its surrounding vehicles dropped below the threshold value of nine seconds, causing exposure to the tactile stimuli (the precise signal). After five minutes of driving, participants were asked to park their car on the emergency lane, and the system exploration scenario was stopped. Participants were then asked what they thought the tactile stimuli communicated, and they were informed about the true nature of the assistance function. This scenario was similar to the experimental scenario by Krüger et al. [2, 3], who found that participants were able to develop an intuitive understanding of the stimuli within four minutes of system exposure. Similarly rapid user understanding times for directional tactile displays were described by Cassinelli et al. [232] and Hogema et al. [343].

7.3.5.2 Experimental Block - Foggy Road: Machine Certain, Human Uncertain (MC-HU)

The foggy road scenario was simulated as a night-time scenario, designed to make the human uncertain by inserting a dense fog field and disabled lights of surrounding traffic. The fog was parameterized to limit the look-ahead distance to about 33 m (Figure 7.5), corresponding to a look-ahead time of about one second assuming the driver drove at the target speed. A temporal distance of one second has been suggested as the threshold below which a driving situation can be considered critical [86, 278]. We assumed that this look-ahead distance would induce uncertainty in drivers, as they would need to be continuously prepared for the occurrence of a critical situation.

Figure 7.5: Visibility in the foggy scenarios. Vehicles disappear at a distance of approximately 33 m.

Machine observations were not affected by the mist or darkness, so a precise signal was communicated for vehicles driving at any distance away from the ego-vehicle. The experimenter triggered the onset of a target vehicle approaching the ego-vehicle according to a fixed script. This approach allowed for an easy verification that participants were driving at the approximate target speed, which was a prerequisite for the correct situation development. When a command was given, the target vehicle started approaching behind the fog barrier from one of the four possible lane directions (front, front-left, rear, rear-left). Vehicles coming from the rear were driving at a speed of 160 km/h. Vehicles in the front were driving at 80 km/h. As a consequence, the target vehicle would overtake (or be overtaken by) the ego-vehicle, assuming that the participant kept driving around the target speed of 120 km/h. Vehicles that approached from the rear on the right lane were programmed to change lanes and overtake the ego-vehicle at a distance of 30 m. After the target vehicle had passed and disappeared into the fog again, and the experimenter confirmed that the participant was driving at the target speed, the next target vehicle was launched. This procedure was carried out 14 times. Directions from which cars approached were pseudo-randomized.

7.3.5.3 Experimental Block - Foggy Tunnel: Machine and Human Uncertain (MU-HU)

The foggy tunnel scenario was identical to the foggy road (MC-HU) scenario, except for the addition of a tunnel that ran for the entire course and a change in *sensor reliability* such that vehicles outside a 33 m radius from the ego-vehicle could at most be signaled via uncertainty communication as described in Section 7.3.3.1. Limitations of the look-ahead distance were the same as in the foggy road condition (33 m, 1 s) for the human. For comparability reasons, traffic definitions were identical to the foggy road scenario (MC-HU).

7.3.5.4 Experimental Block - Rain: Machine Uncertain, Human Certain (MU-HC)

The rain scenario consisted of a straight road on a rainy day. The rain was visually present, though at an intensity at which it did not have much influence on the driver's visual perception. The reliability of the machine was said to be negatively affected by the rain, in the same manner as it was in the foggy tunnel scenario. That is, the look-ahead distance of the machine for precise direction identification and signaling was limited to 33 m. Because the driver's field of view was not obstructed, the traffic setup had to be organized in a different way compared to the fog conditions. The altered traffic profile for the rain scenario is explained in Figure 7.6.

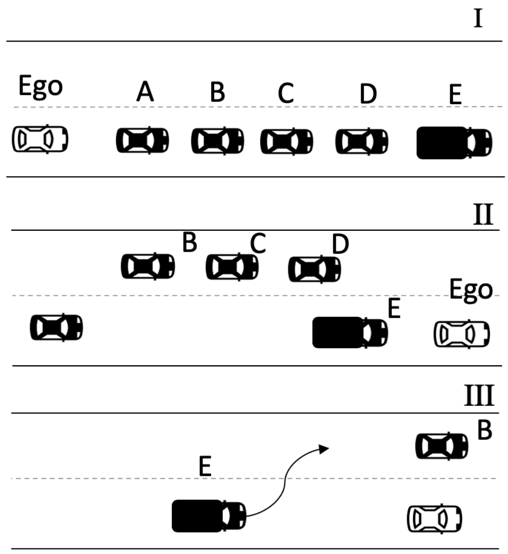


Figure 7.6: Traffic definition in the rain (machine uncertain-human certain condition (MU-HC)) scenarios. Five vehicles were driving on the right lane at 80 km/h, spaced 250 m apart (I). The ego-vehicle could maintain the target speed (120 km/h) by overtaking the vehicles. When the front truck (E) was overtaken, a trigger point was activated that made the trailing cars B, C, and D switch to the left lane, and adjust their speed to 160 km/h (II). This resulted in B, C and D eventually overtaking the ego-vehicle from the rear. When D passed the ego-vehicle (III), the leading vehicle (A) accelerated to 160 km/h, and it changed to the left lane if it came within a distance of 30 m of the ego-vehicle.

7.3.5.5 Dependent Measures

As dependent variables, we recorded subjective measures concerning the usefulness, satisfaction and perceived workload in the different experimental conditions, as well as the overall understanding and experience. In addition, we were interested in objective measures that express effects on peoples' gazing behavior and their performance in a driving task.
We used three questionnaires for the subjective evaluation. These were used to gain insights into the subjective experiences, which the different experimental conditions induced and see whether the conditions were correctly perceived and understood.

7.3.5.5.1 Task Load, Usefulness, Satisfaction

After each experimental condition, the NASA Task Load Index (NASA-TLX, [344]) assessment was conducted. Usefulness and satisfaction ratings were obtained using the Van der Laan acceptance scale [345].

7.3.5.5.2 Understanding and Experience

Furthermore, after every experimental block, participants were asked to rate a number of statements on a 5-point Likert scale (strongly disagree to strongly agree). These statements were included to check if a) the modulation of human perceptual confidence through environmental factors was successful, b) the participants had understood the machine's level of uncertainty, and c) participants experienced that the machine expressed its level of uncertainty.

7.3.5.5.3 Gaze Distributions

The front gaze ratio was computed as the ratio of the number of gaze points in the front window versus the total amount of gaze points in the mirrors and windshield (Equation (7.4)). A higher front gaze ratio indicates that the driver allocated more attention towards the front; a lower front gaze ratio indicates that the user allocated more attention towards the rear. By means of this measure, we aimed at evaluating whether the uncertainty communication caused shifts in visual attention towards the direction of the presented signal.

$$\text{front gaze ratio} = \frac{\text{gaze count on windshield}}{\text{gaze count on windshield} + \text{mirrors}}. \tag{7.4}$$

7.3.5.5.4 Trial Safety

Trial safety was operationalized as the minimum time-to-contact (mTTC) recorded in each trial in any direction. The mTTC can be understood as a conservative measure of safety that only takes the smallest recorded TTC into account and thus indicates how dangerous a trial became at the most (see e.g., [2, 332]).

7.3.5.5.5 Trial Definition

We restricted the analysis of gaze distributions and safety to specific periods of interest, which we refer to as trials. A trial occurred for every vehicle that overtook or was overtaken by the ego vehicle. The starting point of a trial was set to the moment where time-to-passing (TTP) of a surrounding vehicle dropped below nine seconds. Here, we defined the TTP as the time it would take until two vehicles would pass each other if they would maintain their current velocities. The TTP can be understood as a TTC (see Equation (7.1)) without the requirement for being on a collision trajectory. We set the end point of a trial to the moment at which the ego-vehicle and the other vehicle passed each other.

7.3.6 Analysis

We split the analysis of the data into three parts – (1) custom questionnaire data, (2) subjective data on perceived workload as well as on perceived system acceptance in terms of usefulness and satisfaction, and (3) objective behavioral and performance data, including gaze distribution results and measures of trial safety. To rule out potential confounds, we only ran statistical tests between experimental conditions that shared the same traffic profiles. While the differences in traffic profiles prevented comparisons between fog and rain conditions, this design choice did not impair the investigation of our research hypotheses. It allowed us to prioritize internal validity through the implementation of scenarios that contained credible sources of uncertainty for each environmental condition.

Statistical analysis was carried out using the *scipy* python library. Plots were generated using the python packages *matplotlib* and *seaborn*.

7.3.6.1 Custom Questionnaire Data - H1 (Understanding)

Custom questionnaire data for all conditions were analyzed descriptively based on median responses and interquartile ranges. According to H1, we expected participants to indicate understanding of the uncertainty encoding stimuli.

7.3.6.2 Acceptance and Workload - H2 (Subjective Benefit) and H3 (Disturbance)

Usefulness and satisfaction scores were obtained by mapping subsets of Van der Laan Questionnaire responses to two respective scales in the $[-2, 2]$ range [see 345]. Figure 7.7 illustrates the outcome that we would expect for usefulness, satisfaction, and workload under our research hypotheses H2 and H3. We expected usefulness and satisfaction to be higher in human uncertain (HU) conditions with uncertainty communication than when omitting the information. We further assumed that an advantage of the machine certain (MC; red) over the uncertainty communication (dark blue) condition should exist due to the higher information gain achievable by precise signals. On the other hand, for cases with higher human certainty (HC; green) we would expect information from an uncertainty communication to be redundant and therefore to cause no advantage over an omission of signals in the uncertainty range. However, under H3 also no disadvantage from redundant uncertainty communication was assumed.
For workload, measured as the NASA Task Load Index (NASA-TLX [344]), the expected relationship would be reversed because we define the relationship between workload and benefit as inverse, that is, a high workload reflects low benefit whereas a low workload can indicate higher benefit.
We compared scores of human uncertain conditions (MC-HU, MU-HU-uc, MU-HU; red, blue) using Friedmann tests and post-hoc one-sided Wilcoxon signed rank tests with Bonferroni adjusted alpha levels for repeated testing. As there were only two human certain conditions (MU-HC-uc, MU-HC; green), we directly compared scores for these conditions using Wilcoxon signed rank tests with Bonferroni adjusted alpha levels.

	Human Uncertain: **HU**				Human Certain: **HC**			
	Scene	Usefulness	Satisfaction	Workload	*Scene*	Usefulness	Satisfaction	Workload
Machine Certain: **MC**	*foggy road*	++	++	lowest				
Machine Uncertain + Unc. Comm.: **MU-uc**	*foggy tunnel*	+	+	low	*rainy road*	0	0	low
Machine Uncertain: **MU**	*foggy tunnel*	0	0	highest	*rainy road*	0	0	low

Figure 7.7: Predicted outcome of subjective evaluations according to our research hypotheses when assuming successful experimental manipulations. Usefulness and satisfaction: Symbols +, 0, - are used to illustrate the predicted valuation. Relative workload predictions are shown as words. For machine uncertain conditions (blue and green), the light colors mark conditions without uncertainty communication. Their dark counterparts indicate uncertainty communication.

