AFFECTIVE AUTOMOTIVE USER INTERFACES

DISSERTATION

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ABSTRACT

Technological progress in the fields of ubiquitous sensing and machine learning has been fueling the development of user-aware human-computer interaction in recent years. Especially natural user interfaces, like digital voice assistants, can benefit from understanding their users in order to provide a more naturalistic experience. Such systems can, for example, detect the emotional state of users and accordingly act in an empathic way. One major research field working on this topic is *Affective Computing*, where psycho-physiological measures, speech input, and facial expressions are used to sense human emotions.

Affective data allows natural user interfaces to respond to emotions, providing promising perspectives not only for user experience design but also for safety aspects. In automotive environments, informed estimations of the driver's state can potentially avoid dangerous errors and evoking positive emotions can improve the experience of driving.

This dissertation explores *Affective Automotive User Interfaces* using two basic interaction paradigms: firstly, emotion regulation systems react to the current emotional state of the user based on live sensing data, allowing for quick interventions. Secondly, emotional interaction synthesizes experiences which resonate with the user on an emotional level. The constituted goals of these two interaction approaches are the promotion of safe behavior and an improvement of user experience.

Promoting safe behavior through emotion regulation: Systems which detect and react to the driver's state are expected to have great potential for improving road safety. This work presents a model and methods needed to investigate such systems and an exploration of several approaches to keep the driver in a safe state. The presented methods include techniques to induce emotions and to sample the emotional state of drivers. Three driving simulator studies investigate the impacts of emotion-aware interventions in the form of implicit cues, visual mirroring and empathic speech synthesis. We envision emotion-awareness as a safety feature which can detect if a driver is unfit or in need of support, based on the propagation of robust emotion detection technology.

Improving user experience with emotional interaction: Emotional perception is an essential part of user experience. This thesis entails methods to build emotional experiences derived from a variety of lab and simulator studies, expert feedback, car-storming sessions and design thinking workshops. Systems capable of adapting to the user's preferences and traits in order to create an emotionally satisfactory user experience do not require the input of emotion detection. They rather create value through general knowledge about the user by adapting the output they generate. During this research, cultural and generational influences became evident, which have to be considered when implementing affective automotive user interfaces in future cars.

We argue that the future of user-aware interaction lies in adapting not only to the driver's preferences and settings but also to their current state. This paves the way for the regulation of safe behavior, especially in safety-critical environments like cars, and an improvement of the driving experience.

ZUSAMMENFASSUNG

Aktuelle Fortschritte in den Bereichen des Machine Learning und Ubiquitous Computing ermöglichen es heute adaptive Mensch-Maschine-Schnittstellen zu realisieren. Vor allem natürliche Interaktion, wie wir sie von Sprachassistenten kennen, profitiert von einem verbesserten Verständnis des Nutzerverhaltens. Zum Beispiel kann ein Assistent mit Informationen über den emotionalen Zustand des Nutzers natürlicher interagieren, vielleicht sogar Empathie zeigen. *Affective Computing* ist das damit verbundene Forschungsfeld, das sich damit beschäftigt menschliche Emotionen durch Beobachtung von physiologischen Daten, Sprache und Mimik zu erkennen.

Dabei ermöglicht Emotionserkennung natürliche Interaktion auf Basis des Fahrer/innenzustands, was nicht nur vielversprechend in Bezug auf die Gestaltung des Nutzerelebnisses klingt, sondern auch Anwendungen im Bereich der Verkehrssicherheit hat. Ein Einsatz im Fahrkontext könnte so vermeidbare Unfälle verringern und gleichzeitig Fahrer durch emotionale Interaktion begeistern.

Diese Dissertation beleuchtet *Affective Automotive User Interfaces* – zu Deutsch in etwa *Emotionsadaptive Benutzerschnittstellen im Fahrzeug* – auf Basis zweier inhaltlicher Säulen: erstens benutzen wir Ansätze zur Emotionsregulierung, um im Falle gefährlicher Fahrerzustände einzugreifen. Zweitens erzeugen wir emotional aufgeladene Interaktionen, um das Nutzererlebnis zu verbessern.

Erhöhte Sicherheit durch Emotionsregulierung: Emotionsadaptiven Systemen wird ein großes Potenzial zur Verbesserung der Verkehrssicherheit zugeschrieben. Wir stellen ein Modell und Methoden vor, die zur Untersuchung solcher Systeme benötigt werden und erforschen Ansätze, die dazu dienen Fahrer in einer Gefühlslage zu halten, die sicheres Handeln erlaubt. Die vorgestellten Methoden beinhalten Ansätze zur Emotionsinduktion und -erkennung, sowie drei Fahrsimulatorstudien zur Beeinflussung von Fahrern durch indirekte Reize, Spiegeln von Emotionen und empathischer Sprachinteraktion. Emotionsadaptive Sicherheitssysteme können in Zukunft beeinträchtigten Fahrern Unterstützung leisten und so den Verkehr sicherer machen, vorausgesetzt die technischen Grundlagen der Emotionserkennung gewinnen an Reife.

Verbesserung des Nutzererlebnisses durch emotionale Interaktion: Emotionen tragen einen großen Teil zum Nutzerlebnis bei, darum ist es nur sinnvoll den zweiten Fokuspunkt dieser Arbeit auf systeminitiierte emotionale Interaktion zu legen. Wir stellen die Ergebnisse nutzerzentrierter Ideenfindung und mehrer Evaluationsstudien der resultierenden Systeme vor. Um sich den Vorlieben und Eigenschaften von Nutzern anzupassen wird nicht zwingend Emotionserkennung benötigt. Der Mehrwert solcher Systeme besteht vielmehr darin, auf Basis verfügbarer Verhaltensdaten ein emotional anspruchsvolles Erlebnis zu ermöglichen. In unserer Arbeit stoßen wir außerdem auf kulturelle und demografische Einflüsse, die es bei der Gestaltung von emotionsadaptiven Nutzerschnittstellen zu beachten gibt.

Wir sehen die Zukunft nutzeradaptiver Interaktion im Fahrzeug nicht in einer rein verhaltensbasierten Anpassung, sondern erwarten ebenso emotionsbezoge Innovationen. Dadurch können zukünftige Systeme sicherheitsrelevantes Verhalten regulieren und gleichzeitig das Fortbestehen der Freude am Fahren ermöglichen.

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I also want to thank the people who invested their time to review this dissertation. Thank you, **Alexander**, for the valuable feedback and for the incredible Tafelspitz when we first met in Vienna. Thank you, **Ronald**, for your great input, for the initial invitation to Brisbane after my master's, and the pleasant chats at AutoUI.

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Collaboration Statement

None of the work comprised in this thesis would have been possible without the support of many great people: my supervisors, colleagues, students and collaborating partners. I gratefully acknowledge their efforts towards my research by using the scientific *"we"* throughout the text of this dissertation. In this statement I illustrate my personal contribution and the help I received along the way.

All publications are results of a close collaboration with my supervisor Florian Alt, who was involved in every project from idea to presentation. Nora Broy helped me identify open research questions at the very start to define the vision guiding my research. Bastian Pfleging contributed feedback to study designs, manuscripts and co-supervised the methodical evaluations described below. My work at BMW was facilitated through the creative and strategic guidance of Ronee Chadowitz and Florian Weber. These attributions apply to the publications on which co-authorship is stated.

The publications featured in this thesis are based on projects with diverse organizational backgrounds. The students involved either wrote their bachelor's or master's theses with me at LMU or interned with me at BMW. I determined their research topics, supervised the progress through regular feedback and enabled their work with ample assistance. Other contributors were colleagues from several institutions who I collaborated with in shared responsibility. If not stated otherwise, included publications are based on original concepts and prototypes of myself, with feedback from the respective co-authors. I verified all analyses, created the visualizations and wrote and revised the manuscripts.

Methodical explorations: I supervised several student theses on methodological questions. Among them an investigation of emotion elicitation techniques, which my student Simon Weiser contributed to as experimenter and by providing an initial analysis [P4]. My intern Markus Ludwig implemented an emotion sampling tool which was evaluated by Karina Serres as part of her bachelor's thesis [P1].

Emotion regulation: Jonas Schubert supported my work on emotion regulation approaches for his master's thesis [P8]. He integrated the experiment into a research framework and conducted a user study. Sigrid Van Veen gave support in feedback and provision. I further cooperated with Mariam Hassib on a prototypical feedback loop anchored in her personal research, to which she contributed the main concepts and algorithms [P9]. Mariam also provided the machine learning know-how and composed the main part of the manuscript. Another project on emotion regulation was realized in cooperation with Fraunhofer IIS and invaluable programming support by Florian Roider [P3, P6].

Emotional interaction: My student Anja Mainz executed several studies on emotional voice interaction for which she did extensive statistical analysis and helped design agent personalities in cooperation with a screenwriter [P7, P11]. Another project investigating use cases for emotion detection was set up in cooperation with the BMW Tech Office Shanghai [P12]. My intern Guillermo Ponce-Zambrana supported the software design and Jingyi Li translated and replicated the initial study in Chinese. Jingyi also contributed a big part towards the inter-cultural alignment of our work [P10]. Andreas Butz took an advisory role in this project, providing feedback and organizational support.

Table 1 clarifies the contributions of others to individual projects and publications.

