TECHNISCHE UNIVERSITÄT
IN DER KULTURHAUPTSTADT EUROPAS
CHEMNITZ

Predictable and intuitive interactions between automated vehicles and manual road users in shared spaces

Von der Fakultät für Human- und Sozialwissenschaften
der Technischen Universität Chemnitz genehmigte

Dissertation

zur Erlangung des akademischen Grades

Doctor rerum naturalium (Dr. rer. nat.)

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Tag der Einreichung: 03.11.2023

Tag der Verteidigung: 06.02.2024

Veröffentlichungsjahr: 2024

Zitierlink: https://nbn-resolving.org/urn:nbn:de:bsz:ch1-qucosa2-906506

DANKSAGUNG

An dieser Stelle möchte ich mich zunächst bei einigen Personen bedanken, die den Weg zu dieser Arbeit sehr unterstützt haben.

Als Erstes möchte ich mich bei meinem Doktorvater Prof. Josef Krems für die jahrelange Unterstützung, die Begeisterung für diese Forschungsrichtung und die hilfreichen Anmerkungen, sowie die Möglichkeit in diesem Feld zu arbeiten und zu forschen bedanken. Mein Dank gilt ebenfalls meinem Zweigutachter Prof. Tibor Petzoldt für die Unterstützung in früheren Jahren und die Bereitschaft diese Arbeit zu begutachten.

Mein riesiger Dank gilt weiterhin meinen MentorInnen, Matthias Beggiato, Isabel Kreißig und Franziska Hartwich. Danke, dass ihr mich stets so unterstützt, für eure Geduld mit mir über die Jahre und vor allem, dass ich so viel von euch lernen durfte.

Weiterhin möchte ich mich bei allen KollegInnen der AAP und AHF für die Zusammenarbeit bedanken. Ein besonders Dank gilt hierbei meinen (ehemaligen) BürokollegInnen, Tina Morgenstern, Sophie Helene Lux, Anja Klichowicz und Silvio Heß für die Unterstützung, das Mentoring über die Jahre und die stets lustigen Momente mit euch. Außerdem möchte ich Nadine Rauh für die Unterstützung und das Mentoring danken.

Ich möchte auch allen studentischen und wissenschaftlichen Hilfskräften, sowie AbsolventInnen danken, die die Projektarbeit tatkräftig unterstützt haben.

Außerdem möchte ich mich bei allen Projektpartnern und KollegInnen der Forschungsprojekte InMotion, @City-AF und SMO-II, sowie des Sonderforschungsbereiches „Hybrid Societies“ für die tolle Zusammenarbeit bedanken. Ein besonderer Dank gilt hierbei Konstantin Felbel und André Dettmann für die gute Zusammenarbeit.

Nicht zuletzt möchte ich mich bei meiner Familie und meinen Freunden bedanken. Vielen Dank für die schönen Momente mit euch, die Unterstützung, den Mut und die Zuversicht, die ihr mir unermüdlich gebt und dass ihr mein Leben so bereichert!

ZUSAMMENFASSUNG

In den letzten Jahren ist ein immer größerer Anstieg automatisierter Fahrfunktionen zu verzeichnen, die unter anderem potentiell erhöhte Verkehrssicherheit, Verkehrseffizienz und Fahrkomfort ermöglichen. Daraus resultiert perspektivisch ein Mischverkehr, in dem verschiedene Verkehrsteilnehmer[1] (z.B. manuell gesteuerte Fahrzeuge (MF), Fußgänger) mit automatisierten Fahrzeugen (AF) interagieren. Allerdings ergeben sich mit der Einführung von AF potentiell neue Herausforderungen für die Interaktionen mit anderen Verkehrsteilnehmern, da es sich beim Straßenverkehr generell um ein soziales System handelt. Als eine potentielle Herausforderung wird der von MF abweichende Fahrstil von AF diskutiert. Da in derzeitigen Nutzerstudien meist ein sehr defensiver Fahrstil in AF implementiert ist, werden Unsicherheiten über bevorstehende AF-Manöver und Frustration manueller Verkehrsteilnehmer während der Interaktion begünstigt. Außerdem werden veränderte Interaktionen im Mischverkehr zwischen AF und umgebenden Verkehrsteilnehmern erwartet. Es wird angenommen, dass die Fahrzeugautomatisierung perspektivisch als zusätzlicher Interaktionspartner mit umgebenden Verkehrsteilnehmern fungiert, während der Fahrer gegebenenfalls dafür nicht mehr zur Verfügung steht, weil beispielswiese andere Aufgaben ausgeführt werden.