7.3.6.3 Gaze Distribution and Safety - H4 (Safety)

Figure 7.8 illustrates the outcome that we would expect for safety and gaze guidance under H4. While gaze guidance is not directly subsumed in the *benefit* term, here we understand it as a behavioral indicator for an influence on peoples' information sampling, which relates to our second and fourth hypotheses. The assistance system primes relevant regions of interest through tactile stimuli, which may prompt users to shift their gaze accordingly in order to acquire additional information or visual confirmation. Under H2 and H4 we would therefore expect gaze guidance to be observable for conditions in which the system can provide novel information, that is, machine certain (MC; red) and human uncertain with uncertainty communication (MU-HU-uc; dark blue) conditions. In contrast, according to H3 this should not be the case for cases in which human uncertainty is equal or lower than machine uncertainty (light blue and green).
Prior to gaze distribution analysis, we filtered the data to only include trials in which vehicles approached from behind. As driving requires frontal visual attention at most times, especially with low visibility conditions, a comparison of front gaze ratios is more meaningful for situations in which safety-relevant events take place behind the ego vehicle. Due to the presence of outliers and a violation of the normality assumption, we compared front gaze ratios of human uncertain conditions (MC-HU, MU-HU-uc, MU-HU; red, blue) using Friedmann tests and post-hoc one-sided Wilcoxon signed rank tests with Bonferroni adjusted alpha levels for repeated testing. As there were only two human certain conditions (MU-HC-uc, MU-HC; green), we directly compared front gaze ratios for these conditions using one-sided Wilcoxon signed rank tests with Bonferroni adjusted alpha levels.
For the analysis of safety we focused on human uncertain conditions and trials in which vehicles approached from the front right lane because these trials required corrective actions by the driver to ensure safety. In line with H4 we expected safety to be highest in the machine certain (MC; red) condition, lowest in the absence of >33 m signaling (MU-HU; light blue), and intermediate with uncertainty communication enabled (MU-HU-uc; dark blue). MTTC scores (see Section 7.3.5.5.4) were calculated for each trial and mean mTTC scores per participant and condition were compared using a Friedmann test and post-hoc one-sided Wilcoxon signed rank tests with

Bonferroni adjusted alpha levels for repeated testing.

	Human Uncertain: **HU**			Human Certain: **HC**		
	Scene	Gaze Guidance	Safety	*Scene*	Gaze Guidance	Safety
Machine Certain: **MC**	*foggy road*	High	Highest			
Machine Uncertain + Unc. Comm.: **MU-uc**	*foggy tunnel*	High	Medium	*rainy road*	Low	
Machine Uncertain: **MU**	*foggy tunnel*	Low	Lowest	*rainy road*	Lowest	

Figure 7.8: Predicted outcome of behavioral measures according to our research hypotheses when assuming successful experimental manipulations through the introduced conditions. For machine uncertain conditions (blue and green), the light colors mark conditions without uncertainty communication. Their dark counterparts indicate uncertainty communication.

7.4 Results

7.4.1 Subjective Reports

7.4.1.1 Custom Questionnaire - H1 (Understanding)

Response distributions to the eight Likert items that were used in our customized questionnaire are shown in Figure 7.9 for each experimental condition. For human uncertain conditions, participants strongly indicated weather conditions as a cause for feeling unconfident whereas other road users had a smaller influence and belt signals were not negatively affecting confidence. For human certain conditions, none of these three factors reduced confidence. These ratings suggest that our experimental manipulation of human uncertainty through different weather conditions was successful. Statements 4 and 5 targeted the understanding of the tactile stimuli and the machine uncertainty state. In support of H1, participants generally identified system uncertainty when present (MU), especially with uncertainty communication (uc) and correctly indicated its absence (MC). This suggests that the state transparency achieved by the uncertainty communication supported system state understanding. The last three statements were included for an estimate about which modalities the participants relied on during the different conditions. Reliance on own capabilities and visual sensing was highest in the human certain conditions (HC). For human uncertain conditions (HU), reliance on the tactile stimuli was high, especially for the machine certain (MC) and machine uncertain + communication (MU-HU-uc) conditions. This was no longer the case when uncertainty communication was disabled (MU-HU). In support of the hypotheses H2 and H3, this suggests that participants utilized tactile stimuli depending on system reliability and their own confidence state. In summary, participant responses suggest that the experimental manipulations worked as intended and induced different levels of congruency between human and machine perceptual uncertainty.

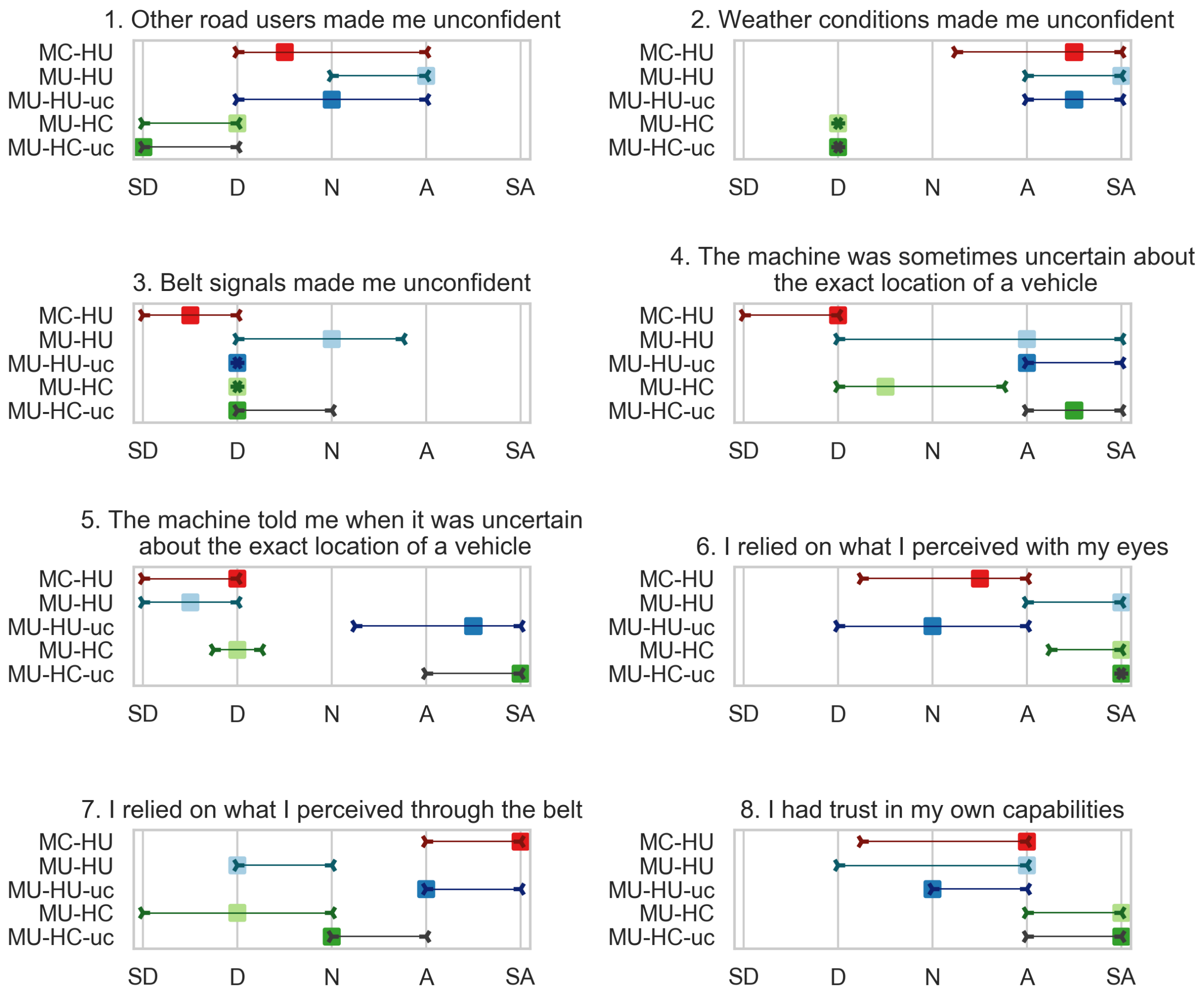


Figure 7.9: Median agreement ratings (square) and 25th and 75th percentiles on a custom 5-point Likert scale questionnaire. SD = Strongly Disagree, D = Disagree, N = Neutral, A = Agree, SA = Strongly Agree.

7.4.1.2 Usefulness and Satisfaction - H2 (Subjective Benefit) and H3 (Disturbance)

An overview of the usefulness and satisfaction scores that were obtained in each experimental condition can be found in Figure 7.10b. As expected, the overall highest score was found for the machine certain and human uncertain condition (MC-HU). The overall lowest score was obtained for the machine uncertain-human certain condition (MU-HC). We were interested in comparing conditions within a given level of human certainty, that is, a comparison between the three human uncertain conditions (HU; red and blue) and between the two human certain conditions (HC; green). The human uncertain conditions (MC-HU, MU-HU-uc, MU-HU) differed significantly for usefulness, $\chi^2(2) = 20.87$, $p < 0.001$ ($<\alpha = 0.025$), as well as for the satisfaction scores, $\chi^2(2) = 16.62$, $p < 0.001$ ($<\alpha = 0.025$). Post-hoc comparisons revealed that usefulness was rated significantly higher with uncertainty communication enabled (MU-HU-uc; dark blue) than disabled (MU-HU; light blue), MU-HU-uc vs. MU-HU: $w = 0.0$,

$p < 0.001$ ($<\alpha = 0.008$) where w denotes the sum of the ranks of the differences above zero[1]. Similarly, usefulness in the machine certain condition (MC; red) was rated significantly higher than in the machine uncertain condition without uncertainty communication (MU-HU), MC-HU vs. MU-HU: $w = 0.0$, $p < 0.001$ ($<\alpha = 0.008$). However, there was no significant difference in usefulness ratings between the machine certain (MC-HU) and the uncertainty communication condition (MU-HU-uc), MC-HU vs. MU-HU-uc: $w = 32.0$, $p = 0.289$ ($>\alpha = 0.008$). The same pattern of results was observed for the satisfaction ratings, MU-HU-uc vs. MU-HU: $w = 10.5$, $p = 0.004$ ($<\alpha = 0.008$), MC-HU vs. MU-HU: $w = 0.0$, $p < 0.001$ ($<\alpha = 0.008$), MC-HU vs. MU-HU-uc: $w = 34.5$, $p = 0.219$ ($>\alpha = 0.008$).
These results support the prediction driven by H2 that usefulness and satisfaction ratings should be higher with enabled than disabled uncertainty communication. However, contrary to our assumption, no advantage of the machine certain (MC-HU) over the uncertainty communication (MU-HU-uc) condition, reflecting a difference in potential information gain, could be confirmed. Also for the human certain conditions (HC–green), we found that usefulness was rated as significantly higher with uncertainty communication enabled (MU-HC-uc) than disabled (MU-HC), MU-HC-uc vs. MU-HC: $w = 16.5$, $p = 0.012$ ($<\alpha = 0.05$). For satisfaction ratings, the differences between human certain conditions were not significant, MU-HC-uc vs. MU-HC: $w = 21.0$, $p = 0.429$ ($>\alpha = 0.05$). While average satisfaction ratings were somewhat neutral for both conditions, the usefulness of a late-supporting system was negatively judged. Average neutral usefulness ratings for the uncertainty communication condition support our predictions made under H3, presumably because it was neither needed nor disturbing.