Project & Publications	Contributions of Others
Affective Use Cases [P10, P12]	Jingyi Li contributed to concept and design, conducted the studies with Chinese participants, analyzed the data thereof, and cooperated on the manuscripts. My intern Guillermo Ponce-Zambrana supported the process.
Ambient Light [P9]	Mariam Hassib envisioned the project and tools, conducted the user study, and composed the main part of the manuscript.
Driver State Displays [P3, P6]	Florian Roider enabled the driving simulation and helped with hardware.
Emotion Detection [P4]	My student Simon Weiser executed the study and initial data analysis.
Emotion Regulation [P8]	My student Jonas Schubert implemented the prototype and conducted the user study.
Emotion Sampling [P1]	My intern Markus Ludwig implemented the software tool and my student Karina Serres conducted the user study.
Fundamentals [P2, P5, P13]	No contributions of others apart from guidance and feedback.
Personality in Speech [P7, P11]	My student Anja Mainz designed the characters, conducted the user studies, and provided an initial statistical analysis.

Table 1: Clarification of the author's personal contribution in each incorporated publication. If not mentioned otherwise, I conceived and executed the work, provided the visual materials, composed the written manuscript, and edited the final version. The co-authors which are not named individually contributed with supervision, feedback on concepts and manuscripts, and/or organizational help.

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1 Introduction

"An IQ test?"
"No. Empathy."
"I'll have to put on my glasses."

Philip K. Dick, Do Androids Dream of Electric Sheep?

1.1 Thesis Statement

Digital user interfaces have taken over car interiors with multimodal input possibilities and ever increasing screen sizes. We interact with our cars not anymore only to manage the steering direction and acceleration but also handle services and remote digital systems via the integrated user interface [36]. One achievement enabled by this development is more natural interaction, e.g., through speech input and synthetic feedback. However, with this we also introduce more demanding activities for the driver, which are not directly related to the driving task and can thus have negative effects on safety. Research shows that driver behavior is substantially connected with the driver's emotional state, which can be influenced through outside events like traffic, social interaction, or the experience of operating the car and its systems [49]. Fortunately, modern technology, like facial expression analysis, allows us to analyze the driver's behavior and gather insights on their emotional state of well-being [32]. This leads us to the primal assertion motivating this thesis: Interaction in the car can be made safer and more enjoyable when systems are able to adapt to the user's emotional state. We concern ourselves with two major applications of this notion within our research:

Promoting Safe Behavior

The protagonists in Philip K. Dick's *Do Androids Dream of Electric Sheep?* utilize a device to regulate their emotional reactions in order to adjust for their daily tasks. The machine, called *Mood Organ*, can induce anything between professional attitudes and crippling depressions, it can be of help handling conflicts by dissolving anger, or maximize motivation and combative spirit [13]. To keep expectations at bay: we do not have access to such a device. Yet, we can appreciate the benefits an effective means of influencing emotions would have on traffic safety if used wisely.

In this work, we investigate more realistic strategies to regulate driver emotions. For example, we aim to calm down drivers displaying signs of anger, as aggressive driving endangers everyone inside and outside the car [P8]. The same goes for drivers in sad or highly activated states: preoccupation with personal sentiments, i.e., lessens awareness of the streetscape [P13]. Our approaches to regulating driver emotions are less intrusive than proposed in the book: we compare the effects of implicit cues, visual mirroring and empathic speech on the driver's emotional state and driving performance.

Improving User Experience

To stay with sci-fi analogies, we motivate the second theme with *Marvin the Paranoid Android* from Douglas Adams' *The Hitchhiker's Guide to the Galaxy* [1]. He serves as our counterexample for the opportunities of emotional natural interaction to improve the user experience of digital systems. Marvin is the starship's human-machine interface in the form of a talking robot. When interacting with humans, he shows unmistakable signs of condescendence and self-pity because no task given by a human could ever utilize his vast computational power. This overly dramatic expression of an existential crisis makes every interaction with Marvin practically unbearable.

The approach we follow in this work stresses the opposite extreme: we embrace the stance that emotional interaction can improve the user experience of systems, given they adapt to the context and user characteristics. Instead of self-pity, a system can show empathy to build trust with the user. Systems can adapt their behavior to user traits, like personality, to more resemble a human co-driver [P7] or show thoughtfulness with regard to cultural backgrounds [P12]. This way, users feel less of an emotional dissonance in interaction, resulting in a more positive user experience.

Apart from these two main themes concerning the design of affective automotive user interfaces, this thesis entails methodical contributions supporting researchers with the evaluation of such systems [P1, P3, P4, P10] and a model to combine both approaches of adaptation into combined practice [P5]. This thesis does not include a distinct section collating related work apart from fundamental knowledge presented in the section *Background*. The interested reader may consult our literature review for more information on the effects of emotions on driving safety and related concepts [P13].

After presenting our main contributions, I reflect upon our work with regard to the applicability of emotion-aware interaction in combination with the assessment of cognitive influences and physical well-being and discuss in what sense the current research landscape might be restricted, e.g., through technological optimism. I further point out the dangers of empathic agents enabling user manipulation and the expected benefits of affective systems for safety improvements in automated driving.

1.2 Contributing Publications

This dissertation cumulates the findings of our research on affective automotive user interfaces based on 12 peer-reviewed publications and one publication currently under review. We illustrate the bigger picture in which our work is located and discuss its implications from a further distance than possible within the single papers. Contributing publications are marked with a prefixed [P] throughout the document and are available by following the DOIs provided below.

[P1] Michael Braun and Karina Serres. *ASAM: An Emotion Sampling Method for the Automotive Industry*. In: *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '17. ACM, 2017, pp. 230–232. DOI: 10.1145/3131726.3132044.

[P2] Michael Braun, Bastian Pfleging, and Florian Alt. *A Survey to Understand Emotional Situations on the Road and What They Mean for Affective Automotive UIs*. In: *Multimodal Technologies and Interaction*. Vol. 2. 4. MDPI, 2018. DOI: 10.3390/mti2040075.

[P3] Michael Braun, Florian Roider, Florian Alt, and Tom Gross. *Automotive Research in the Public Space: Towards Deployment-Based Prototypes For Real Users*. In: *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '18. ACM, 2018, pp. 181–185. DOI: 10.1145/3239092.3265964.

[P4] Michael Braun, Simon Weiser, Bastian Pfleging, and Florian Alt. *A Comparison of Emotion Elicitation Methods for Affective Driving Studies*. In: *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '18. ACM, 2018, pp. 77–81. DOI: 10.1145/3239092.3265945.

[P5] Michael Braun and Florian Alt. *Affective Assistants: A Matter of States and Traits*. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI EA '19. ACM, 2019, 2321:1–2321:6. DOI: 10.1145/3290607.3313051.

[P6] Michael Braun, Ronee Chadowitz, and Florian Alt. *User Experience of Driver State Visualizations: a Look at Demographics and Personalities*. In: *Human-Computer Interaction – INTERACT 2019*. Springer, 2019, pp. 158–176. DOI: 10.1007/978-3-030-29390-1_9.

[P7] Michael Braun, Anja Mainz, Ronee Chadowitz, Bastian Pfleging, and Florian Alt. *At Your Service: Designing Voice Assistant Personalities to Improve Automotive User Interfaces*. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. CHI '19. ACM, 2019, 40:1–40:11. DOI: 10.1145/3290605.3300270.

[P8] Michael Braun, Jonas Schubert, Bastian Pfleging, and Florian Alt. *Improving Driver Emotions with Affective Strategies*. In: *Multimodal Technologies and Interaction*. Vol. 3. 1. MDPI, 2019. DOI: 10.3390/mti3010021.

[P9] Mariam Hassib, Michael Braun, Bastian Pfleging, and Florian Alt. *Detecting and Influencing Driver Emotions using Psycho-physiological Sensors and Ambient Light*. In: *Human-Computer Interaction – INTERACT 2019*. Springer, 2019, pp. 721–742. DOI: 10.1007/978-3-030-29381-9_43.

[P10] Jingyi Li, Michael Braun, Andreas Butz, and Florian Alt. *Designing Emotion-aware In-car Interactions for Unlike Markets*. In: *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. AutomotiveUI '19. ACM, 2019, pp. 352–357. DOI: 10.1145/3349263.3351324.

[P11] Michael Braun and Florian Alt. *Identifying Personality Dimensions for Characters of Digital Agents*. In: *Character Computing*. Ed. by Alia El Bolock, Yomna Abdelrahman, and Slim Abdennadher. Springer, 2020, pp. 123–137. DOI: 10.1007/978-3-030-15954-2_8.

[P12] Michael Braun, Jingyi Li, Florian Weber, Bastian Pfleging, Andeas Butz, and Florian Alt. *What If Your Car Would Care? Exploring Use Cases For Affective Automotive User Interfaces*. In: *Proceedings of the 22nd International Conference on Human-Computer Interaction with Mobile Devices and Services*. MobileHCI '20. ACM, 2020. DOI: 10.1145/3379503.3403530.

[P13] Michael Braun, Florian Weber, and Florian Alt. *Affective Automotive User Interfaces – Reviewing the State of Emotion Regulation in the Car*. In: *Under Review*. 2020. eprint: https://arxiv.org/abs/2003.13731.

[P3] received the *Best Work in Progress Poster Award* at AutomotiveUI '18.

1.3 Guiding Research Questions

This thesis consists of contributions of empirical, conceptual and technical nature, structured into six main areas and associated research questions, outlined in the table below.