In geteilten öffentlichen Verkehrsräumen (Shared Spaces), wie zum Beispiel auf Parkplätzen, in denen verschiedene Verkehrsteilnehmer auf beschränktem Raum miteinander agieren, es allerdings nur begrenzte gesetzliche Regelungen (Straßenverkehrsordnung (StVO) §1) und wenige Straßenmarkierungen gibt, sind Interaktionen und die Koordination von Manövern besonders notwendig. Für diese Koordination von Manövern ist deren Antizipation besonders bedeutsam, welche durch verschiedene Kommunikationssignale ermöglicht wird und die Verkehrssicherheit und Verkehrseffizienz, sowie den Interaktionskomfort im Straßenverkehr unterstützt. Durch den Einsatz von Kommunikationssignalen können Manöver einzelner Verkehrsteilnehmern antizipiert werden, was wiederrum die Anpassung des Verhaltens anderer Verkehrsteilnehmer ermöglicht.

Daraus ergab sich der Forschungsbedarf, wie zukünftige Interaktionen im Mischverkehr, besonders in Shared Spaces, für manuelle Verkehrsteilnehmer intuitiv und vorhersehbar gestaltet werden können. Zum einen, um bevorstehende AF-Manöver intuitiv antizipieren und darauf reagieren zu können, aber auch AF zu befähigen bevorstehende Manöver manueller

[1] Im Folgenden wird für alle Akteure bei Interaktionen im Straßenverkehr zur verbesserten Lesbarkeit das generische Maskulinum verwendet. Natürlich sind damit aber *alle* im Straßenverkehr beteiligten Personen gemeint.

Verkehrsteilnehmer verlässlich antizipieren zu können. Wie oben beschrieben wird angenommen, dass sich Interaktionen im Straßenverkehr durch die Einführung von AF verändern und es neue Herausforderungen für die Koordination von Manövern einzelner Akteure geben wird. Deshalb gibt es ein stetig wachsendes Forschungsfeld zu diesem Thema. Das Ziel dieser Dissertation war es, wissenschaftliche Erkenntnisse zu diesem Feld beizutragen. Die Dissertation besteht aus drei wissenschaftlichen Artikeln, die in internationalen Fachzeitschriften publiziert wurden. In einer vorangestellten Synopse werden übergreifende theoretische Grundlagen dargelegt, wesentliche Ergebnisse der Artikel aufgegriffen und diskutiert, sowie theoretische und praktische Implikationen abgeleitet.

Der erste Artikel beschäftige sich mit Fahrparametern während Einparkmanövern auf Parkplätzen mit besonders hohem Interaktionsbedarf zwischen einzelnen Verkehrsteilnehmern. Interaktionen im Straßenverkehr werden häufig durch räumliche und zeitliche Lücken im Verkehrsfluss koordiniert. Indem spezifische Fahrparameter von MF quantifiziert und als Rollenmodell angewendet werden, könnten diese als Orientierung für intuitive und vorhersehbare AF-Fahrfunktionen genutzt werden, die Interaktionen im Mischverkehr unterstützen könnten. Deshalb wurden akzeptierte Lücken im Verkehrsfluss aus Fahrerperspektive für das Manöver vorwärts Einparken auf einem Parkplatz mit verschiedenen heranfahrenden Verkehrsteilnehmern und potentielle Einflussfaktoren auf die Lückenwahl in einer Laborstudie genauer untersucht. Die Ergebnisse zeigten, dass kleinere Lücken bei kleineren heranfahrenden Verkehrsteilnehmern für die Initiierung eines Parkmanövers akzeptiert wurden, als bei größeren Verkehrsteilnehmern. Außerdem wurden kleinere zeitliche Lücken bei höheren Annäherungsgeschwindigkeiten der Interaktionspartner akzeptiert. Auch Personenfaktoren, wie das Alter der Probanden, hatten einen Einfluss auf die Lückenwahl. Zusammenfassend kann festgehalten werden, dass MF nicht *die* eine zeitliche Lücke für die Initiierung eines Parkmanövers im Verkehrsfluss wählten, sondern verschiedene Faktoren diese Wahl beeinflussten. Für intuitive und vorhersehbare Interaktionen im Mischverkehr sollten solche spezifische Einflussfaktoren auch in AF-Fahrfunktionen implementiert werden. Diese könnten eine verbesserte Antizipation von AF-Fahrverhalten durch umgebende Verkehrsteilnehmer ermöglichen. Außerdem könnten AF dadurch bevorstehende Manöver von MF verbessert antizipieren.