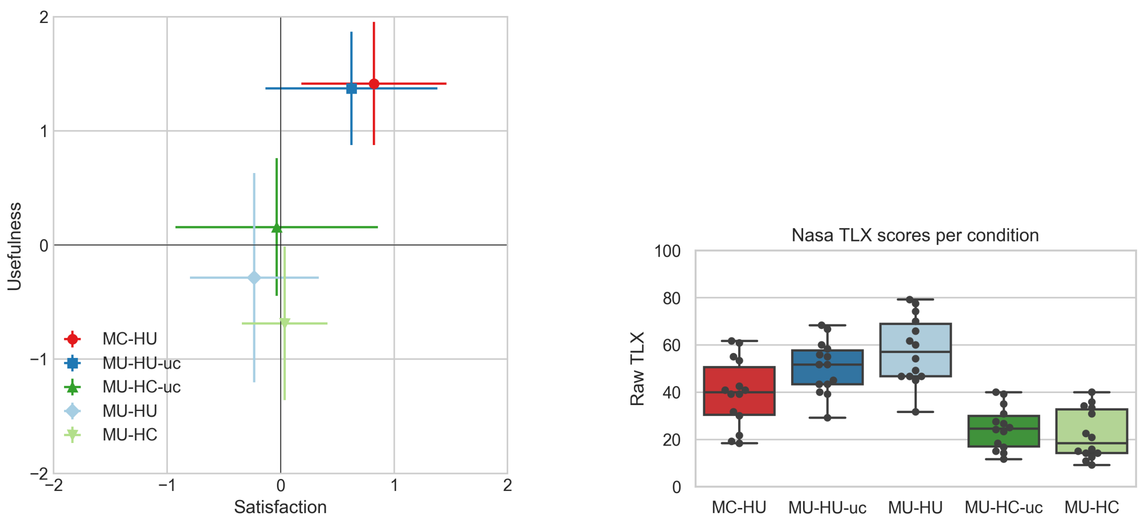
7.4.1.3 Workload - H2 (Subjective Benefit) and H3 (Disturbance)

NASA TLX workload ratings (Figure 7.10c) differed significantly between human uncertain conditions (MC-HU, MU-HU-uc, MU-HU), $\chi^2(2) = 11.66$, $p = 0.003$ ($<\alpha = 0.05$). Post-hoc comparisons revealed that workload was rated significantly lower with uncertainty communication enabled (MU-HU-uc; dark blue) than disabled (MU-HU; light blue), MU-HU-uc vs. MU-HU: $w = 14.0$, $p = 0.008$ ($<\alpha = 0.016$). Also in the machine certain condition (MC; red), workload was rated significantly lower than in the machine uncertain condition without uncertainty communication (MU-HU), MC-HU vs. MU-HU: $w = 1.0$, $p = 0.001$ ($<\alpha = 0.016$). These results confirm the prediction that workload should be reduced when enabling uncertainty communication and thus support H2. However, differences in subjective workload between the machine certain (MC-HU) and the uncertainty communication condition (MU-HU-uc) were not significant, MC-HU vs. MU-HU-uc: $w = 19.0$, $p = 0.032$ ($>\alpha = 0.016$). In contrast to H2, an assumed advantage of the machine certain (MC-HU) over the uncertainty communication (MU-HU-uc) could therefore not be confirmed.
For the human certain conditions (HC; green), workload ratings were comparably low and did not differ significantly between conditions with uncertainty communication enabled (MU-HC-uc; dark green) and disabled (MU-HC; light green), MU-HC-uc vs. MU-HC: $w = 31.0$, $p = 0.310$ ($>\alpha = 0.05$). When contrasted with results from the human uncertain (HU) conditions, the low averages and the lack of difference in satisfaction and workload between the two

[1]In contrast to test statistics of many parametric tests, a small value for w is therefore a strong indicator for consistent and significant differences.

	Human Uncertain: HU				Human Certain: HC			
	Scene	Usefulness	Satisfaction	Workload	*Scene*	Usefulness	Satisfaction	Workload
Machine Certain: **MC**	*foggy road*	1.41 (0.54)	0.82 (0.64)	39.6 (14.5)				
Machine Uncertain + Unc. Comm.: **MU-uc**	*foggy tunnel*	1.37 (0.50) *	0.62 (0.76) *	50.5 (11.1) *	*rainy road*	0.16 (0.50) *	-0.04 (0.76)	24.8 (9.1)
Machine Uncertain: **MU**	*foggy tunnel*	-0.28 (0.92)	-0.23 (0.56)	57.7 (14.3)	*rainy road*	-0.68 (0.67)	0.03 (0.38)	22.1 (10.6)

(a)



(b) (c)

Figure 7.10: Results of subjective measures for different conditions. Conditions are visually represented by distinct colors. For machine uncertain conditions (blue and green) the light colors mark conditions without uncertainty communication. Their dark counterparts indicate uncertainty communication. (**a**) Mean usefulness, satisfaction, and NASA-TLX scores for each condition. Standard deviations are shown in brackets. Asterisks indicate statistically significant differences between conditions linked by brackets; (**b**) Mean usefulness and satisfaction scores of the assistance functionality in MC-HU (Foggy Road), MU-HU-uc (Foggy Tunnel), MU-HC-uc (Rain), MU-HU (Foggy Tunnel, no UC), MU-HC (Rain, no UC). Error bars display the standard deviation; (**c**) NASA-TLX scores per condition. Scores of individual questions were averaged to obtain the overall TLX score in the range [0,100].

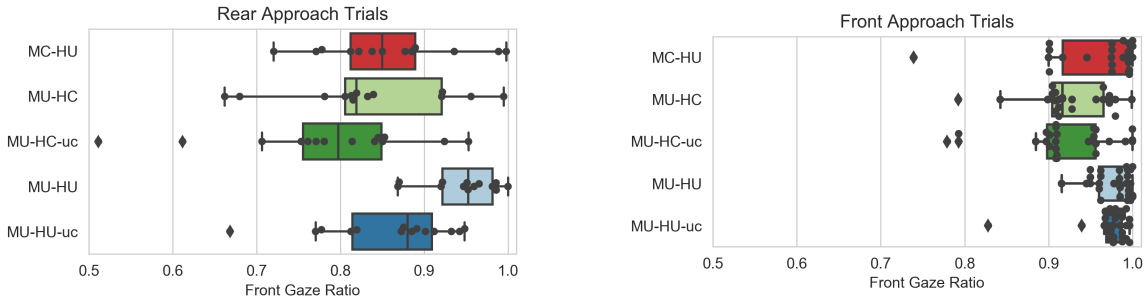
human certain (HC) conditions may be seen as support for H3. However, due to the use of different driving profiles, a formal comparison of differences would not be valid.

7.4.2 Gaze Distribution - H2 (Subjective Benefit) and H4 (Safety)

Figure 7.11b shows the ratio of gaze points on the front (front window) divided by front+back (front window + mirrors). Front gaze ratios differed significantly between human uncertain conditions (MC-HU, MU-HU-uc, MU-HU) for trials in which vehicles approached from the back, $\chi^2(2) = 16.0$, $p < 0.001$ ($< \alpha = 0.05$). Post-hoc comparisons revealed that the front gaze ratios were significantly lower with uncertainty communication enabled (MU-HU-uc; dark blue) than disabled (MU-HU; light blue), MU-HU-uc vs. MU-HU: $w = 0.0$, $p < 0.001$ ($< \alpha = 0.016$). Also in the machine certain condition (HC; red), front gaze ratios were significantly lower than in the machine uncertain condition without uncertainty communication (MU-HU), MC-HU vs. MU-HU: $w = 2.0$, $p < 0.001$ ($< \alpha = 0.016$). Differences in front gaze ratios between the machine certain (MC-HU) and the uncertainty communication condition (MU-HU-uc) were not significant, MC-HU vs. MU-HU-uc: $w = 14.0$, $p = 0.007$ ($< \alpha = 0.016$ but $w > w_{critical} = 12$).
Between human certain conditions (MU-HC, MU-HC-uc; green), differences in front gaze ratios could not be regarded as significant for trials in which vehicles approached from the back, MU-HC vs. MU-HC-uc: $w = 24.0$, $p = 0.037$ ($> \alpha = 0.016$ and $w > w_{critical} = 12$). These findings indicate an increased overt attention guidance for conditions in which the assistance can provide novel relevant information. They are therefore in line with our predictions (see Table 7.8) made under H2 and H4.
For comparison, for situations in which vehicles approached from the front (Figure 7.11c), the gaze distributions substantially shifted to the front (MU-HC: $M = 0.92$, $SD = 0.05$; MU-HC-uc: $M = 0.91$, $SD = 0.06$; MU-HU: $M = 0.97$, $SD = 0.02$; MU-HU-uc: $M = 0.96$, $SD = 0.04$; MC-HU: $M = 0.94$, $SD = 0.07$) across all conditions. Differences between uncertainty communication and no uncertainty communication diminished as stimuli with uncertain direction encoding only drew attention to front regions.

	Human Uncertain: **HU**			Human Certain: **HC**		
	Scene	Front Gaze Ratio	MTTC	*Scene*	Front Gaze Ratio	MTTC
Machine Certain: **MC**	*foggy road*	0.86 (0.08)	3.92s (1.11)			
Machine Uncertain + Unc. Comm.: **MU-uc**	*foggy tunnel*	0.85 (0.08)	2.59s (0.88)	*rainy road*	0.78 (0.11)	
Machine Uncertain: **MU**	*foggy tunnel*	0.94 (0.04)	1.42s (0.46)	*rainy road*	0.83 (0.09)	

(a)



(b) (c)

Figure 7.11: Front gaze ratios for different conditions. Conditions are visually represented by distinct colors. For machine uncertain conditions (blue and green), the light colors mark conditions without uncertainty communication. Their dark counterparts indicate uncertainty communication. (**a**) Mean front gaze ratios and mTTC scores for each applicable condition. Standard deviations are shown in brackets. Asterisks indicate statistically significant differences between conditions linked by brackets; (**b**) Gaze ratio for conditions in which the machine was uncertain and for trials in which vehicles were approaching from the rear. Lower values indicate more gazing towards the mirrors. Due to failed eye-tracking recordings, $n = 13$ (instead of 14) for all conditions; (**c**) Gaze ratio for conditions in which the machine was uncertain and for trials in which vehicles were approaching from the front.