Empirical	Conceptual	Technical
RQ1 – Effects of Emotions: How is road safety influenced by the driver's emotional state?		
Investigation of triggers for emotional experiences while driving [P2]. Literature review on their effects on safety [P13].	Discussion of contextual triggers of emotions as motivation for affective automotive user interfaces [P2].	Driving simulation setup to allow for an assessment of driving performance in varying emotional states [P8, P9].
RQ2 – Emotion Detection: How can we automate the collection of driver state information?		
Review of related work on emotion detection. Reasoning for facial expressions as primary input channel in the car [P13].	Emotion sampling approach with adaptations for minimized distraction during driving [P1].	Prototypes detecting emotions from physiological data [P9], user sampling [P1] and facial expressions [P8, P12, P6].
RQ3 – Methodology: How can affective automotive user interfaces be assessed?		
Literature review on previously used methodologies [P13]. Comparison of emotion elicitation methods [P4].	Concept for the amalgamation of driver states and traits from various input streams inside the car [P5].	Prototype to assess affective systems with a large number of participants in a public driving simulation setup [P3].
RQ4 – Emotion Regulation: Which strategies can be used to influence the driver state?		
Review of emotion regulation in research and industry [P13]. Investigation of strategies to negotiate negative emotions and their effects on driving [P6, P8, P9].	Concept for reactive interaction based on driver states [P5]. Emotion regulation through speech interaction, visual mirroring and ambient light [P8, P9].	Implementation of emotion regulation strategies using visual mirroring, ambient lighting and voice interaction [P8, P9]. Prototypes of driver state displays [P6].
RQ5 – Emotional Interaction: How can we design meaningful affective features?		
Investigation of the design space for digital characters [P11]. Requirement workshops with future users from different cultural backgrounds [P10].	Concept for adaptive systems with regard to driver traits [P5]. Discussion of cultural influences on the design of affective features [P12, P10].	Design space for digital assistant characters [P11]. Inclusion of users from different cultural groups into an iterative design process [P10].
RQ6 – User Experience: How can affective user interfaces improve the driving experience?		
Investigation of the effects of voice assistant character adaptation on trust, acceptance and user experience [P7]. Intercultural assessment of acceptance and UX of emotional interaction [P12].	Recommendations for the market introduction of affective automotive user interfaces [P12]. Insights on the criticality of context for emotional interaction in real traffic scenarios [P7].	In-car prototype of an adaptive voice assistant based on the user's personality [P7]. Prototypical implementation of a set of use cases for affective interaction in the car [P12].

Table 1.1: Overview of the research questions and associated contributions amounting to this thesis.

1.4 Research Approach

In this section we describe our operating principles for the exploration and design of affective in-car systems. Our overarching research approach follows a design thinking process [38] and the guidelines for user-centered design as defined in ISO 9241-210 [15]. This entails an iterative process of problem definition, needfinding, benchmarking, ideation, prototyping and testing in active exchange with real users and necessary stakeholders [15, 38]. The section *Background* represents the initial problem definition and needfinding process motivating the design of affective automotive user interfaces. The benchmarking consists of a literature review on previously conducted research on the topic [P13] and our contributions to research methods described in the section *Methodology*. There, we focus on methods for working with emotions, e.g., sampling and inducing lifelike emotional states with users, and methods for the design of affective systems in a user-centered setup, e.g., through intercultural workshops or publicly accessible driving simulator studies.

The main sections *Promoting Safe Behavior* and *Improving User Experience* both incorporate redefinitions of the problems and design spaces according to our understanding at the time, followed by phases of ideation, prototyping, and user testing. The projects were not necessarily conducted in the structural order they are presented in, as a clear vision of our work's main themes emerged during the research itself. We also substantially abridged the contributing publications. Thus some aspects of our design process, e.g., early iterations and prototypes, are not being reported within this thesis but can be looked up in the respective papers.

Empirical Research Methods

The most important part of user-centered design is the collection of feedback from users throughout the process. We attached importance to using viable feedback methods in hands-on environments, ensuring realistic experiences and thus more valuable insights from our users. We used investigative research techniques to inform initial designs and formative studies to iterate upon our systems [2]. All our system evaluations were conducted with interactive prototypes in the car, either on the road or in driving simulation setups, if interacting with the system while driving could have caused distracting effects. We relied on quantitative and qualitative data collection methods to assess these prototypes.

Research Settings We incorporated different research settings depending on the requirements on each study. Our start into any topic consisted of reviewing related literature for a basic understanding and to identify open research questions. We did this for the vast majority of publications and especially for the model of affective automotive user interfaces [P5] and our overarching literature review on emotion regulation in the car [P13]. In one project, we used an online study to learn about drivers' experiences with emotions on the road [P2]. We also collected user feedback on early system designs using an online community setup [P6]. Both online settings allowed us to recruit participants from overseas and compare input from different communities. Furthermore, we conducted several lab studies for fundamental questions on emotional interaction and emotion regulation [P4, P11]. Lab studies are important tools to quickly test basic assumptions where the interaction frame of the car interior is not required. We also experienced in-car assessments without a driving task as valuable tool to get hands-on feedback from participants for use cases that require their full attention [P12]. Another application of lab studies are design workshops, which we relied on to ideate use case concepts [P10].

Driving simulations are used to evaluate in-car user interfaces which may potentially have negative effects on driving performance or safety. Especially investigations on emotion regulation techniques are required to take these precautions because they usually entail the prior elicitation of emotions, which can have equally negative effects on safety as visual distraction [P6, P8, P9]. We used visual stimuli [P9] and autobiographical recollection [P8] to elicit emotional states in our research, as shown most effective in our comparison of induction techniques [P4].

Less distracting interface prototypes, e.g., auditory interfaces without GUI representation could be tested in real traffic, which allows us to incorporate more natural driving tasks [P7]. We further applied ideation methodology into the setting of a driving car with car-storming sessions [P10]. This workshop style technique allows for direct inspiration through traffic events in a constantly changing scenery. The approach was used to improve existing ideas and ideate culturally specific adaptations regarding live examples occurring along the way.

Prototyping We realized all our concepts as interactive prototypes with as much functional implementation as appropriate for an evaluation of future systems. This means that we applied mature technologies like touch interfaces and text-to-speech frameworks with rather experimental features like facial expression detection. Additionally, we made use of the Wizard of Oz paradigm to simulate system intelligence in some prototypes, as a human operator can interact more naturally than current decision-based systems, resulting in better flexibility while limiting implementation overhead [31]. Our prototypes are based on various technology stacks, ranging from simple click dummies with audio feedback [P11] over deployable Wizard of Oz interfaces for remote experimenters [P7, P8, P12] to distributable software packages with additional connectivity features [P1, P6]. Prototypes incorporating emotion detection through facial expression analysis are implemented using the Affdex SDK, providing metric expressions of dimensional emotion evaluations [33].

Data Collection Qualitative feedback to interaction often tells a story about the participant's personal understanding of systems, which does not necessarily need to correspond to the actual technology behind the system. This can help us design better interfaces and prioritize features. We conducted interviews regarding users' observations and experiences in all of our studies [P2, P7, P8, P9, P10, P11, P12]. Questionnaires allow us to query subjective evaluations, e.g., regarding perceived workload, user experience, but also general information like demographics. We also used questionnaires to assess subjective information in all our studies [P2, P7, P8, P9, P10, P11, P12]. Additionally, we relied on information gathered through emotion sampling [P9] and objective data on the user's behavior when interacting with systems, including driving performance records [P8, P9] and the analysis of facial expressions [P6, P7] and psycho-physiological data [P8, P9].

Participants We recruited participants from different sources, depending on the type of study. Early prototype concepts were evaluated with limited sample sizes and with participants recruited among university students [P4] or BMW employees [P8, P9, P11]. Working with employees makes it easier to show new concepts from an information security standpoint and provides insurance for real driving studies. We also used academic newsletters and car enthusiast forums for answers on more general questions [P2, P4]. For the further assessment of refined prototypes, we insisted on evaluations by real users with a focus on premium customers from the main automotive markets Germany, USA and China [P6, P10, P12]. This market segment will most likely be the first to receive updates for affective features and these three countries represent the biggest markets for premium cars.

Research Context

I had the immense pleasure to conduct my doctoral research in residence at the BMW Group Department for Research, New Technologies, Innovations in very close cooperation with the LMU Munich Chair of Media Informatics. All simulator studies were conducted at the BMW Driving Simulation Center in Munich and all lab studies at the BMW Research Campus in Garching, except for a public project at Joseph's Innovation Lab in Nuremberg [P6] and a replication study at the BMW Tech Office in Shanghai [P12]. All project expenses and my stipend were funded by the BMW Group.

Many projects in this time were realized in cooperation with researchers from other institutions. Next to the already mentioned organizations, I also collaborated with my peers at the CARISSMA Research Center at TH Ingolstadt, the CODE Research Institute at the Bundeswehr University, the Department of Industrial Design at TU Eindhoven, the DLR Institute of Transportation Systems, the Fraunhofer Institutes for Industrial Engineering IAO and Integrated Circuits IIS, and Spiegel Institut.

I received great support from these excellent people, for which I am very grateful.

2
Background

This chapter conveys background information on the fundamental concepts facilitating emotion-aware systems and motivates their adaptation to in-car environments in the sense of a needfinding process in design thinking theory [38]. We keep this introduction to the topic brief in the name of clarity. An extensive overview of related work can be found in our literature review [P13].

2.1 Concepts Of Human Emotion

There are various popular opinions on the definition of emotions and their role in interaction and interpersonal communication. Generally, emotions are characterized as positive or negative responses accompanied by distinct patterns of conscious or unconscious psycho-physiological activity [14]. Classical theorists describe emotions as evolutionary endowed mental reactions with relevance to outside events, bodily movements, cognition, feelings and behavior [14]. They are thought to be dictated by our genes but allow for individual variability as they are contingent on appraisal [16]. Research often assumes six basic emotions when working with categories [14], or organizes them continuously within the dimensions of valence and arousal [41].