Um die Vorhersehbarkeit von Manövern und Handlungen einzelner Akteure in potentiell veränderten Interaktionskonstellationen im Mischverkehr zu unterstützen, beschäftigt sich die Forschung außerdem mit zusätzlichen Kommunikationssignalen, die perspektivisch in AF eingesetzt werden könnten. Dafür könnten LED-Lichtleisten genutzt werden, da diese technisch leicht in bestehende Infrastruktur zu implementieren und barrierearm sind (z.B. hinsichtlich erforderlicher Sprachkenntnisse). Jedoch zeigen diese Lichtleisten eher abstrakte Signale zur Kommunikation an. Der zweite Artikel beschäftigte sich deshalb mit der Bewertung

solcher abstrakten Lichtsignale als zusätzliches Kommunikationsmittel in AF. Es wurde eine Feldstudie (mit der Wizard-of-Oz-Methode) auf einem Parkplatz durchgeführt. Mittels eines Sitzanzuges, welches den Fahrer des Testfahrzeuges verdeckte, wurde eine AF-Bedingung simuliert, die anschließend mit einer MF-Bedingung mit sichtbarem Fahrer verglichen wurde. Hierbei bewerteten Fußgänger abstrakte Lichtsignale nach einer Interaktion mit dem Testfahrzeug, ohne jedoch weiteres Vorwissen über deren die Bedeutung der Signale zu haben. Generell fühlten sich die Probanden in der MF-Bedingung mit sichtbarem Fahrer sicherer. Die untersuchten abstrakten Lichtsignale wurden als unverständlich beurteilt, was potentiell auch das bewertete Vertrauen und die eingeschätzte Nützlichkeit der untersuchten Signale negativ beeinflusste. Aus den Ergebnissen lässt sich schlussfolgern, dass abstrakte Lichtsignale als Kommunikationsmittel ohne Vorwissen über deren Bedeutung keinen Mehrwert zur Erhöhung der Vorhersehbarkeit von Manövern in der Situation lieferten und bevorstehende Manöver von AF potentiell nicht verbessert antizipiert werden konnten. Allerdings konnten die Ergebnisse ein allgemeines Potential für Lichtsignale als zusätzliches Kommunikationsmittel in AF aufzeigen, da die Probanden einen generellen Einsatz solcher Signale in AF als nützlich bewerteten.

Der dritte Artikel beschäftigte sich mit dem Einfluss von Interaktionserfahrungen mit zusätzlichen Lichtsignalen als Kommunikationsmittel bei gegebenen Vorwissen über deren Bedeutung. Außerdem wurden die Auswirkungen von potentiell sicherheitskritischen Fehlfunktionen des Systems (d.h. ein Widerspruch zwischen den eingesetzten Lichtsignalen und den Fahrzeugbewegungen als eigenständiges Kommunikationssignal) auf dessen Bewertung betrachtet. In einer Laborstudie wurden den Probanden kurze Interaktionssequenzen mit dem System in einem Parkplatzsetting präsentiert. Das eingesetzte Videomaterial zeigte ein heranfahrendes Interaktionsfahrzeug aus Fußgängerperspektive, an dem zusätzliche Lichtsignale augmentiert wurden. Generell vertrauten die Probanden dem System und akzeptierten die zusätzlichen Lichtsignale, die Bewertungen stiegen nach kurzen Interaktionssequenzen mit dem System außerdem an. Daraus lässt sich schlussfolgern, dass ein positiver Einfluss von Interaktionserfahrungen mit technischen Systemen im Allgemeinen auch spezifisch auf zusätzliche Lichtsignale als potentielles Kommunikationsmittel in AF anwendbar ist. Weiterhin gaben die Probanden an, sich in der Interaktion sicher zu fühlen. Nach erlebten Systemfehlern sank das Vertrauen, die Akzeptanz und die angegebene subjektive Sicherheit während den Interaktionen ab. Es wurde deutlich, dass eine adäquate Systembeurteilung notwendig ist. Zum einen sollte die Einschätzung des Systems eine generelle Nutzung dessen ermöglichen, um die potentiellen Vorteile, wie erhöhter Vorhersehbarkeit bevorstehender AF-Manövern, auszuschöpfen. Jedoch sollte auch verhindert werden, dass sich zu sehr auf eingesetzte Lichtsignale als Informationsquelle

verlassen wird und beispielsweise Fahrzeugbewegungen als Kommunikationsmittel zu wenig Berücksichtigung finden, um sicherheitskritischen Situationen vorzubeugen.