7.4.3 Trial Safety - H4 (Safety)

Figure 7.12 displays the mTTC scores for human uncertain conditions. We only considered the data of the human uncertain (HU; blue and red) conditions for statistical tests. MTTCs differed significantly between human uncertain conditions (MC-HU, MU-HU-uc, MU-HU), $\chi^2(2) = 24.14$, $p < 0.001$ ($< \alpha = 0.05$). We found that the mTTCs were significantly higher for the MU-HU-uc condition ($M = 2.59$ s, $SD = 0.88$) than for the MU-HU condition ($M = 1.24$ s, $SD = 0.46$); $w = 4.0$, $p = 0.001$ ($< \alpha = 0.016$). Furthermore, driving safety in terms of mTTC was also significantly higher in the MC-HU condition ($M = 3.92$ s, $SD = 1.11$) than in the MU-HU-uc condition, $w = 7.0$, $p = 0.002$ ($< \alpha = 0.016$) and the MU-HU condition, $w = 0.0$, $p < 0.001$ ($< \alpha = 0.016$). In poor visibility conditions (MU), imprecise tactile direction signaling (MU-HU-uc) appears superior to a variant only capable of signaling specific, reliable observations within a substantially constrained spatial range (MU-HU). In accordance with H4, participants thus seem to have taken advantage of the information available in the tactile stimuli to adjust their driving behavior for achieving higher safety.

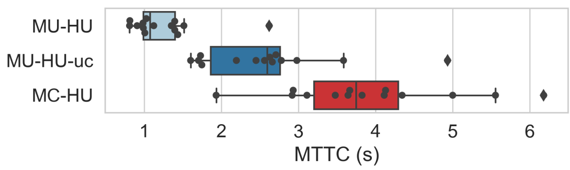


Figure 7.12: Minimum Time-to-Contact (mTTC) scores for human-uncertain conditions (n = 14).

7.5 Discussion

In the present driving simulator study, we investigated the effects of a novel approach to encode spatial uncertainty in the stimuli of a vibrotactile assistance system. We aimed at evaluating the influence of the uncertainty communication on subjective measures that are indicative of perceived usefulness, satisfaction, and workload as well as on behavioral measures, that is, driving safety and gaze allocation. We assumed that any effect of the uncertainty communication would be influenced by the relation of spatial uncertainty in human perception and the assistance system. Therefore, we experimentally varied the driving scenarios to simulate machine uncertainty (tunnel + fog, rain) and to induce human uncertainty (fog, tunnel + fog). We found that our suggested uncertainty communication mode was understood by participants and had significant effects on both subjective and objective behavioral measures. Thereby, the utility of the system seemed to depend on the driver's perceptual confidence state. In our experiment, the uncertainty communication was regarded as beneficial and had a measurable influence on driver behavior in cases where the human driver was uncertain as well.

7.5.1 Signal Understanding and Experiment Validation

A prerequisite to this study was that our environmental scenario manipulations had the effect that we intended. Data from our custom questionnaire indicate that this was indeed the case. Participants reported that they felt uncertain due to the weather conditions and agreed that they relied more on the belt signal than on their own perception in the human uncertain conditions. Furthermore, participants experienced higher workload in the human uncertain conditions compared to the human certain conditions.

Besides, we were interested in the participants' subjective agreement on understanding the manipulation of machine uncertainty and the respective uncertainty communication signal. This was important to further validate our experimental procedure and the design of our uncertainty signal. Participants indicated that they had understood when the machine was uncertain and that they understood the meaning of the signal. Interestingly, they seemed to have noticed the machine uncertainty more strongly in the conditions in which the uncertainty communication was enabled, which suggests that this feature helped to make the machine state more

transparent. Taken together, in support of hypothesis H1 (Understanding), these results indicate that our experimental manipulations were valid and that participants seemed to have an appropriate understanding of the uncertainty communication.
An important difference between earlier studies that have demonstrated successful communication of uncertainty (e.g., References [326, 329, 335]) and the work presented here, is that we relied on an *implicit* representation of uncertainty in the tactile modality: The uncertainty component was encoded within the spatiotemporal signaling functionality of our vibrotactile interface. Instead of explicitly stating that “I am uncertain”, the machine agent implicitly communicates uncertainty by being less specific in its display of the location of objects. We argue that the distinction between *implicit* and *explicit* uncertainty communication may be useful for the future design of reliability displays. Implicit uncertainty communication is characterized by an increase in ambiguity or vagueness, or a decrease in specificity of presented information. One example of implicit uncertainty communication that we encountered in the literature is by Finger and Bisantz [327], who added distortions to an image to make it increasingly difficult to specify the underlying image.

7.5.2 Uncertainty Signaling in Human Uncertain Conditions

In terms of behavioral adaptations and user acceptance, we found substantial differences in the results between the human certain and the human uncertain conditions. In particular, in case of both human and system uncertainty, uncertainty communication was perceived as significantly more useful and satisfying compared to the no uncertainty communication conditions. Uncertainty communication also yielded significantly lower workload, increased driving safety and more strongly guided gaze behavior, indicating that more attention was allocated towards the direction of the uncertainty signal. These results support hypotheses H2 (Subjective Benefit) and H4 (Safety) by showing that the vibrotactile uncertainty communication had beneficial effects on driving comfort and safety.
In the human uncertain conditions, the uncertainty communication signal was not perceived as significantly different from the precise signal in terms of perceived usefulness and satisfaction, as well as in perceived workload. This is somewhat surprising as one might think that participants would naturally value the accessibility of the full information that is provided by the precise signal more than the more ambiguous uncertainty information signal. Overall, this outcome indicates that making the vehicle’s perceptual state transparent is appreciated by participants. Our results suggest that users are still satisfied with the directional cues and recognize the usefulness of the uncertainty signals, despite the lower quality in terms of information specificity. However, in case of driving safety, we observed a significant advantage of the precise signal over the uncertainty communication signal. That is, we observed the safest driving behavior in terms of mTTC scores in conditions where the machine’s sensory capabilities were unaffected by the environment.
We conclude that the precise signal was appropriately used by participants to acquire a more accurate understanding of the direction of surrounding objects. This finding is in line with the reports by Krüger et al. [2, 3], who found that participants rapidly gained an understanding of vibrotactile stimuli and presented safer driving behavior using the same vibrotactile assistance with a precise signal mode compared to driving without it.

7.5.3 Uncertainty Signaling in Human Certain Conditions

Analysis of the eye-tracking data revealed that visual attention distributions were affected significantly by the uncertainty signaling in scenarios in which human visibility was limited (human uncertain conditions), but not in the human certain conditions. Furthermore, usefulness and satisfaction ratings showed neutral ratings in the human certain conditions. In agreement with hypothesis H3 (Disturbance), this suggests that there is no direct disadvantage but also no benefit in sharing observations continuously when the human user is confident.
For successful human-machine cooperation [1, 321] or teaming, a human mental representation of system uncertainty may not be enough. When the machine also has a representation of human confidence in different environments, it allows the machine to decide under what conditions to provide support to the user. However, such a selective and presumably personalized communication could induce confusion when violating a user's assumptions on what the machine is communicating. In this example, it might not even be possible for a user to unambiguously distinguish between cases in which the machine is not providing stimuli because it has not detected a potential collision event and cases in which it has selectively disabled communication because it could confirm that the user has a sufficient scene understanding. Selectively deactivating systems that implicitly encode the absence of issues through an absence of stimuli could therefore be problematic but may be an important challenge to tackle in the design of future driving assistance systems.

7.5.4 Limitations

Despite the relatively small sample size, the results show clear statistical significance and accordingly provide support for the benefits of uncertainty communication. A limitation of the current study is that the sample (technically schooled, 13/14 male) was not balanced to be representative of a diverse population. Consequently, inferences are restricted to mostly male drivers younger than 42 years. It is well known that age is associated with sensory and cognitive decline [346]. However, prior work on sensory integration [203] and proximity alerting [347] suggests a positive relationship between age and multimodal facilitation effects such as reaction time shortening. Future work should investigate whether such a relationship also exists with our system. Another limitation comes from the restriction to highly challenging situations for cases with human uncertainty. An advantage of the fast succession of safety-critical situations is that it ensured exposure to the functionality of the device, which currently only provides stimuli when operating outside a safety margin. This means that in safe conditions the system does not produce any stimuli. The fact that the system proved its usefulness in challenging situations can be seen as a strength. However, we do not know if the observed effects would remain with less frequent system activation under more common traffic conditions. Future work could address this issue by implementing easier scenarios where a participant encounters fewer safety-critical events for an overall longer exposure time.

7.6 Chapter Summary

Opaque driver assistance systems that inform a driver about situation conditions can complicate driver inferences about the reliability of the underlying information. As a consequence, driver understanding of assistance capabilities may be misaligned, potentially resulting in misuse or disuse. To counter such effects, assistance could resort to only provide information under high confidence. But support is typically valued most when one's confidence about a situation is low, not when things are easy.

This chapter therefore investigated an alternative approach for handling uncertainty in driver assistance. For this purpose the previously introduced LLI prototype (see Chapter 5) was extended to encode uncertainty about hazard direction in tactile stimuli on top of encoding the temporal proximity. In a driving simulator study, participants were exposed to a selection of scenarios with different levels of machine and human uncertainty, depicted by characteristic environment and traffic conditions. Accordingly, assistance varied by being a) highly confident and available also for temporally distant hazards (machine certain), b) uncertain beyond close ranges but signaling distant hazards with added spatial uncertainty (machine uncertain + uncertainty communication), and c) uncertain and unavailable beyond close ranges (machine uncertain). Human driver uncertainty was effectively varied by simulated weather conditions that strongly affected visibility.

We were interested in whether drivers 1) could perceive and understand the tactile encoding of direction uncertainty, 2) would subjectively benefit from an uncertainty-signaling LLI, 3) would be disturbed by such a communication in cases of information redundancy, and 4) gain higher objective safety from using an uncertainty-signaling LLI. Subjective understanding and benefit were measured using Van der Laan acceptance ratings, NASA-TLX scores, and a custom questionnaire. The objective benefit was quantified by the minimum time-to-contact (mTTC) and the gaze distribution during safety-relevant events as a measure of attention guidance. Participants were able to easily perceive and understand the encoded direction uncertainty as well as the original spatiotemporal information from the LLI. They were not disturbed by this signaling in cases of information redundancy and purposefully utilized it to achieve higher safety levels when needed. Naturally, the impact of uncertain stimuli on driving safety depended on the participants' own level of uncertainty modulated by environment conditions. Although uncertain signals are inherently less informative than precise signals across the same temporal distance range, participants rated the uncertain signals as equally useful and satisfying.

These findings illustrate the value of making the confidence of machine inferences transparent to users and suggest that the tactile sense can provide a suitable interface for conveying such information intuitively without interfering with concurrent visual processing. The operating range of driver assistance systems that employ tactile stimuli may hence be meaningfully expanded by conveying spatial uncertainty.

Part III

Beyond Driver Awareness Augmentation

8

Cooperative Driver Support

"No man is an Iland,
intire of itselfe;
Every man is a peece of the Continent,
a part of the maine;"

John Donne, [348]

The main part of this dissertation related to an approach for driver assistance through augmentation (Section 3.4), which was motivated by existing challenges in mobility and inspired by a potential applicability of theories and findings about human sensorimotor processes (Section 4.5). One reason for pursuing an augmentation-guided approach was its implied promise of circumventing issues of substitutive technology, especially those that relate to being *out-of-the-loop* due to disengagement from the substituted task, its requirements, and its dependents. Cooperation, a third approach to human-machine interaction (HMI), which also relies on user engagement, at least for a subset of a task, can be another strategy for driver assistance that may counteract downsides of substitution (Section 3.3). However, interaction with a cooperative system also entails added requirements for both user and machine to be capable of monitoring and interfering with or adapting to one another for the purpose of achieving a common goal (Section 3.3.3).