A more recent school of thought considers the determination of emotional reactions a misconception. They argue emotions are constructed from the memories of previous experiences and inherent knowledge about core emotions [6]. While these concepts are not so disparate at first sight, they have different implications for affective sciences: natural emotions are thought to be objectively recognizable, which would not be the case if they were a product of intent [6].

In this work, we assume that a majority of humans are capable of feeling the six basic emotions of fear, anger, joy, sadness, disgust and surprise [14] and that they are connected to common physiological and behavioral patterns. In our understanding, categorical emotions can be arranged within the dimensional model by Russell, consisting of valence (unpleasant – pleasant) and arousal (deactivated – activated) [41]. Extreme anger, for example, would be classified as unpleasant and highly activated.

2.2 Automotive Environments

The human-machine interface (HMI) in cars allows users to control functions related to driving, adjust car controls, and consume entertainment contents. During manual driving, interacting with an HMI can distract the driver or increase their cognitive load to a level where situational awareness and driving performance are harmfully impaired [39]. Thus, the goal of research on automotive user interfaces is “to design systems that make driving safer while providing for the users’ needs” [42].

Automotive UIs are enabled by official standards, for example a set of principles for ergonomic audio-visual interfaces defined in ISO 15005-15008, and evaluation guidelines by institutions such as the Alliance of Automobile Manufacturers, the Society of Automotive Engineers, or the Commission of the European Union [39]. They include requirements for visual demand and maximum allowable task times which can be used for usability tests and exemption of liability. In recent developments, automotive UIs include more and more additional input modalities like speech, gaze, gestures as well as the driver state. This allows for a distribution of workload to the best fitting input (and output) channels but might also introduce additional sources of distraction.

At the time of writing, cars are still largely operated by human drivers. Automotive UIs in fully autonomous vehicles will likely have to live up to different standards and might provide new opportunities. For now, we are working with manual and partly automated systems, which require an operator to be accountable and focussed, at least for certain periods of the ride.

2.3 Emotions While Driving

The emotional state of the driver can influence driving performance and safe behavior. Our analysis of related work shows that angry driving correlates with aggressiveness, increased reaction times, impaired risk perception and road element localization, higher subjective workload, lower subjective safety levels and a raised willingness to take risks [P13]. Other basic emotions with negative valence, like sadness and fear, as well as extreme forms of happiness, are also connected to forms of unsafe driving, while a medium level of arousal is widely seen as the sweet spot for performance [11, 54]. We establish a driver state model which depicts these relationships in a two-dimensional framework [P5]. Figure 2.1 visualizes a safe driver state at medium arousal and positive valence.

Figure 2.1: Driver state model putting safe driving at medium levels of arousal and positive valence [P5]. One aim of affective automotive UIs is to restore a safe driver state through means of emotion regulation.

To tackle the problem of emotional influences on driving, we need to also understand where emotions come from. Negative emotional states while driving can oftentimes be credited to driving-related events like traffic, (near) accidents and rude drivers, while positive emotions are mostly due to enjoying the scenery or driving experience, media consumption and social interaction [P2]. We must admit that contextual triggers like traffic are often beyond our control. However, if they cannot be avoided in the first place, they might be compensated for once they appear.

2.4 Emotion Detection

It is supposed that affect regulation techniques can be used to mitigate the severity of emotional experiences and their effects on driving [26]. For this to become reality, we ought to assume a direct connection between emotions and observable bodily reactions [6]. There exist a myriad of approaches for the automated detection of emotions, e.g., by analysis of physiological responses, facial expressions or speech, which we summarize in more detail in our literature review [P13]. The car provides a great environment for such systems, as the user is confined to a still position within a limited space, making them easily observable. In our work, we implement emotion detection by the use of facial expression recognition. This method is currently our first choice in the car, as it is contactless – as opposed to physiological sensing – and works with a continuous information stream – as opposed to speech analysis [52]. We also incorporate subjective measures of emotion, which are further expanded on in the chapter *Emotion Sampling*. Future systems are expected to fuse input from multiple sensors in order to provide more robust solutions for emotion detection in the car.

2.5 Emotion Regulation

The data derived from emotion detection enables an affective driver-vehicle interaction loop [40]. Such systems aim to sense potentially dangerous states and interact with the user with the goal of reinstating safe behavior. There are three basic levels of emotion regulation approaches.

Raising Awareness. The most basic application of affect recognition is displaying the data. Picard envisions wearable feedback systems to allow for self-reflection and communication of emotions [37]. In the car, we can also think of mirroring the users's state visually or to deploy interventions in dangerous states. These could, e.g., motivate the driver to engage in ways to calm down on their own.

Implicit Cues. Modern cars already come with plenty modalities to craft atmosphere in the interior. Affect regulation systems can use these features to set an environment which influences the user implicitly, e.g., by means of ambient light, temperature control or adaptive music playback [P13].

Natural Interaction. Finally, we can adapt interpersonal behavior into the interaction approach. Humans are great at empathizing with each other and twisting narratives. A digital agent aiming to regulate the user's affective state could converse with them in natural language and get to the bottom of their emotions. It could also provide grounding or reappraisal when users get unproportionally agitated over situations [18].

We provide a more in-depth overview of emotion regulation approaches in our literature review [P13].

2.6 User Experience

When we interact with digital systems, we assign them certain characteristics and qualities. Our approach to the perception of user experience is based on the dimensions of hedonic and pragmatic quality [19]. Pragmatic quality specifies instrumental properties regarding usability and effectiveness, while hedonic quality concerns the attractiveness and appeal of a product. The final evaluative component of user experience is the emotional perception resulting from both types of qualities [48].

We extend the initial scope of affective user interfaces from sensing and reacting to emotions with the goal to evoke emotions in the user. Picard suggests that affect recognition can be used to understand the perception of aesthetics [37] – we argue that synthesizing emotional interaction can vice versa improve the hedonic qualities of products. In the context of the car this means that user interfaces can adapt to the driver and the situation in order to simultaneously optimize joy and safety-relevant aspects, and thus improve the driving experience [43].

2.7 Distinction Of Themes

Our understanding of affective automotive user interfaces entails two pillars of interaction, which can be combined into a joint product but initially serve disparate goals and use different methods to achieve them. Our contributions to both themes are illustrated in the sections *Promoting Safe Behavior* and *Improving User Experience*.

Promoting Safe Behavior Through Emotion Regulation

The first theme is anchored within the safety-critical functions of automotive UIs. We envision emotion-awareness as a safety feature which can detect if a driver is unfit or in need of support. The propagation of robust emotion detection technology is a basic prerequisite for this vision to become reality. These systems are reactive in behavior, meaning they can only act if triggered. The triggers, however, might be of explicit or implicit nature.

Improving User Experience With Emotional Interaction

The second theme has its roots in user experience design. Systems capable of adapting to the user's preferences and traits in order to create an emotionally satisfactory user experience do not require the input of emotion detection. They rather create value through general knowledge about the user and the output they generate. For this, naturalistic interaction technologies like speech synthesis can be used. Emotionally interactive systems can act proactively, embodying a digital co-driver that supports the user at having a good time.

3 Affective Automotive User Interfaces

Affective automotive user interfaces promote safe driving behavior through emotion regulation and improve the user experience of in-car HMI by enhancing interaction with emotion.

Definition

This chapter presents our contributions to the field of affective automotive user interfaces, which we define as stated above. It is structured into three contribution areas : 1) the *Methodology* we developed out of necessity for appropriate research tools, 2) an investigation of emotion regulation techniques with the goal of *Promoting Safe Behavior* and 3) concepts aimed at *Improving User Experience* by emotionalizing interaction in the car. We outline concepts, challenges and results of our research in distilled form. For further details we refer to the respective publications.

3.1 Methodology

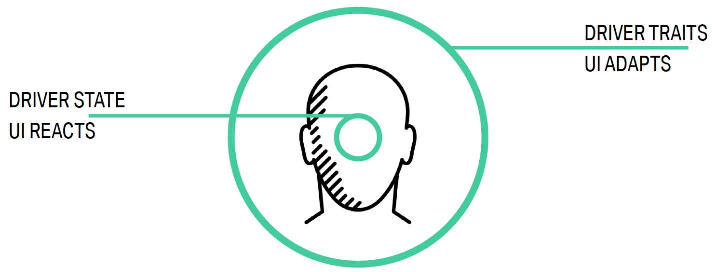

Figure 3.1: Affective UIs can adapt to time-stable user traits and react to fluctuating user states [P5].

Affective user interfaces are by definition reactive to the user's emotions. In our understanding, they can also adapt to other features to achieve emotionally valuable interaction. We present a model for affective UIs which is based on inter- and intraindividual differences that describe drivers of stability and change in human behavior [P5]. The model considers permanent preferences and traits of users, to which a system can adapt to in the long term by collecting knowledge, and temporary user states, which a system can react to spontaneously to improve the situation. Traits are free of situational or interactional effects and can consist of demographic information, cultural affiliation, personality, and more [46]. States are situational or interactional components which changes rapidly, eintailing emotions, cognitive load, distraction, physical condition, and so on [46]. Figure 3.1 illustrates the two aspects visually. This understanding of the user pervades all our work with varying focus on either reaction or adaptation. Our vision combines both aspects into one system. In the following section we provide methodical contributions of our own regarding research on emotion-aware, as well as adaptive emotional user interfaces in automotive environments.

3.1.1 Working With Emotions

Affective systems intend a feedback loop between user emotions and system behavior. With the current technological state of emotion detection, it is often wise to eliminate the uncertain outcomes of such prototypes. In this research, we use emotion sampling and emotion elicitation methods to control for input and output variables we assume as solved by technological progress in the foreseeable future.