Fußgänger über 65 Jahren sind im Straßenverkehr durch altersbedingte Beeinträchtigungen besonders gefährdet. Dadurch könnten sie besonders von einer erhöhten Vorhersehbarkeit bevorstehender AF-Manöver durch zusätzliche Signale profitieren. Deshalb untersuchte die Studie, welche im dritten Artikel berichtet wird, zusätzlich Unterschiede in der Bewertung des Systems zwischen jüngeren (18 – 40 Jahren) und älteren (≥ 65 Jahren) Probanden. Generell gaben die älteren Probanden eine positivere Systembewertung als Jüngere an, jedoch passten sie ihre Systembewertung im Fall von erlebten Fehlfunktion auch weniger an. Diese geringere Anpassung der Bewertung könnte im Fall von Systemfehlfunktionen besonders hohe sicherheitskritische Auswirkungen auf Ältere haben (z.B. längere Reaktionszeiten um auf nicht erwartete Fahrzeugbewegungen zu reagieren).

Insgesamt unterstreichen die Ergebnisse der Dissertation die Notwendigkeit einer menschzentrierten Produktenwicklung hinsichtlich der Implementierung spezifischer Fahrparameter, sowie potentieller zusätzlicher Lichtkommunikationssignale in AF. Verschiedene theoretische Konzepte und Annahmen der Mensch-Maschine-Interaktionen im Allgemeinen können auch auf AF und Lichtsignale als potentielles zusätzliches Kommunikationsmittel im Mischverkehr angewendet werden. Konkret zeigen die Ergebnisse der Arbeit, dass verschiedene Einflussfaktoren für vorhersehbare und intuitive AF-Fahrparameter berücksichtigt werden sollten. Außerdem konnte gezeigt werden, dass zusätzliche Lichtsignale zur Kommunikation in AF ein generelles Potential haben, zukünftige Interaktionen im Straßenverkehr zu unterstützen. Wie in anderen Bereichen der Mensch-Maschine-Interaktion sollten jedoch auch hier verschiedene Faktoren, wie das Vorwissen über und die Interaktionserfahrung mit diesen Signalen, sowie die Anforderungen spezifischer Nutzergruppen beachtet werden. Zukünftige Forschung sollte weitere Verkehrsszenarien und Einflussfaktoren auf Interaktionen im Straßenverkehr untersuchen, sowie die Bedürfnisse spezifischer Nutzergruppen genauer beleuchten. Insgesamt kann die Arbeit dazu beitragen, Anforderungen und Voraussetzungen für vorhersehbare und intuitive Interaktionen im Mischverkehr besser zu verstehen. Weiterhin können aus den Ergebnissen der Dissertation Strategien und praktische Maßnahmen für die Gestaltung von vorhersehbaren und intuitiven AF-Interaktionsverhalten im Mischverkehr mit manuellen Verkehrsteilnehmern abgeleitet werden, welche sich positiv auf die Nutzung und Akzeptanz von AF auswirken könnten.

SUMMARY

In recent years, the introduction of automated driving functions rapidly increased due to the potential benefits of enhanced road safety and efficiency as well as driving comfort. Since road traffic represents a social system that requires a coordination of actions of different road users, manual traffic participants (e.g., manually driven vehicles and pedestrians) need to prospectively interact with automated vehicles (AVs) when introduced to the marked, describing mixed road traffic. However, potential interaction challenges are assumed. In particular, the currently diverging driving behavior of AVs compared to manually driven vehicles is discussed in the literature as potentially challenging. Previous studies mainly implemented and investigated a highly defensive driving behavior of AVs, resulting in decreased traffic efficiency and in ambiguous encounters with manual road users. In addition, it is expected that the introduction of automated driving functions potentially modifies the driver's role. Specifically, the on-board user in the driver's seat in an AV might no longer be available as interaction partner for surrounding traffic participants in the currently established form, since being allowed involving in other tasks than driving. Therefore, the vehicle automation will prospectively act as interaction partner for surrounding traffic participants during encounters leading to transformed interactions in mixed road traffic.