This chapter revisits the principle of cooperation. Guided by a need for transparency about mental states and the challenge to effectively handle traffic complexity, it references research that exemplifies aspects of potential cooperation in driver assistance and human-robot interaction. In light of this work, it discusses the possible confluence of different principles for human-machine interaction.

Contents

8.1 Publication Disclosure **140**
8.1.1 Bibliographic Information 140
8.1.2 Author's Contribution 141
8.2 Open Challenges **142**
8.3 A Window to the Mind **142**
8.3.1 Passive Gaze Monitoring 143
8.3.2 Active Gaze-Based Communication 143
8.3.3 Cooperative Eyes 144
8.4 Reaching Limits **145**
8.5 Inclusivity **145**

8.1 Publication Disclosure

This chapter references a selection of publications with personal contributions. They occur in the order shown in the following list.

8.1.1 Bibliographic Information

[17] Matti Krüger and Christiane Wiebel-Herboth. "Method for assisting operation of an ego-vehicle, method for assisting other traffic participants and corresponding assistance systems and vehicles". U.S. pat. 10636301. Apr. 2020.

[6] Christiane B. Wiebel-Herboth, Matti Krüger, and Martina Hasenjäger. "Interactions between Inter- and Intra-Individual Effects on Gaze Behavior". In: *Adjunct Publication of the 28th ACM Conference on User Modeling, Adaptation and Personalization*. UMAP '20 Adjunct. Genoa, Italy: Association for Computing Machinery, 2020, pp. 35–40. ISBN: 9781450379502. DOI: 10.1145/3386392.3397595.

[8] Christiane B. Wiebel-Herboth, Matti Krüger, and Patricia Wollstadt. "Measuring inter- and intra-individual differences in visual scan patterns in a driving simulator experiment using active information storage". In: *PLoS one* 16.3 (2021), e0248166. DOI: 10.1371/journal.pone.0248166.

[16] Matti Krüger and Christiane Wiebel-Herboth. "Gaze-guided communication for assistance in mobility". U.S. pat. 10543854B2. Jan. 2020.

[9] Chao Wang, Matti Krüger, and Christiane B. Wiebel-Herboth. ""Watch out!": Prediction-Level Intervention for Automated Driving". In: *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '20. Virtual Event, DC, USA: Association for Computing Machinery, 2020, pp. 169–180. ISBN: 9781450380652. DOI: 10.1145/3409120.3410652.

[10] Chao Wang, Thomas H. Weisswange, Matti Krüger, and Christiane B. Wiebel-Herboth. "Human-Vehicle Cooperation on Prediction-Level: Enhancing Automated Driving with Human Foresight". In: *IV21 - Workshop on Trust Calibration for Human-AV Interactions* (2021).

[12] Matti Krüger, Martin Weigel, and Michael Gienger. "Visuo-tactile AR for Enhanced Safety Awareness in Human-Robot Interaction". In: *VAM-HRI 2020 The Second International Workshop on Virtual, Augmented and Mixed Reality for Human-Robot Interaction*. 2020.

[13] Matti Krüger, Bruce N. Walker, and Lewis Chuang. "The Embodied Vehicle". In: *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings*. AutomotiveUI '19. Utrecht, Netherlands: Association for Computing Machinery, 2019, pp. 50–55. ISBN: 9781450369206. DOI: 10.1145/3349263.3350763.

8.1.2 Author's Contribution

Personal contributions to the listed references are specified according to the Contributor Roles Taxonomy (CRediT) [24]. *Italicized* terms indicate secondary contributions where co-authors have taken the lead.

[17] Conceptualization, investigation, methodology, visualization, writing - original draft

[6] *Data curation*, software, *writing - review & editing*

[8] *Conceptualization*, data curation, investigation, *methodology*, *writing - review & editing*

[16] Conceptualization, investigation, methodology, writing - original draft

[9] *Conceptualization*, data curation, methodology, visualization, *writing - original draft*, *writing - review* & editing

[10] *Conceptualization*, methodology, software, *writing - original draft*, *writing - review* & editing

[12] Conceptualization, investigation, methodology, project administration, software, visualization, writing - original draft, writing - review & editing

[13] Conceptualization, project administration, visualization, writing - original draft, writing - review & editing

8.2 Open Challenges

The driver augmentation approaches described in the previous chapters address a variety of the situation awareness (SA) challenges described in Chapter 2. These include shortcomings of visual perception, future uncertainty, risk judgement, temporal judgements, and feedback about the impact of own actions. At least conceptually there is also potential for supporting attention and counteracting driver biases by making potential hazards more noticeable. Nevertheless, some existing challenges remain unaddressed by the LLI and its variants.

A major challenge is dealing with other traffic participants. Seeing them only as simple physical objects that follow fixed trajectories disregards the unknown variation and uncertainty, which they may introduce as independent actors with concealed mental states. The LLI gives no direct insight into mental states of traffic participants, such as their awareness about their surroundings or their intentions. When considering its probabilistic interpretation (see Chapter 7), information about mental states may at most be used to refine direction and time uncertainties [see 5]. Also information about mental states of the LLI user is not taken into account directly. On the one hand, this means that it provides information regardless of whether the driver already has awareness of an approaching hazard or not, making signaling in some situations redundant. On the other hand, predictions communicated through the LLI can be false when the driver's intention does not align with the current trajectory on which predictions are based. But how could information about a driver's mental states, such as intention and attention be acquired?

8.3 A Window to the Mind

Chapter 4 described the active nature of perception and how actions can be driven by predictive processes to sample information from sources of interest. To some extent, actions thus also express human understanding (see Section 2.1.4.4) and may be monitored to make inferences about underlying mental processes. In other words, through its active component, perception is not only the inference about causes of sensory input but also a window into the inference process itself.

One mode of perception that is particularly action-driven and happens to be dominant in driving is visual perception (see Section 2.1.2). This makes vision-related actions such as eye and head movements promising sources of information about a driver's mental states. As described in Section 2.1.2.1, detailed vision relies on an alignment of the fovea with the direction of interest. The viewing direction hence reveals what a driver is seeing with high acuity and is likely to be attending overtly. During movement, such as driving, people also tend to look most into their direction of movement [78, 349] (see Section 4.5.1), making the viewing direction not just reveal aspects of attention but also (movement-)intention. When taking further cues such as head movements into account, intention-driven predictive gaze can further be distinguished from a "surprise-induced" bottom-up dependent redirection of attention [350–355]. Also a strong indicator for a lack of attention is expressed through "sleepy" or closed eyes. This effect is already being utilized for systems that monitor the driver's wakefulness [101, 356]. Another mental state signal is present in the pupil diameter. The diameter typically changes in response to changing illumination as a brightness adjustment but it has also been linked to workload [128, 357–359]. When accounting for effects of illumination, this signal can help in estimating how challenging a situation is for the driver.

8.3.1 Passive Gaze Monitoring

Monitoring of vision-related actions can therefore yield rich information about a driver's mental states. An example for a driver assistance concept that aims to provide information that has been missed by a driver has been introduced by Petersson, Fletcher, and Zelinsky [360]. Their system monitored whether the driver's gaze fell onto identified traffic speed signs and gave feedback about unattended signs, thus using gaze to make inferences about a driver's lack of awareness and compensating for that failure within a limited scope.

Another form of assistance that monitors gaze to estimate what aspects of the scene a driver is aware of has been proposed by Krüger and Wiebel-Herboth [17]. Rather than just informing the respective driver about missed scene elements, this approach describes a propagation of information about a lack of awareness to other traffic participants in order to support them in forming a better understanding of the mental states of actors in their surroundings.

Not only fixation content but also patterns of eye and head movements can be informative for driver assistance, especially for the classification of driver intentions. For instance, prior to lane changes, characteristic gaze [361] and head movement patterns [362] have been identified and lane change prediction intent systems that utilize such patterns have been proposed accordingly [e.g., 363–365]. Patterns in gaze do not just depend on task or context but have also been found to vary reliably between individuals [e.g., 6]. Indeed, also for lane changes, Wiebel-Herboth, Krüger, and Wollstadt [8] found gaze pattern predictability, modeled over extended temporal horizons [see 366], to improve when personal variations are taken into account. This suggests that gaze-based driver intent prediction systems could benefit from an increased accuracy achievable through personalization. As pointed out in Section 2.2, personalization can improve the subjective relevance of driver assistance systems with notification or warning capabilities. Because lane changes are typically fully determined by actions of the driver, concerns about a precedence of safety considerations over personal preferences raised in Section 2.2.1 therefore do not apply in this case. But in addition to analyzing gaze patterns what other means are available for extracting personally relevant information from viewing behavior?

8.3.2 Active Gaze-Based Communication

The previously described approaches utilize information that is implicitly contained in viewing behavior. As long as drivers use actions to sample the environment they do not need to be aware of the action monitoring for it to be functional. But head and eye movements can also be utilized explicitly. We can control voluntarily where we look and thus use the orientation of head and eyes for explicit communication. Such a purposeful utilization of gaze for communication can be advantageous. Essentially it allows us to repurpose available degrees of freedom in eye movement control to communicate arbitrarily complex information when agreeing on a common code or language [367]. Here the discussion is limited to a utilization that could be regarded as intuitive in the sense of connecting to established associations and concepts.

A perhaps obvious form of active gaze utilization is to use it as a pointing mechanism. In interactions between humans, following each other's gaze is a major contributor to joint attention [368] that even infants have been found to be capable of [369, 370]. In humans, gaze following is anatomically facilitated by the strong visible contrast between colored iris and white sclera of the eye. This has even led to the *cooperative eye hypothesis* [371], according to which the human eye evolved this orientation transparency for the purpose of communication and cooperation. The utilization of deictic gaze [372] in human-machine interaction (HMI) appears to be a logical step. In the domain of driver assistance the use of gaze as an active pointing mechanism has been proposed in the context of infotainment control [e.g., 373, 374]. A method for actively requesting information about external objects has been proposed by Krüger and Wiebel-Herboth [16]. In what may be considered as a variation of the LLI, a driver would indicate objects of interest via deictic gaze to selectively inquire information about the risk levels associated with the respective objects.

8.3.3 Cooperative Eyes

An assistance concept in which information is not requested but actively provided through gaze input has been introduced by Wang, Krüger, and Wiebel-Herboth [9, 10]. The concept, which is intended for employment in automated driving systems, consists of letting drivers or passengers point out vehicles in the environment, which they consider to be a potential safety or comfort risk. The person just needs to look towards the corresponding vehicle and say "watch out!" to point out an object as a potential risk. By making the communication bimodal, verbal referencing can be simplified. The utterance suffices to indicate that a risk is present while the pointing gaze provides the information about the origin of the perceived risk. Especially for time-critical applications, such as driving, this simplified and yet accurate communication of location and meaning can be particularly beneficial. The "injection" of personal concerns into an otherwise autonomously operating system could be framed as a form of active momentary system personalization through which users can make sure that their personal preferences and assessment of the situation are being taken into account. Looking back at the requirements for human-vehicle cooperation derived in Section 3.3.1.1, another way to see it is as a form of cooperation. According to these requirements the cooperating agents need to be able to sense and interpret aspects of the same scene, relate these to the attainment of a common goal, plan and carry out interfering actions in case the goal is in jeopardy, and provide sufficient transparency to enable mutual understanding and constructive interference or adaptation.