There exist several approaches to the understanding of emotions. The driver state model presented in Figure 2.1 is based on the circumplex model by Russell [41], which provides a good theoretical tool to classify emotions from behavior. Ekman's categorical model [14], though lacking in subtleties, has its benefits because it is easily understood by anybody. It makes for, example, more sense to instruct participants to think back to a moment of anger than to a memory of high arousal and low valence, just because the concept is easier to grasp. User-centered research on affective systems thus often works with the categorical model or hybrids of both.

Emotion Sampling

One method to anticipate automated emotion detection is the sampling of subjective feedback. We used two different methods depending on the limitations given by the study design. In settings where the user was primed into a categorical basic emotion, we can use simple scales to query the intensity of that emotion. Offering an auditory scale with vocal feedback and timing the inquiry to sections without further stimuli can prevent an overabundance of cognitive load and the connected decrease in driving performance during driving studies, as used in [P8].

Settings without narrow emotional priming require a more versatile approach of emotion sampling. For this, the circumplex model is more appropriate than categorical emotions. Previously available tools bring two main problems with them: firstly, examiners need to explain arousal and valence to participants, which requires time and often caused comprehension problems in the past. Secondly, existing questionnaires are based on segmented scales, which introduce visual distraction on a level unsuitable for driving studies [9]. We designed the *Automotive Self-Assessment Method (ASAM)* as a tool to sample emotions without requiring long explanations and limited visual distraction [P1]. The system consists of an interface with two sliders and a representation of the input as emoticon. Users get feedback of their input through a calm and easy to understand visualization, reducing visual distraction from the driving task compared to existing approaches. Both approaches are optimized for the use in simulated driving experiments. Auditory sampling is also frequently used in real driving studies [44], while the visual interface would first require an assessment of liability.

Eliciting Emotions

Many of the emotion regulation approaches from related work are only applicable for certain emotional states and not for others. For example, interventions with calming effects might be appropriate when drivers are upset but not when they are fatigued. It is important to be able to induce emotions in a controlled manner to evaluate these approaches. There are a number of methodologies to elicit emotions which we analyzed for best fit in a driving environment [P4]. Our research shows that *Autobiographical Recollection* as introduced by Baker & Guttfreund [5] has the highest impact on emotional involvement, as it is based on personal experiences. For this elicitation technique, participants are tasked with thinking themselves back into a situation where they strongly felt the required emotion and write it down. They then narrate the scene with the goal of reviving the intended emotional state. Emotions induced this way last approximately 5 ± 3 minutes, which can be prolonged by playback of adequate music. Other approaches like emotional images, music videos or film fragments have shown to induce weaker emotions for briefer periods of time. Autobiographical recollection can also be utilized while driving to renew the stimuli, as it requires no visual input. The main drawbacks of this technique are the intimacy of the narrated story, which requires a secure environment and trust towards the operator, and the potentially harmful reactions of participants when uncovering personal traumata. This needs to be avoided and, if necessary, dealt with conscientiously. We want to underline that none of these methods are appropriate to use in real traffic because of their implications for road safety. Experiments utilizing elicitation of potentially dangerous driver states are to be conducted in simulated driving environments only.

3.1.2 Adapting To The User

We state above that our understanding of affective systems does not only include emotion-awareness but also any other kind of interface allowing for interaction which can be considered emotional or adaptive to the context of emotions. Affective systems are, thus, a specification of adaptive user interfaces as they incorporate the variability in user behavior into their design [10]. We contribute methodological considerations regarding the design of adaptive digital characters, adaptivity towards cultural peculiarities and the deployment of prototypes in order to reach heterogenous user samples.

Designing Digital Characters

One plausible application area for adaptive UIs with impacts on emotional experience are digital agents. An in-car speech assistant could, for example, adapt its character to the user's personality. We investigate a design approach to identify dimensions for assistant personalities inspired by characters from popular media [P11]. Users interacted with characters whose typical behaviors spread among Argyle's model of attitudes towards others, from dominant to submissive and hostile to friendly [3].

Our work identifies truthful representation of intelligence and skills as a hard requirement for characters of digital agents. Recognition of stereotypical behaviors from friends or public figures had positive influences on the evaluation and humorist remarks polarized heavily without real positive effects. Two dimensions showed to be the most promising adjusting levers for character design of in-car assistants: Firstly, the balance of power between assistant and user was accepted from subordinate to an equivalent status. Characters which were assessed as condescending or arrogant, however, were rated as inappropriate. Secondly, the varying relational levels between user and assistant were accepted in all designs, yet it received heterogenous feedback. This means that the spectrum spanning from very casual to highly formal is applicable but dependent on the user. This two-dimensional model – ranging from equivalent to subordinate and from casual to formal [P11] – is further used to adapt an assistant's character to the user's personality within our research on affective systems.

Considering Cultures

We further investigate how to design affective systems with adaptation to cultural backgrounds. Much of the research in the field comes from industrialized regions in the west. Yet the significance of emotions in interpersonal interaction is very different among regions. Furthermore, cultural differences as postulated in Hofstede's cultural dimensions [21] have long been shown to influence requirements for user interfaces, calling for culturally sensitive design methods [20]. We introduce an iterative method consisting of several workshops with users from different cultural backgrounds, consisting of ideation phases, an evaluation of requirements while driving in car-storming sessions, and iterative improvements with respect to the different conditions identified [P10]. We used this method to define initial application areas for affective automotive UIs with Chinese and German participants.

Testing With Real Users

Designing for adaptivity means incorporating uncertain variability of user behavior into our designs. In order to assess such adaptive UIs, we need to define the expectable variance in advance – or recruit a highly diverse sample group to provide a wide spread in behavior. We put the latter approach into practice with a public driving simulator setup for unsupervised studies with high participant throughput [P3]. The deployment serves as an effective method to collect feedback from hands-on, first contact interactions. By positioning our research tools in the public space, we open up our sample pool to potential users from all demographic backgrounds and account for high variability in driving experience, brand loyalty, personality types, and much more.

Public deployment also contains challenges which are not to be expected in the lab. Prototypes need to be built very sturdy to handle the wear and tear of high user volumes. Tasks have to be appealing in order to attract participants and easy to understand without introduction. We also experienced a varying level of data quality, which requires more complex analysis [P3]. The approach comes with increased complexity that must be justified with research questions investigating issues concerning behavioral variance across all demographics.

> **Summary of *Methodology***
>
> We contribute a set of methods facilitating research on affective automotive user interfaces. Our understanding of emotions and the techniques we introduce to sample and elicit emotional states are evolutions of recognized knowledge, specialized for usage while driving or in driving simulations. We further provide procedures to enable emotionally adaptive systems in the form of adaptive digital characters and an approach for the culturally sensitive design of affective systems. Furthermore, we propose an experiment setup in the public space to assess affective systems with big sample groups and realistic behavioral variance.

3.2 Promoting Safe Behavior

The data stream of emotion detection technologies provides affective systems with the input required to sense potentially dangerous states. They can then interact with the user in order to reinstate safe driving behavior. Such strategies used to influence components of emotional responses are defined as emotion regulation techniques [16]. They vary depending on the initial state of the user and the projected goal, e.g., whether up- or down-regulation is intended [8]. Our literature review elaborates in more depth on related work and application examples [P13]. This section presents our contributions to regulation approaches using implicit cues, raising awareness by mirroring the user state and empathizing with the user through natural interaction, as introduced in the section *Emotion Regulation*.

Challenges of Emotion Regulation

Digital systems with emotion-awareness need to overcome a set of challenges before they can be applied to the driving environment. The current state of emotion detection technology contains plausible proof of the concept but for affective systems to interfere in real driving situations we need more precision than possible with current applications. Instead of analyzing explicit expressions, which can be influenced by humans, the focus should shift onto subconsciously emitted micro expressions, which are, however, much more complex to detect [P13]. We are, furthermore, waiting to see robust approaches of sensor fusion working with posture, mimics, phonetics, semantics and psycho-physiological data.

Our work primarily deals with emotions, though we are aware of the impact other driver states can have on safe behavior. Cognitive demand and physiological activities, for example, can have a toll on the driver similarly to emotions [44]. Future research would benefit from models which incorporate different manifestations of the driver's condition for more sophisticated affective systems. Additionally, we need to take into account that users might show reactance towards outside interference in their personal affairs or experience system propositions as paternalistic [P8].

Opportunities for Promoting Safe Behavior

Emotion regulation approaches can achieve a considerable improvement in road safety by influencing drivers to keep calm in potentially aggravating situations [26]. They can mellow the driver in highly energetic states or when they feel flustered and activate them when they are displaying low energy. We also see emotion regulation as a beneficial tool for use in semi-automated vehicles. That is, when drivers can delegate control over driving for a period of time but need to get back to full awareness in case of take-over requests. Emotion regulation techniques could be used to prepare the driver for take-over, especially in planned routes where the system knows well in advance.

3.2.1 Implicitly Influencing The User

Our contribution to emotion regulation through implicit cues is based on adaptive ambient lighting. Previous work by Spiridon & Fairclough suggests calming effects of blue light on angry drivers, however only when they were primed beforehand [45]. Research in aviation shows that ambient lighting can also be used effectively to influence the circadian rhythm of passengers and reduce discomfort and jet-lag in long-distance flights [29]. This is already in production in commercial airliners like the

Airbus A350 and the Boeing 787 [4]. Our application aims at regulating negative driver emotions with ambient light cues, which we evaluated in two user studies with separate prototypes [P8, P9].

With the first prototype we present a concept to detect driver emotions using psycho-physiological data in order to implicitly influence drivers once they are classified in a low valence state [P9]. Ambient lighting in blue and orange color tones was used as regulating stimulus without a priori information about their meaning. The system provided subtle visuals through an LED stripe placed over the whole width of the car in the windshield's stem area. Both color stimuli concurred with improved lane keeping compared to baseline. However, participants described the orange light as rather alerting, while blue light was perceived as calming. In direct comparison, users performed better in the driving task with the orange stimuli, which they classified as an awareness cue that becomes uncomfortable over time. The blue light had the further effect of reducing the heart rate of the driver, adding evidence for a more relaxing atmosphere.

The second prototype also focussed on low valence situations. It implemented a blue light stimulus supposed to calm down drivers in low valence and high arousal (induced as anger) and a green-yellow tint aimed at activating participants in low valence and low arousal (induced as sadness) [P8]. In this study, ambient lighting was not connected with an improvement of driving performance. The data rather suggests increased lateral deviations for both approaches, however, within the limits of the norm. We can also report an effect on facial expressions of positive emotions, which increased for participants experiencing the green-yellow activation light. Participants overall assessed the feature as desirable in combination with more active interaction approaches but not as a standalone approach.

We conclude from these two studies that ambient lighting can have positive effects on the emotional state of drivers. We show that light colors have dissimilar properties: orange/red lighting had an alerting effect on drivers, green/yellow lighting was perceived as activating and blue lighting created a relaxing atmosphere. These effects were evident in tendencies and with limited concrete proof of positive effects on driving performance. Thus, we cannot envision this form of implicit cues as a standalone application of emotion regulation. It is most likely rather suitable to support other approaches by adapting the general ambiance.

3.2.2 Mirroring The User State

Another approach to regulate emotions are explicit driver state displays, the foundations of which were set at the MIT AwareCar project [12]. We carried on with their initial ideas of displaying detected driver states to allow for self-reflexive improvements on driving safety. Related work by Völkel et al. informs us that progressive indication of the state with notifications in safety-critical situations seems to be a promising approach [51]. We contribute studies with users from Germany, the US and China, investigating GUI implementations [P6] and the acceptance of driver state displays [P12, P8].

At the outset of our research on driver state displays we conducted a workshop with drivers from the US and Germany to identify general requirements for acceptance. Users were less concerned about the visualization itself and more about the topics of data security and paternalism [P6]. Especially the impression of being told how they feel resonated rather negatively among participants. Our first approach for an acceptable driver state display following these insights consisted of a representation using emoticons. We figured a less technical representation could work well at inspiring users to reflect upon their state without appearing patronizing. We compared the visual feedback with the previously introduced approach of ambient lighting and an empathic speech agent in the driving simulator [P8]. The concept was not accepted well by users. Participants gave to record that the emoticon rather amplified their negative emotions or seemed silly. The general idea of a driver state display, however, was rated as promising if implemented differently. This extends our understanding of the requirement for continuous driver state displays insofar as negative representations might have to be avoided.

We then came up with three possible graphical implementations which we tested with a facial analysis feedback channel in a public simulator setting [P3]. The concepts incorporated 1) a continuous display of emotion levels, 2) notifications kindly hinting at detected negative emotions and 3) a gamified approach allowing to boost the "fun level" by smiling. All implementations were accepted by the users with a preference for the continuous display. Notifications worked most effectively in improving the user's facial expression of positive emotions. Participants also noted that an inclusion of health-related data would be of value [P6].

With these insights on the design of driver state displays, we conducted an evaluation of a continuous GUI in comparison with multiple other affective use cases [P12]. The study itself is described in more detail in the section *Designing Desirable Features*. In this comparative research approach, driver state displays were rated as intrusive and unprofessional, especially with other passengers inside the car. Some users, however, wished for a passenger state display so they could provide for the well-being of family and friends along the ride.

The bottom line of our research on driver state displays is that the anticipated problem of paternalism can be tackled with unintrusive visualizations, which afford self-reflection instead of cautioning the user. The main issue, however, turned out to be acceptance in social situations. Many drivers did not see an advantage in having their current state displayed and found the system to breach boundaries by giving others access to their personal data [P12]. We thus recommend to offer optional visualizations for an overview of all occupants' states instead of a continuous driver state display.

3.2.3 Empathizing With The User

The third approach to emotion regulation we investigate is empathic speech interaction with a digital voice assistant. Nass et al. first introduced emotional voice interaction to the driving context [34]. Their findings suggest promising improvements regarding accident rate, attention to the road and even openness towards interacting with the system when the voice assistant's expression of emotions fit the driver state. Harris & Nass later extended this work by influencing drivers to reevaluate situations through spoken reappraisal, which led to improved driving performance and less negative emotions than in neutral interaction [18]. We continue this approach by building a speech assistant that empathizes with users to improve their emotional state.

Our contribution incorporates proactive spoken recommendations to engage the user in a dialog when negative emotional states are detected. The system empathizes with the user by relating to seemingly personal experience, stating it understands how the user feels. It then offers some minor activity like turning on the radio to get their mind off what is causing negative emotions. We evaluated the system in comparison with a non-empathic recommender with the same pragmatic functionality, as well as with the aforementioned concepts of ambient lighting and visual representation [P8]. Speech interaction understandably caused an increase of auditory workload but the empathic assistant could in return decrease subjective ratings of cognitive load. Measures of facial emotion expression were also affected positively, as well as self-reported joy of use. Participants preferred the empathic assistant over all other emotion regulation techniques.

Empathic voice interaction turns out to be an effective means of emotion regulation. Both subjective and objective measures show advantages over ambient light and visual mirroring. Participants also did not perceive the interaction as patronizing, although the system made use of recommendations.

Summary of *Promoting Safe Behavior*

Within this thesis, we contribute several experimental investigations of emotion regulation techniques towards the advancement of affective automotive user interfaces. Latent manipulation through implicit cues like ambient lighting showed weak effects which differed dependent on the used colors. Visual feedback was not accepted by users due to a lack of compatibility in social situations and privacy concerns. Emotion-aware speech interaction, however, was accepted very well and was not perceived as paternalizing.

While the realization of emotion regulation currently lacks reliable emotion detection and an integrating understanding of the interplay between emotions and other driver states, we see enticing opportunities for affective systems using empathic speech interaction to regulate driver emotions in manual and semi-automated driving.

3.3 Improving User Experience

In this section, we outline our efforts towards the design of automotive user interfaces incorporating affective interaction in order to improve the experience of the driver. In contrast to usability engineering, where the focus lies on removing instrumental problems and avoiding frustration in the use of a product [19], our approach to the design of new features follows the overarching goal of adapting to the user to actively facilitate a more positive kind of interaction. We rely on the previously introduced definition of *User Experience* consisting of pragmatic and hedonic qualities and the resulting emotional evaluation. The systems we envision do not necessarily require emotion detection technology but rather create an emotional experience by adapting to the user like a human co-driver would do, corresponding to our model for affective systems visualized in Figure 3.1.

Challenges of Emotional Interaction

Our work faces challenges inherent to any experience design process. If we aimed at optimizing task completion times or eye glance durations of a button press, we could easily deduct the necessary actions as increasing the target size, positioning the button within the field of view and so forth. But what if we want the driver to enjoy pressing the button? We have little choice but to build the interaction first and experimentally identify the proper adjustments in the process. We are moreover confronted with the fact that cars are being interacted with everywhere in the world. Thus, future users can come from backgrounds with varying social conventions and myriads of nuances regarding emotions and their expression in social settings, which frequently take place while driving.

Opportunities for Improving User Experience

Emotionally interactive systems are no dreams of the future. Many digital products already implement characteristic interaction styles, including emotions, to define their brand. Especially natural and conversational user interfaces, as currently popularized through digital voice assistants, increasingly incorporate humanization and delightful tidbits in interaction [32]. The contemporary tech stack used for these systems allows us to understand user intents and synthesize and modulate human speech. We can, thus, create natural user interfaces that allow for emotional experiences analogous to a driver-passenger situation. We are the first to explore a wide range of affective user interfaces in an in-car environment. From this we identify promising approaches for a timely realization of such systems with real user value.

3.3.1 Adapting Natural Interaction

Digital voice assistants are currently the most predominant representatives of natural user interfaces. They are widely used in mobile applications and are advancing more and more into automotive UIs. The characters of digital assistants are usually designed to reflect the brand image of the enclosing system, e.g., Apple's Siri and Google Assistant. We think the character could be adapted to improve the user experience of interacting with the system. Nass et al. have previously worked on personality adaptation and they state that people prefer to interact with alike personalities [35]. We build upon this similarity-attraction hypothesis and the personality dimensions we identified based on the work of Argyle [3], as described in the section *Designing Digital Characters*.

In our work, we focus on the the balance of power between assistant and user in a range from subordinate to equivalent and their relational level in a range from casual to formal [P11]. We contribute insights from a driving study in real traffic with four assistant personalities in comparison with a baseline character [P7]. Personalized assistant characters were trusted more than the default and non-fitting user-assistant matches. Subjective user experience evaluations also showed matched characters as most likable and inverted assignments as unappealing. Adaptive characters showed no benefit on usefulness or satisfaction. However, mismatched personalities were reported as significantly less useful and less satisfying than the baseline and personalized assistants. All characters were rated as suitable for automotive UIs regarding the induced workload.

Participants considered the display of personality most appropriate in situations with less driving-related activity and for functionalities that are not time sensitive, like controlling distant IoT devices. From this, we derive the requirement for context-aware adaptation, as driving-related information needs to be presented in precise language without an abundance of stylistic or emotional expressions. We also found that implicit adaptation to the user's personality is more prone to produce mismatches than explicit choices made by the user, which hence are to be preferred.