Here human and machine both sense and interpret the same driving scene and share the goals of achieving safe and comfortable mobility. But their assessment of the driving scene in relation to these goals can occasionally differ. For example, due to bad personal experiences with drivers of a specific vehicle model, a passenger may assess the risk of driving behind such a car as being much higher than the risk classifier of the autonomous vehicle. The passenger then utilizes the bimodal input to make that personal risk assessment transparent to the vehicle automation. Depending on what options then remain without violating the primary safety goal, the vehicle might alter its trajectory plan accordingly. However, as it is primarily responsible for the driving task itself, it is also capable of keeping its original plan in case a special consideration of indicated hazards conflicts with the safety objective.

It is important to note that in the described case a cooperation between human and machine does not take place in the driving task itself but only on the level of estimating the potential impact of elements in the environment. Looking back at the original objective of improving awareness in mobility, this case of human-vehicle cooperation is rather special as it is not the machine that improves human awareness but it is the other way around. Also the motivation for this concept differs from that of many other forms of assistance in that it originates from a wish to improve comfort rather than a need to ensure safe mobility. So what factors would create necessity for cooperation in driver assistance?

8.4 Reaching Limits

Besides the challenge of identifying and accounting for mental states of traffic participants, another challenge for driver awareness that the LLI might only be able address to a limited extent is situation complexity (see Section 2.1.3.2). The larger the requirements to monitor and understand elements in the environment, the more challenging it becomes for a driver to acquire all relevant information with limited perceptual bandwidth and finite cognitive resources. Such an increase in requirements can, for instance, be due to a large number of traffic participants, more diverse behaviors, or a faster rate of change in relevant events. Similarly, a corresponding increase in requirements to act can bring any individual to its limits. An issue of augmentation-guided assistance is that the requirement for inclusion in a human sensorimotor feedback loop also entails 1) a limitation to the bandwidth and speed of the utilized sensory channels and 2) a limitation to the mental processing abilities of the assisted person. These abilities can vary substantially from person to person or within a person over time, e.g., due to exhaustion, and may in some cases not even suffice for handling the demands of everyday traffic, which effectively excludes a part of the population from the freedom of individual mobility. This is where automation and cooperation can shine. When task demands surpass an individual's abilities complexity must be broken down. A subset of the task must then be handled by an assistance component that is capable of autonomous performance. An example for an assistance system that carries out such a complexity reduction and workload distribution in demanding situations is the *cooperative speech-based on-demand intersection assistant* by Heckmann et al. [108–110], which was previously described in Section 2.2. In left-turn scenarios with laterally crossing traffic this system can reduce task demands by monitoring traffic that approaches from the right side while the driver can focus on the other side. Only in situations deemed to be of relevance for the driver, i.e., potentially available gaps in traffic approaching from the right, a notification to the driver is triggered.

8.5 Inclusivity

A distribution of a task into subsets that are then handled by cooperating agents has a curious implication: The agents substitute one another in the subtask carried out by the respective cooperation partner.

In the case of prediction level intervention by Wang et al. [9], the autonomous vehicle substitutes a human driver on perception, processing, and control levels and is hence likely to also reduce human ability for meaningful contributions on the prediction level in the long run due to deteriorating effects of substitution (see Section 3.2.2) and the interdependencies between perception, understanding, prediction, and action (see Section 2.1.1). In the case of intersection monitoring assistance by Heckmann et al. [108–110], a partial substitution of the traffic monitoring task takes place. Right side monitoring is reduced to a validation of communicated gap availability. However, the need for validation could suffice to counteract adverse substitution effects in this case.

It follows that, despite alleged conceptual differences between cooperation and substitution, the two can co-occur within the same interaction paradigm. For the relation between augmentation and cooperation it appears to be similar. Within this chapter approaches for monitoring driver behavior in order to make mental states more transparent for driver assistance were described. In the case of the assistance described by Krüger and Wiebel-Herboth [16], this addition of a cooperation requirement served in an augmentation-guided approach. The conceptual boundaries between substitutive, augmentative, and cooperative HMI create no limitations for system development. In terms of requirements it could even be argued that cooperation subsumes the other two (see Figure 3.2c in Section 3.4) while also inheriting some of their respective consequences (e.g., with respect to actors being in the loop) depending on how pronounced substitution or augmentation components are.

An example for a mixed cooperation and augmentation paradigm in the domain of human-robot interaction (HRI) was introduced by Krüger, Weigel, and Gienger [12]. In this paradigm a person has to cooperate with a robot in jointly picking up, turning, and carrying a motorcycle wheel to a target location. The robot is capable of coordinating and changing grasp holds as well as moving autonomously between wheel source and target location (see Gienger et al. [375] for a detailed description). The joint task requires high visual attention from the cooperating person. However, at the same time the person should also remain aware of elements in the surroundings to be able to avoid potential hazards and obstacles that could be present in the environment. This second objective creates competition for visual resources and could impair performance in the cooperative task. To avoid this issue without compromising awareness, the task of continuously monitoring the environment in relation to the person is taken over by a location monitoring system. The system determines what region is regarded as safe and provides visual and tactile feedback in case the cooperating person approaches the boundaries of that safe zone or even surpasses them. As with the LLI prototypes, tactile stimuli are provided through a belt containing vibrotactile actuators. In contrast to the LLI, these actuators are not driven by a temporal distance but by the spatial distance to the boundary of the safe zone such that the vibration intensity of the actuator located closest to the zone boundary increases as a function of the proximity to that boundary (see Figure 8.1). For visual grounding during first exposure as well as for external monitoring by a third person, the person's relation to the safe zone is further visualized in a 3D rendering that encodes boundary approach or violation in the color and shape of visualized zone tiles (see Figure 8.1).

Elements of cooperation, augmentation, and substitution are unified in this paradigm: 1. Human and robot cooperate in the wheel turning and carrying task. 2. A location monitoring system takes over the task of detecting whether hazardous areas are entered or approached, thereby effectively substituting the human in this task. 3. Information acquired by this system is translated into tactile stimuli in the human's frame of reference, providing an augmented awareness about existing or approaching location-safety violations.

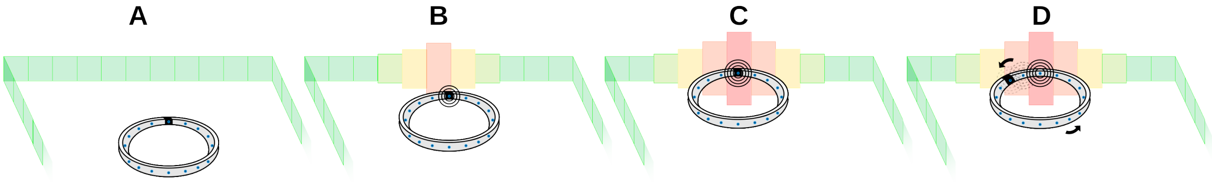


Figure 8.1: Functionality of the visuo-tactile safety augmentation introduced by Krüger, Weigel, and Gienger [12]: "(A) When located inside an area considered to be safe, the tactile interface produces no output and the visualization shows the boundary-elements of the virtual fence in green. (B) When approaching a border, the border elements located most closely to the user start growing and changing color such that elements grow and turn from green to yellow to red with decreasing distance. The tactile interface starts vibrating at the tactor that is located most closely to the border at a low intensity. (C) When reaching the border, the color change, element size, and vibration intensity are at maximum. (D) Rotating the belt shifts activity from the previous actuator to the actuator now located closest to the border." [12]

In summary, the presence of other independently acting traffic participants suggests that assistance systems that account for their mental states can have advantages in reducing uncertainty about future scene development. The monitoring of driver gaze appears to be a particularly promising tool for feeding inferences about such mental states. For instance, the superposition of gaze directions with simultaneous scene monitoring can yield an estimate of whether or not a driver has perceived relevant scene elements and therefore allow for complementary assistance. Alternatively, gaze may also be used actively as an explicit form of communication, e.g., to inform an assistance system about sources of worry while speeding up accuracy and speed of spatial references compared to pure verbal communication. The discussed addition of transparency about mental states marks a transition towards cooperative human-machine systems. While this increases system complexity, in some situations the task demands may necessitate the introduction of cooperative features to avoid being constrained by human mental capacity. Nevertheless, this does not exclude the possibility of preserving properties of augmentation. To illustrate the possible co-employment of substitution, cooperation, and augmentation, a paradigm from the domain of human-robot interaction was presented.

9

Conclusions and Future Work

As previously listed in Chapter 1, the contributions that are made by this dissertation can be briefly summarized as follows:

1. The motivation and theoretical development of an approach for enabling people to expand their sampling and understanding of spatiotemporal information
2. The introduction of exemplary systems that are guided by this approach in the context of driver assistance
3. Empirical investigations of effects that functional prototypes of these systems have on driver perception, behavior, and safety in a range of simulated road traffic scenarios
4. A connection of the primary augmentation-guided approach of this dissertation to work on cooperative human-machine systems

This chapter is an attempt to look beyond these contributions and see the research directions to which the conclusions made throughout this work may lead. It begins with a recapitulation of the main takeaways of the three thesis parts and then presents topic blocks that further discuss specific findings of interest to derive targets for future research.

Contents

9.1 Recapitulation . . . 150
9.1.1 Motivation and Approach Development . . . 150
9.1.2 Exemplary Systems and Empirical Investigation . . . 151
9.1.3 Connecting HMI Strategies . . . 152
9.2 Future Research . . . 152
9.2.1 Opaque Risk Predictions . . . 152
9.2.2 Long-Term Adaptation . . . 153
9.2.3 Perceptual Scaling . . . 153
9.2.4 Embodied Cooperative Mobility . . . 155

9.1 Recapitulation

9.1.1 Motivation and Approach Development

The primary objectives of this work were to develop and investigate ways for raising a driver's awareness of safety-relevant elements in the environment. A particular emphasis was put on investigating how information about dynamically changing scene aspects can be provided early on to maximize the flexibility for drivers to predict, plan, and act appropriately. Another feasible strategy to support drivers consists of breaking down task complexity. However, depending on the strategy by which such a breakdown is realized, distinct consequences may have to be considered.

These consequences were discussed for three approaches to human-machine interaction (HMI) termed substitution, cooperation, and augmentation based on their embedding within human and machine feedback loops. The disengaging nature of substitution-based HMI was identified as a fundamental source of negative consequences. While systems that are instead guided by a cooperative approach may circumvent many of these issues, the requirements for making driver and vehicle co-adapting team players also entail a rise in system complexity and task demands. Instead, an argument was presented in favor of augmentation as a desirable interaction principle due to its requirement for active user engagement and a consequential preservation of user competence and authority with low interaction complexity overhead. This would make augmentation-based HMI particularly suitable for addressing the previously identified challenges.

One target of human-machine systems that are guided by augmentation is to enable a user to perceive, act, or reason *through* the added technology. Fundamental theories and findings on human sensorimotor processes were therefore discussed to establish a theoretical basis for fulfilling this promise in the mobility context. This resulted in the connection of three main observations:

1. Actions are the expression of predictive processes that actively shape our perception.
2. The interpretation of sensory stimuli is not restricted to particular sets of stimulus sources but can be flexibly remapped and integrated with signals registered by other senses to enrich perception, e.g., in terms of speed and accuracy.
3. The predictive action-perception process is driven by the subjective relevance of the sampled information.

Accordingly, the first part of this thesis concluded with the following recommendations for a realization of perceptual augmentation in mobility: Information about scene elements that are relevant in the near future, such as potential safety hazards, should be conveyed in a manner that varies as a function of driver actions as well as external events in a predictable manner. In accordance with the uncertainty that is inherent to future predictions, propagating such uncertainty may support drivers in accepting and planning for unaccounted variability in system output. While different sensory organs may be recruited, the potential congruency between new stimuli and established sensorimotor processes should be considered to avoid negative interference and take advantage of multimodal facilitation.

9.1.2 Exemplary Systems and Empirical Investigation

The second part presented a concept and functional prototype that aims to follow the guidelines developed in Part 1. The prototype, termed lateral line interface (LLI), establishes a consistent mapping between a temporal hazard vector and tactile stimulus direction and intensity to augment the perception of potential traffic hazards. An investigation of LLI effects on participants in a driving simulator study resulted in the following conclusions:

- Drivers can intuitively perceive and understand direction and temporal distance information encoded in the LLI stimuli.
- Drivers can benefit subjectively and objectively from the LLI-based augmentation, i.e., both in terms of perceived support and driving safety.
- The perceived support appears to increase with situation difficulty, whereas a link between scenario difficulty and a gain in LLI impact on driving safety could not be confirmed.

The results of the investigation also raised new questions about effects of the LLI, such as whether LLI benefits were due to a continuous time-intensity encoding and whether similar utility could be found in intersection scenarios or highway driving with lower criticality events.

Therefore, another driving simulator study with a new set of driving scenarios was carried out. This study utilized an expanded LLI prototype capable of handling crossing traffic and with an option for binary instead of continuous signaling. Results of the study confirmed the prior finding that drivers could acquire a quick understanding of the direction and time characteristics of LLI stimuli and felt supported in the driving task. In terms of driving safety, similar levels were observed in the tested conditions of reduced urgency for LLI-supported and unsupported driving. While this result differs from results of the first study with higher criticality, it is not unreasonable that measurable safety benefits decreased with criticality. No difference in safety levels between a binary and a continuous LLI variant was found. Whether or not safety effects of the LLI can be attributed to its continuous scaling or any initial alerting characteristics could not be concluded based on driving performance. But surprisingly, even participants who were only exposed to a binary variant of the LLI reported perceiving variable risk-dependent stimulus intensities. This raised questions about what other factors contribute to tactile intensity perception and to what extent intensity scaling of tactile stimuli should account for possible cross-modal influences. Therefore, based on subjective reports, the variable signal intensity clearly played a role in the subjective perception, even in cases in which it was not intended to be perceived as variable.

Part 1 of the dissertation briefly touched upon a possible benefit of including the uncertainty that is inherent to future predictions in the encoding of stimuli intended for awareness augmentation. In a third driving simulator study this topic was explicitly addressed through an investigation of the role of uncertainty in the LLI context. Results of the study showed that participants were able to perceive and understand an added tactile stimulus dimension of direction uncertainty without effort. Subjective ratings for uncertainty-encoding stimuli were as high as those for spatially precise signals of equal range. The perceived support was also reflected in an improved driving safety in scenarios with impaired visibility. These results indicate that transparency about the machine confidence levels conveyed through tactile stimuli may be appreciated and purposefully utilized by drivers to increase safety.

9.1.3 Connecting HMI Strategies

After having investigated the topic of perceptual augmentation in the second part of this thesis, the third part revisited the principle of cooperative human-machine interaction. Motivated by the wish to account for uncertainty about scene development that arises from the presence of independent traffic participants, the potential of driver gaze monitoring to enable inferences about mental states was discussed. Examples for passive monitoring as well as an active utilization of gaze as a communication medium were introduced. The introduction of such inferential capabilities is a step towards a more cooperative system. While this entails an increase in interaction complexity, it was argued that a cooperative approach may become preferable when the information processing bottleneck of a human driver is insufficient to meet task demands. In reference to examples for HMI paradigms that contain elements of substitution, cooperation, and augmentation it was concluded that their conceptual bounds stand in no conflict with their co-employment but should rather be seen as indicators for potential consequences that require consideration in system design.

9.2 Future Research

9.2.1 Opaque Risk Predictions

The presented studies about different variants of the LLI confirmed that a time-to-contact (TTC) encoding in tactile stimuli can be intuitively understood and utilized by drivers to improve their driving safety and driving experience. Even with an additional stimulus dimension of direction uncertainty and a corresponding increase in stimulus complexity this utility seems to persist (see Chapter 7). This suggests that drivers may also be able to handle a transition from a deterministic TTC-based risk to a stochastic risk estimation and communication that considers further contextual factors. In theory, an inclusion of additional contextual factors would enable responses to a larger set of critical situations. Furthermore, a decoupling of severity and probability may be achieved and support stimulus prioritization in the presence of multiple risk sources. A future task would therefore be to investigate whether stochastic risk models can successfully substitute TTC-based risk estimation in the LLI in terms of driving safety and perceived support.

One possible issue of such a transition is that it hides the causal relationship between factors in the environment and risk estimation. The TTC is a simple model that has visual correlates in optical flow [88, 89] and already appears to implicitly underlie some driver actions [86], even without the LLI (see Section 2.1.4.3). When this relationship is weakened, drivers may have difficulties in causal attribution and thus fail or only slowly gain an intuitive understanding and inclusion within sensorimotor processes. It is also possible that overall effectiveness could be weakened due to a lack of congruent stimuli from other sensory modalities. Another future research question is hence whether stimuli that are based on complex causal relationships with a variety of possible stimulus causes can still be understood and utilized as intuitively as TTC-based stimuli.

On the other hand, the appreciation for the transparency of machine confidence levels about hazard direction, which participants expressed in the study reported in Chapter 7, could suggest that the perception of stochastic stimuli without a clearly defined cause may integrate well into the natural mode of perception. After all, perception can be seen as an act of signal disambiguation that regularly has to take imprecise signals sampled from individual modalities into account. An opacity and vagueness about stimulus causes may result in lower correlation with existing senses but also entail a higher complementarity and therefore possibly even more purposeful integration. Fears of complicating the understanding of stimuli with more complex underlying risk models could therefore turn out to be unfounded.

9.2.2 Long-Term Adaptation

In all presented driving simulator studies on the LLI, each participant was only exposed to the LLI for relatively short periods of less than one hour in total. Opportunities to experience the LLI and learn how to integrate its feedback into the driving process were hence limited. Citing prior examples [e.g., 210] of successful tactile sensory augmentation after first exposure, Section 4.5 provides an argument for why such short exposure may suffice for first effects when the information content is simple or when correlation with established sensorimotor processes is apparent. Indeed, results of all LLI user studies confirm that participants very quickly gained an intuitive and correct understanding of all dimensions encoded in the stimuli and that they could use the conveyed information effectively to increase driving safety compared to unassisted driving. Nevertheless, also in the mentioned prior work the stimulus utilization by participants became much more refined after prolonged exposure. This suggests that also LLI experience and utilization might further develop over time.
Future research on LLI-like systems should investigate the effects of long-term exposure, in particular with regards to the accuracy of time or risk perception as well as driver reliance on system output. Prolonged exposure can, in principle, be achieved through a series of driving simulator sessions. But LLI application in real traffic would likely be advantageous for studying long-term adaptations due to the natural event variability and because regular driving would then not be “LLI-free” and possibly counteract adaptations acquired during simulator practice.

9.2.3 Perceptual Scaling

Section 2.2.1 in Chapter 2 discussed a tradeoff between how early a signal about a risk can be provided and the chance that such a signal is considered to be a false alarm. While a late signal is more likely to be relevant, it only leaves very little time to act on. On the opposite side, a signal that occurs too early or very frequently can create a cry wolf effect and might not be acted on at all. In Chapter 2 it was argued that this tradeoff concerns salient alerts in particular but that it may be less pronounced when utilizing gradually scalable signaling where the salience is proportional to the risk level. In none of the user studies did participants indicate being annoyed by the LLI, although its onset threshold was considerably earlier than that of traditional warning systems. On the contrary, participants largely reported feeling supported by LLI stimuli, even in situations that they could handle equally well without the tactile assistance (see Section 6.4.1). This results supports the view that gradually scalable signaling can be an effective way of circumventing or at least shifting the tradeoff between signal onset and its perceived adequacy. However, for gradually scalable, risk-contingent interfaces the perhaps

more interesting challenge comes after deciding on a signaling range:
The mapping from risk to stimulus intensity can follow diverse functions. A linear mapping might be the most straightforward: each step in risk increase should be accompanied by a step in stimulus intensity of the same magnitude. But rather than a physical magnitude this should be a perceived magnitude, which requires its own modality-specific psychophysical model. In the case of the LLI, this was implemented by applying a power law that models tactile intensity perception around the core of the body in the 50-240 Hz range (see, e.g., Section 6.3.1). A (perceptually) linear mapping creates a direct stimulus correspondence to the underlying risk model while any variation through a different scaling function modifies how risk estimates are propagated. But a direct correspondence might also be disadvantageous in some cases, such as when risk only changes at a very slow rate that makes changes in stimulus intensity difficult to notice. Future work could explore if and how modifications of this propagation, such as emphasis or discretization, affect LLI utility across different classes of driving scenarios.

9.2.3.1 Cross-Modal Effects

One finding that relates to LLI psychophysics was presented in Chapter 6. A group of study participants never experienced the LLI with a variable, TTC-contingent stimulus intensity. Instead they received stimuli of constant intensity whenever the TTC was below the signaling threshold. Nevertheless, also these participants consistently reported perceiving a risk-contingent variation in intensity. In congruence with this unexpected result, participants showed no signs of being annoyed by an early constant intensity signal either, although also this LLI variant triggered stimuli much earlier than classical warning systems. On the contrary, participants reported feeling supported to the same extent as those participants in the continuous LLI group. One possible explanation for this phenomenon would be cross-modal effects on tactile stimulus magnitude perception. Support for the feasibility of such effects comes from research on peripersonal space (PpS) perception.
The PpS is a representation of the space surrounding an agent's body, which serves as an interface between the agent and environmental elements [298, 299]. A representation of this space between body and environment is thought to be achieved by binding information from multiple sensory modalities, which respond to proximal and distal stimuli such as vision and touch. Early indicators for this kind of binding came from electrophysiological studies in macaque monkeys, which identified neurons responding both to visual and tactile information in several brain regions [302, 376–378], [cf. 299]. Brozzoli et al. [379] reviewed further evidence from neuroscientific studies, including indicators for functionally homologous PpS representations in humans revealed by studies on cross-modal extinction [300, 301]. One property of neural structures associated with the PpS is that their response to approaching visual stimuli is modulated by the visible distance between the object and the neuron's tactile receptive field such that closer stimuli elicit stronger responses. But would similar effects also be justified in the case of the LLI, which is not driven by spatial but by temporal situation characteristics? Fogassi et al. [380] discovered that the velocity of an approaching visual stimulus modulates the receptive field depth in macaque V4/PMVc neurons such that it increases with the approaching velocity. Conversely, Amemiya et al. [381] observed a link between simulated walking and an expansion of peripersonal space in the frontal direction, which supports a velocity-based PpS modulation. With velocity being an expression of covered space over time, it may be reasonable to assume

that peripersonal space does not only depend on spatial but also on temporal stimulus characteristics. To test whether a context-dependent modulation of tactile intensity perception indeed takes place in the case of the LLI, future work could contrast a physically binary LLI with a presumed perceptual binary LLI that is characterized by a weakening of stimulus intensities as the risk increases to counteract cross-modal effects. A confirmation would have consequences for the design of future perceptual scales.