Digital assistants in the car act as virtual co-drivers and can, thus, contribute to a positive atmosphere but also cause dismay or distract the driver. The user should therefore always be in charge of enabling or disabling the assistant. We also see advantages in user-initiated adaptation of the assistant's behavior, for example by telling them to stop the chit chat. As novice users of digital systems usually delay personalization, the assistant should to some extent also take the initiative to adapt itself incrementally. This requires technology to derive preferences or user traits from behavior. Furthermore, we see the increase in automation as favorable factor for personalized natural interaction, as it provides more time for secondary tasks. In-car assistants could in this case help to optimize situational awareness to prepare for take-over requests.

3.3.2 Interacting In Cultural Contexts

The systems we introduce into cars are going to be used by customers from all over the world. This presents challenges for the design of affective user interfaces, as emotions are dealt with differently from society to society [7]. We investigate cultural influences on emotional interaction for German and Chinese users, as the two regions stand for cultures with disparate values within Hofstede's cultural dimensions [21] and at the same time represent a big share of the global car market. The German culture is known as rather individualistic with moderate power structures, while the Chinese culture is seen as rather collectivist and acceptant of hierarchies [21]. Inter-personal interaction in China is based on high-context cues, meaning, e.g., tone of voice and body language are necessary to fully understand the meaning of language [17]. This means emotions are often hidden behind behavioral signals. In low-context cultures, like Germany, the spoken words communicate all the information intended, including emotional evaluations [17]. Related work further states Germans value functionality over prestige and rather aim for personal satisfaction, while Chinese users place a high importance on the appearance of products and prioritize their family before themselves [28].

The goal of designing affective user interfaces with cultural characteristics in mind led us to apply a user-centered design approach with German and Chinese users [P10]. The method is described in detail in the section *Considering Cultures*. We found that both user groups were open towards emotional interaction in the car but Germans were generally more skeptical regarding the benefits and feasibility of the technology [P12]. Differences in subjective feedback can be brought into connection with the theory of high- and low-context cultures [17]. Chinese participants stressed the concepts of three generations in one car as an important use case which was not addressed at all by German participants [P10]. Chinese participants in the car-storming sessions also highlighted differences in infrastructure, traffic rules and the way people drive as reasons for a different self-understanding of drivers in China [P10]. As an example they mentioned that pedestrians are expected to give way for cars and that in traffic the bigger car usually gets the right of way. We further learned that the importance of power structures in China is reflected as a sense of responsibility by the drivers towards the well-being of their passengers [P12]. Germans were less enthused by social media integrations of affective technology than Chinese users, yet they were more open towards sharing their personal data with the manufacturer to provide affective features [P12]. Here, again, the social collectivism of Chinese culture is showing in combination with a rather new data awareness which is currently evolving on top of traceable digital lifestyles with omnipresent face scanners and prevalent expectations of transparency in every area of life.

Apart from this user feedback approving of cultural differences, we also encounter observations that speak for the weakening of cultural separation, especially among younger demographics. Related work attributes such effects to increasing worldwide connectivity and movement, leading to a *global village* in the sense of disappearing boundaries of location-dependency through globalization [24]. In this light, requiring adaptation to the user's cultural background might prove as fallacy if there are more sensible approaches to improve the user experience. For this reason, we suggest not to automatically adapt the system to express cultural awareness but rather provide users the choice [P12].

3.3.3 Designing Desirable Features

We set ourselves the goal to provide recommendations for feasible affective automotive user interfaces with positive impacts on user experience. The design of worthwhile features requires the inclusion of users into the process. This way, we can iteratively improve the features to arrive at a first set of affective functionalities with wide acceptance among potential customers. Our approach consists of wireframe prototypes and successive addition of fidelity until a realistic user interface is created. This iterative design approach and the insights on cultural factors described in the previous section led to a set of 20 affective features we implemented in a car-mounted prototype and used to conduct a study with customers in Germany and China [P12].

The implemented use cases incorporate affective data from the fleet to enhance routing features, they allow proactive behavior of the voice assistant based on user state detection, provide throwbacks to memorable experiences, offer entertainment when suitable within the context, help looking after the offspring in the backseat, allow for controlling systems with facial expressions and setting the atmosphere inside the car, supply emotionally adaptive playlists and sharing functions for happy moments, communicate emotions to other traffic participants, or help reflecting on emotional experiences by quantifying affect recognition data [P12]. All ideas are results of the concepts and methods previously presented within this thesis.

Feedback from the user study confirms a high demand for affective features. The data suggests somewhat inflated user experience ratings, most likely because of the novelty of the presented ideas and a prevalent technology affinity among our customers. Nevertheless, more than two thirds of participants state that their future car should include an affective system [P12]. Participants preferred the enhancement of navigation features with fleet affect data over all other ideas. Germans rated affective sensing as input for system controls as second most attractive, while Chinese users opted for use cases based on the needs of their family as second most important. Proactive recommendations by the voice assistant based on the user's affective state were also accepted well by users from both countries. The feedback on our set of affective sample applications can be structured into four main influencing factors:

Demographics. Chinese participants were overall more positive in the evaluation of the proposed features. This confirms the assumptions of more openness towards innovation and a higher context of communication made in the previous section, as the feedback was likely masked by politeness. Qualitative feedback shows that the eagerness for novel gadgets to show off to others is also prevalent among the German sample [P12]. The most disparate resonance was created by a selfie feature, which allows users to make a picture of the car's occupants with a short voice command and a smile to release the trigger. Chinese participants assessed the feature with high hedonic and pragmatic qualities, whereas Germans, except for a few young users, penalized the idea as pointless [P12]. We can also report that female participants across cultures were more open towards emotionalizing the driving experience, e.g., by setting a mood before entering the car.

Data Privacy. Participants from both countries were more open towards sharing the data collected by emotion detection with the system provider after they experienced their applications [P12]. 82% of the Chinese and 91% of the German participants agreed to accessing their information. This shows a shift towards a post-privacy stance among Germans which has long been fueled by software companies offering convenience for data access. Chinese users are likely more reserved regarding the usage of personal data as their daily life already entails maximized data collection efforts for payment, social credit and law enforcement.

Paternalism. We initially worried that emotionally aware systems that take the initiative to interact with the user in order to improve their emotional state would be assessed as paternalistic. In fact, only a limited number of suggested use cases gave rise to complaints regarding paternalism. These were features which displayed the detected emotional state to be seen by others [P12]. Users who stated more often that they felt paternalized were skeptical towards emotion detection and proactivity in general. We thus think that proactivity itself is not the problem, but rather missing limits of privacy the system should comply with.

User Experience. Emotional interaction aims at creating more positive moments to increase the hedonic aspects of user experience. Some of our ideas are purely hedonic in nature and others augment pragmatic functionalities users already know from their current cars. The presented affective features were best accepted when they provided both pragmatic and hedonic qualities [P12]. We find that the emotional component of interaction manages to add hedonic value to previously pragmatic features like routing or adjusting interior settings. This could also be a promising strategy for the introduction of affective automotive user interfaces, as the benefits of affective systems can be experienced without fear of the unknown when familiar features confer the user a sense of competence.

Summary of *Improving User Experience*

This thesis contributes a number of insights regarding the improvement of user experience of emotional interaction. We design emotional experiences through the adaptation of voice assistant characters to the user's personality, thereby heightening the system's perceived trustworthiness and likability. We further apply a user-centered design approach with a focus on the cultural backgrounds of users, the most diversified aspects of which are social fabrics and attitudes towards data privacy. At the same time, we observe a weakening of cultural separation through global connectivity, especially among younger demographics. It further shows that the introduction of affective interaction to well-known features could add hedonic quality on top of widely appreciated pragmatic functionalities.

3.4 Limitations

Thematic Distinction We acknowledge that the research at hand focusses on emotions as driver states in a vacuum, detached from other important influencing factors such as cognitive load and distraction. In our opinion, it is important to combine all of these aspects but first a comprehensive understanding of affective systems at their own is required, which we contribute to in this thesis.

Novelty Our evaluations were constrained in time, as participants would experience a prototype and interact with it for a limited period. The resulting evaluations therefore might have been more positive than what long-term usage would have produced. We can also expect a novelty effect for applications of emotion detection systems, as not many users have previously been in contact with this new technology. We are uncertain whether these effects lead to more skepticism or openness.

Experiment Settings There are many approaches to the design of HCI evaluations, of which we implemented an online survey [P2], lab studies [P11, P1, P4], driving simulator studies [P6, P8, P9] and an evaluation in real traffic [P7]. Lab settings are very limited in their validity regarding effects on driving safety [P13], which is why we only used the method for informative preliminary studies. Online surveys and the public setup we used [P6] introduce higher levels of uncontrollability compared to lab studies but also provide feedback from a wider audience. Driving simulations show good validity compared to real driving but are also expensive in operation. We thus weighed up whether the overhead would add informative value to the expected outcomes and decided accordingly.

Participants The users we recruited for our studies were selected among relevant groups from the general population. We are aware that restrictions on the user sample might not be able to represent the wider population in every aspect, e.g., in some samples we did not manage to provide gender balance, and the feedback from car enthusiasts [P2] seemed hardly generalizable. We also did not investigate people from specific demographic groups like elderly or children, who could potentially benefit from special use cases of affective systems in future cars. Our studies included either US or Chinese users, as recruiting in two overseas regions gets costly. We accentuate the comparison with China, as the cultural differences to Germany are more extensive [21]. A comparison between US and Chinese customers would have also been interesting as those cultures are very dissimilar.