9.2.4 Embodied Cooperative Mobility

One aspect of a joint employment of substitutive, cooperative, and augmentative components, as discussed at the end of Chapter 8, is that although human and machine have individual roles, they are also closely connected through their interdependence in the joint task and the augmentation of human scene awareness through machine-acquired information. From a metaphysical perspective one question that arises is whether this close connectivity also leads to any change in self-perception, specifically if perceived personal bounds might expand to the communicated system boundaries or whether machine actions carried out in cooperation are being attributed to oneself. Section 4.1 discussed the subtraction of reafferent signals from sensory input as a basis for distinguishing between self-induced and externally caused events. In extension, *predictive coding* [155, 382] paradigms view perception as the creation and updating of inferences about the causes of sensations where inferences are driven by top-down connections that encode sensory predictions and bottom-up connections that propagate prediction errors, which top-down connections failed to account for [383]. An enactive view [e.g., 217, 220, 384] would add a need for reafferent grounding and understand the exercise of sensorimotor processes itself as part of the anticipatory inference, characterized by selective sampling through actions to reduce causal uncertainty.

In a causal inference about sensations, the outcome of one's own actions should be attributed to oneself as their origin. For an event that is the result of cooperation, there may be no unique cause. Instead causality is shared between cooperating agents. This is not a case of ambiguity due to an availability of multiple causes that could explain the event equally well because none of these determinants could create the event in isolation. Only their joint occurrence and coordination can be asserted as cause. So when an effect has multiple causes, it binds these causes. The "we" emerges as the origin of the cooperation outcome.

Yet a persistence of boundaries between oneself and other constituents typically remains reasonable, also during cooperation. But once sensorimotor processes start being exercised through other agents this claim might become more difficult to defend. Sensory augmentation, such as through application of the LLI or the visuo-tactile safety zone (see Figure 8.1), is defined as an inclusion of machine competence within human sensorimotor feedback loops (see Section 3.4 and Figure 3.2d on page 44). By enactive accounts of perception and cognition (see Section 4.4), the exercise of these feedback loops provides the basis for inferring the causal relationships or sensorimotor contingencies that they are subject to. As top-down predictions of actions on augmented sensory input become more refined, a dissociation from *classical* senses gradually loses significance. Simultaneously, refined access to novel object features provided by the augmentation may enrich the access to information and uncover new distinctions in the world.

In a mixed cooperation and augmentation paradigm where agents do not just interact with but also through each other, boundaries between cooperating constituents might fade accordingly. For work in the mobility domain, the effects of such an embodiment of components and competencies of a cooperating vehicle, with which driving responsibilities are shared, could be particularly interesting. As a start, with a personal identification with vehicle capabilities one could expect an overall increase in the awareness of augmented features, even during automated driving. If these features should contribute to situation awareness formation, it would further be reasonable to hypothesize a facilitation of control transitions after periods of automated driving as a consequence of the continuous awareness about the vehicle perception of these features. But these are future research topics, not conclusions. So let's take a closer look at them together.

ACRONYMS

ACC	Adaptive Cruise Control.
ANOVA	Analysis of Variance.
AoI	Area of Interest.
AR	Augmented Reality.
bLLI	binary Lateral Line Interface.
BOLD	Blood-Oxygen-Level-Dependent.
CD	Corollary Discharge.
CI	Confidence Interval.
cLLI	continuous Lateral Line Interface.
CRediT	Contributor Roles Taxonomy.
DRF	Driver's Risk Field.
FEF	Frontal Eye Field.
fMRI	Functional Magnetic Resonance Imaging.
FN	False Negative.
FP	False Positive.
HC	Human Certain.
HMI	Human-Machine Interaction.
HRI	Human-Robot Interaction.
HU	Human Uncertain.
HUD	Head-Up Display.
iACC	intelligent Adaptive Cruise Control.
LLI	Lateral Line Interface.
MC	Machine Certain.
MSTd	dorsal Medial Superior Temporal area.
mTTC	Minimum Time-To-Contact.
MU	Machine Uncertain.

NASA-TLX	NASA Task Load Index.
OF	Optical flow.
ORD	Optical Rearrangement Device.
PpS	Peripersonal Space.
RF	Receptive Field.
RHI	Rubber Hand Illusion.
SA	Situation Awareness.
SMC	Sensorimotor Contingency.
THW	Time Headway.
TLC	Time-To-Lane-Crossing.
ToM	Theory of Mind.
TTC	Time-To-Contact/Time-To-Collision.
TTP	Time-To-Passing.
TVSS	Tactile Vision Substitution System.
uc	Uncertainty Communication.
V4/PMVc	Premotor Ventral Caudal Cortex.
V5/MT	Middle Temporal Visual Area.
VIP	Ventral Interparietal Area.

Glossary

adaptive cruise control	A class of driver assistance systems for automatic braking and acceleration to maintain either a specified target velocity or a desired minimal distance to a front vehicle.
binary LLI	LLI with a binary TTC-intensity encoding.
blood-oxygen-level-dependent	A blood oxygenation signal that is used as an indirect measure for local changes in neuronal activity.
continuous LLI	LLI with a continuous TTC-intensity encoding.
corollary discharge	Another common term for the concept of reafference.
cry wolf effect	Phenomenon characterized by an ignorance of alarms that have been wrong in the past.
deictic gaze	Gaze that “points” to a direction of interest through a purposeful orientation of eyes and/or head towards that direction.
intelligent adaptive cruise control	An extension of the classical ACC that is capable of anticipatory and thus smoother cruise control [129].
inverse effectiveness	An increase in multisensory/redundancy gain as the effectiveness of unisensory stimuli decreases.
lateral line	A system of sensory organs available to many aquatic vertebrates. It is sensitive to displacements of a surrounding medium (e.g., water), which makes it useful for detecting movements and vibrations.

lateral line interface	Interface that utilizes a belt of tactile actuators to create stimuli that encode direction and TTC information.
McGurk effect	An effect that demonstrates how the visual perception of a speaking person can modulate the perceived utterance such that entire consonants are substituted when visual and auditory stimuli are in conflict.
minimum time-to-contact	Smallest value in a set of TTC estimates.
optical flow	The motion-induced spatial displacement of visual elements across the visual scene over time.
optical rearrangement device	Device that alters the relationship between the visual world and visual sensory input (e.g., through rotation, mirroring, distortion, displacement).
reafference	The subtraction of efference copies of motor commands from sensory input in order to cancel out effects of one's own actions. *Reafferent* information refers to self-caused sensory input while *exafferent* information is caused externally.
receptive field	"The specific part of the world to which a receptor organ and receptor cells respond" [164].
redundancy gain	A phenomenon characterized by increased performance in, e.g., speed and accuracy of perception when information is (redundantly) conveyed through multiple senses.
rubber hand illusion	Sensory illusion in which the perception of one's own body parts is altered by exploiting the integration of visual, tactile, and proprioceptive information.
sensory augmentation	A systematic alteration of signal sources for a sensory apparatus in order to provide access to novel sensorimotor contingencies.
sensory substitution	The translation of signals collected with one sensor into stimuli for another sensory organ.
situation awareness	"The perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future." [26].

somatogravic illusion	A perceptual illusion during which acceleration is perceived as tilt.
time headway	Time distance to the current location of another object.
time-to-contact	Also *time-to-collision*. The time it would take for two objects to collide when assuming that velocities and trajectories are maintained.
visual acuity	The spatial resolution of the visual system. It depends on optical factors, such as the focus of the image projected onto the retina, the density of photoreceptors on the retina, and the brain's ability to merge and interpret incoming retinal information.

LIST OF FIGURES

2.1 Situation Awareness . . . 15
2.2 Probability and relevance . . . 23
2.3 Distance, TTC, and THW . . . 26
2.4 Shaping probabilities . . . 27

3.1 Components of cooperative assistance . . . 42
3.2 Feedback loops in substitution, cooperation, and augmentation . . . 44

4.1 Reafference principle . . . 48

5.1 Temporal equivalents in relative movement . . . 64
5.2 Traffic scenario and temporal proximity signals . . . 66
5.3 Static driving simulator setup and LLI prototype . . . 68
5.4 Subjective LLI understanding and utility . . . 73
5.5 mTTC distributions . . . 74
5.6 mTTC over time . . . 75
5.7 Average velocity distributions . . . 76

6.1 TTC estimation in 2D . . . 86
6.2 Experimental procedure . . . 89
6.3 Exploration drive questionnaire (binary and continuous LLI) . . . 95
6.4 Subjective understanding (binary and continuous LLI) . . . 96
6.5 Test drive questionnaire (binary and continuous LLI) . . . 97
6.6 Helpfulness ratings (binary and continuous LLI) . . . 98
6.7 Acceptance ratings (binary and continuous LLI) . . . 99
6.8 mTTC for both LLI variants and scenarios . . . 100
6.9 Occurrence of critical trials in each scenario . . . 101
6.10 Occurrence of LLI activation for both variants and scenarios . . . 102

7.1 Foggy tunnel simulation setup . . . 115
7.2 Illustration of uncertainty-based LLI activation . . . 117
7.3 Illustration of tactile uncertainty encoding . . . 118
7.4 Experimental conditions . . . 119
7.5 Low visibility scenario . . . 121
7.6 Rain-scenario traffic definition . . . 122
7.7 Subjective evaluation predictions . . . 125
7.8 Behavioral outcome predictions . . . 126

7.9 Subjective agreement ratings 127
7.10 Subjective evaluation outcome 129
7.11 Front gaze ratios for all conditions 131
7.12 mTTC scores for human-uncertain conditions 132

8.1 Visuo-tactile safety augmentation 147

LIST OF TABLES

1.1 Contributions to primary publications 8
1.2 Contributions to auxiliary publications 9

5.1 Experiment components and durations. 69

6.1 Scenarios and objectives of the exploration track 90
6.2 Helpfulness ratings regression table 98
6.3 mTTC regression table 100
6.4 Critical event rate regression table 101
6.5 LLI activation regression table 102

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Eidesstattliche Versicherung

(Siehe Promotionsordnung vom 12.07.11, § 8, Abs. 2 Pkt. 5)

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

Obertshausen, den 08.12.2021

Matti Krüger