3.5 Guiding Questions for Designers

This section presents an overview of insights and learnings, cumulated into a list of questions for designers and researchers in the field. They are grounded on our initial *Guiding Research Questions* and are meant as a fundamental structure that provides guidance for the creation and assessment of future affective automotive user interfaces.

Who is your target user? It makes sense to involve real users early in the design and evaluation processes. Specifying a target audience allows for a better understanding of their needs and the design of a tailored experience. Get feedback from diverse people within the sample, not just your peers.

Which user state is at the center of your attention? User states have different implications for driver safety. Focusing on a limited set of states per feature enables more efficient regulation techniques. The anticipated level of automation also determines whether emotions are relevant at all.

How do you sense the user state? The system requires some sort of user state input if adaptive features are envisioned. This can range from simple preferences or inquiries, over real-time detection of emotions, cognitive states and the interaction context, to long term behavioral analyses. You need to take measures for data protection and ensure informed consent when processing personal data.

Which assessment tools do you employ? Different evaluation approaches are appropriate, depending on expected influences on driving safety, target audience, and maturity of the feature.

How does the feature improve the user experience of driving? Affective user interfaces can be designed to improve the emotional experience of driving. However, some approaches can have unforeseen effects on the user's perception. Designers should consider implications regarding manipulation and paternalism and their effects on user experience.

How does the feature contribute to driving safety? It all comes down to this. We see it as crucial that the impacts of new in-car systems on driving safety are never negative in any context. Affective systems should improve safe behavior within defined use cases and otherwise not divert attention.

4 Conclusion

"A computer that can express itself emotionally will some day act emotionally, and the consequences will be tragic."

Rosalind W. Picard, Affective Computing, 1997

4.1 Reflection

To conclude this thesis, we reflect upon our envisioned applications of affective technology in the car. First, we address that interactive technology commonly finds its way into the car after being established in the consumer electronics world. How would the automotive domain suddenly become pioneers for affective technology? While disruptive technologies, like touch interfaces and voice assistants, have factually been introduced into cars because of customer demands fueled by CE devices, there is also the example of mid-air gestures, which have found useful applications in automotive user interfaces but are otherwise not widely available. This is likely owed to the required interaction space around the device. Mobile phones, for example, cannot provide a fixed space in the periphery because they are freely movable by the user. Car interiors, in contrast, are static in themselves, allowing for the placement of sensors with unobstructed view of the user. Affective systems also profit from this advantage, being able to sense the user's behavior from a certain distance with the user being confined to a restricted interaction space. Thus, car interiors provide more optimal surroundings for the sensing of human affect and behavior than mobile environments. Furthermore, the technology to power emotion detection and emotional interaction is already being built by the driving forces behind face recognition, fitness wearables, and speech interaction. Thus, the comparably limited development capabilities of the automotive industry can be used to apply the technology in innovative products.

Another topic worth addressing is the expected benefit of affective systems. The emotional aspect of user experience is nothing new and product designers have been working to improve hedonic quality maybe even before the term was coined. Our approach, however, combines safety aspects of emotional states with user experience. The presented studies observe single scenarios for emotion-awareness but a mature product would combine many such aspects into one approach, for example an empathic agent which keeps the driver in a safe state and at the same time is fun to talk with. The model we present suggests reacting to user states and adapting to user traits as the two overarching feedback approaches for affective systems [P5]. Here again, the adaptive part is already prevalent in everyday products, at least to certain extents. The reactive interaction extends the human-machine feedback loop with context information that allows to assess driving safety in the first place. We only investigated a fraction of what is possible with awareness to the user state. Future systems will hopefully include other aspects, such as limits to cognitive load and the physical well-being of the driver and passengers. Concurrently, awareness of the context outside the car will be required for affective systems to be accepted as intelligent interfaces [P7].

The introduced concepts analyze behavior to inform a better understanding of the user. We have seen that incautious handling of this sensitive information can lead to reactance towards suggested interfaces. This was, on one hand, due to perceived paternalism when the user felt the system wanted to influence them and, on the other hand, and more importantly, a break of privacy when the system displayed the detected state visually [P8]. We need to be aware of the car as a social space, where drivers have guests, travel with family, or experience intimate moments. Even when driving alone, privacy is an important issue for users [P12]. Affective systems need to behave in a way that users can trust. For this reason, we expect that implicit cues aimed at influencing the user in a hidden way will be overlooked in favor of more trustworthy approaches for the introduction of first affective automotive user interfaces.

Systems with the ability to influence users implicitly might in the long run even pose a risk for societies. We come back to an example from science fiction to highlight our thoughts: in the dystopian world of the movie *Blade Runner 2049* [50] the protagonist's agent *Joy* accompanies him everywhere, they live together and enjoy each other's company. He even occasionally surprises her with add-ons to her system. In a realistic world shaped by capitalism, the manufacturer of this digital agent would have easy game exercising influence on the user through the apparently close emotional relationship. Such a trusted access point into people's lives would be the perfect tool to fuel blind consumerism through product placement. Given that sad people have been shown to pay higher prices [30], retailers could even profit from emotionally aware price adaptations. These systems could further reinforce the echo chamber phenomenon we already experience today in order to radicalize the masses. To think this is far from reality would be short-sighted. Many law enforcement agencies are already using facial recognition technologies for surveillance [23]. With affective technologies they could effectively monitor reactions to public appearances or online contents and identify who approves of or shows skepticism towards which agenda. This power in the hands of totalitarian states could have serious implications for people's lives. We thus need to think about the ethics of affective systems and how to allow informed consent to ubiquitous sensing.

In our work, we also touch upon topics of intercultural research. Our theoretical starting point are Hofstede's comparisons of cultural dimensions [21], which are not beyond dispute within the community. We find support for both Hofstede's theories as well as for a gradual change towards a globalized younger generation that fits more into the concept of postcolonial computing [24]. As with many things, the truth most likely lies in between the extremes: people internalize views from all over the world and are at the same time products of the society they grow up in. Accordingly, we see indisputable cultural differences regarding, e.g., the social settings in which affective automotive user interfaces are to be deployed, but also many aspects in which users from different regions voice corresponding attitudes. An adaptation to cultural disparities might improve the acceptance of some features. However, we can also imagine that one would buy a German car exactly because of the functional design that is expected from a product developed in a country of engineers.

Another potential problem for affective systems across cultures is the inconsistent empirical knowledge we have on the universality of emotional expressions. Affect recognition needs to work on the same level in every region, which will be a hard case to crack as there are significant differences in the way people handle emotions, as criticized by Feldmann Barrett et al. [7]. We generally perceive an abundance of technological optimism within the community, which might eventually be curbed by reality setting in, like it has been happening recently with the craze for automated driving. The Gartner Hype Cycle for 2019 fittingly places emotion AI on the verge from technology trigger to the phase of inflated expectations [22]. This means that widespread emotionally aware systems in production are not to be expected before 2030. Until then, emotional interaction might be able to pave the way for the acceptance of affective features in the car.

We nevertheless see an application area for affective systems in automated vehicles. Conditional automation of the driving task according to SAE Level 3 [47] is said to be around the corner, and with it driver monitoring systems are being introduced into cars. Affective systems, given technological maturity of emotion detection, have the potential to significantly improve current driver monitoring approaches, e.g., in order to evaluate attention levels in case of take-over requests. This way, affective automotive user interfaces can contribute to increased driving safety in the near future, even without the availability of functioning emotion regulation systems.

4.2 Outlook

This thesis applies the principles of affective computing into the domain of automotive user interfaces. We show that emotion detection and regulation, as well as the synthesis of emotional system behavior, can have positive influences on driving safety and the user experience of future cars. In this conclusive part, we propose research directions to advance the field in continuation of our work.

User Modeling We introduce a general model for adaptivity towards user states and traits [P5]. Future work could explore how to derive user states (emotions, cognitive load, health, . . .) and traits (personality, preferences, driving skill level, . . .) from behavior. A comprehensive view on the user will be necessary to build empathic assistants that really have an impact on behavior [32].

User Experience Design User experience is a continuous stream of assessing interactions with a strong emotional factor [19]. Future user experience design approaches could employ feedback loops of detected user reactions and system adaptations over time to gradually optimize any system for a maximum of joy or other desired experiences.

Automated Driving In conditionally automated vehicles, drivers still need to take over control in certain situations and thus stay alert even when they are not paying attention to the road. Affective systems can help to monitor the driver in hands-offs phases and motivate them to stay within the limits of safe take-over performance [25].

Specific Users Fully automated vehicles can make mobility accessible for user groups who today cannot move freely without help from others [27]. Research on caregiving systems for physically impaired users, young children and the elderly could be expanded into the automotive domain and such systems would benefit hugely from empathic abilities. The segmentation of the market also requires tailoring affective systems to regional and demographic usage characteristics.

Ethical Considerations Affective computing helps us to understand users. This technology can not only be used to improve the product, but also to assert influence on users. System need to be designed deliberately incapable of exploiting their users. We hope to see regulatory decisions to protect users from greedy intelligence technologies, for example, with regard to biometric identification, as supposed by the European Commission [53]. Failing to limit the exploitation of this new technology could be a myopic error able to change the future of societies.

LIST OF TABLES AND FIGURES

1 Clarification of the author's personal contribution in each incorporated publication. If not mentioned otherwise, I conceived and executed the work, provided the visual materials, composed the written manuscript, and edited the final version. The co-authors which are not named individually contributed with supervision, feedback on concepts and manuscripts, and/or organizational help. xii

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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.

München, den 28. April 2020

Michael Braun