In shared spaces, such as parking areas, a diversity of different traffic participants needs to coordinate their actions. However, since being characterized by a low amount of road markings and rather undefined statutory regulations (for Germany merely StVO §1 of the road traffic regulations are applicable), interactions and the mutual coordination of road users' maneuvers are highly relevant. The coordination of actions is supported by different communication signals that are applied by the different traffic participants due to the predictive and anticipatory function of these signals. Therefore, prospective maneuvers of the different road users might be increasingly anticipated by involved interactions partners, enabling for proactive interactions that support safety, efficiency and driving comfort.

Given the previously assumed challenges for mixed road traffic, there is a fast growing research field considering intuitive and predictable interactions between AVs and surrounding manual road users. To support such predictable and intuitive encounters in mixed road traffic, AVs should be enabled to anticipate prospective actions of surrounding traffic participants and react accordingly. Moreover, AVs' upcoming driving maneuvers are also required to be predictable for surrounding manual road users. The current thesis aimed on contributing to this research field with a specific focus on shared spaces settings, highly requiring for interactions of various traffic participants. In the thesis, three peer-reviewed research articles are included that have been published in international scientific journals (subsequently labeled as Paper I-III). A framework that connects the journal papers of the thesis and theoretical concepts are

introduced in the synopsis. Moreover, the main results of the papers are highlighted and discussed. In addition, deduced theoretical and practical implications are presented within the synopsis.

The study of Paper I considered driving parameters for initiating parking actions within shared spaces that highly require a coordination of maneuvers between different traffic participants. Encounters in road traffic are frequently coordinated by spatial and temporal gaps in traffic flow. To support predictable and intuitive interactions in mixed road traffic, specific parameters of manual driving, such as accepted gaps in traffic flow, could be derived and might be used as a basis for AVs' driving functions. Therefore, manual drivers' gap acceptance (GA) for initiating parking actions when encountering different traffic participants was investigated in a laboratory study. Specifically, the effect of size and speed of the approaching traffic and the influence of driver characteristics on GA was invested within the study. The findings revealed smaller GA for initiating parking maneuvers when encountering smaller interaction partners. Moreover, smaller temporal gaps were accepted by manual drivers for starting parking actions during higher approach speeds of encountering traffic participants. Individual driver characteristics were also shown to influence GA. Overall, the findings revealed that there is no one specific gap that is consistently selected by manual drivers when initiating parking maneuvers in shared spaces. Rather, various factors influenced the individual gap selection. To provide predictable and intuitive interaction capabilities in mixed road traffic, influencing factors and their specific effect on driving parameters should be also implemented in AVs' driving functions. Therefore, the predictability of AVs' upcoming driving actions might be supported. Moreover, AVs would be increasingly enabled to anticipate driving maneuvers of surrounding manual road users, enhancing proactive interactions in mixed road traffic.

To support the predictability of upcoming maneuvers in mixed road traffic, additional communication signals might be potentially applied in AVs. Therefore, LED light bands displaying additional signals are discussed as a potential application since being technically easily installable into vehicles. Moreover, communication signals presented by this technology would not require specific language skills. Thus, light bands seem a promising approach for displaying additional signals as potential means of communication in AVs. However, signals provided by such LED light bands are rather abstract. Therefore, the study of Paper II investigated the assessment of abstract visual signals as potential means of communication in AVs. The study applied a Wizard-of-Oz approach, simulating an AV where the driver was covered by a seat suit. A manual driving condition comprising a visible driver was also included in the study. A light bar displaying the abstract signals as potential means of communication in AVs was placed to the roof of the interaction vehicle. Participants without prior knowledge about the signals' meanings assessed these signals after interacting with the system in a shared space scenario. Generally, the participants indicated a higher subjective feeling of

safety during encounters in the manual driving condition including a visible driver compared to the simulated AV condition with the applied seat suit. The investigated abstract light signals for potentially enhancing the predictability of encounters were assessed as unintuitive without prior knowledge about the assigned meanings. This might have also influenced participants' indicated trust and usefulness of the applied light signals. It might be concluded that the investigated abstract light signals as potential means of communication in AVs could not support predictable and intuitive interactions in mixed road traffic between AVs and manual road users without prior knowledge about the assigned signals' meanings. However, participants assessed a general application of these signals as useful, revealing an overall potential of applying light signals as means of communication in AVs.

In the study of Paper III, the development of participants' system assessment due to interaction experience considering additional light signals as means of communication in AVs, given prior knowledge about their assigned meanings, was investigated. Moreover, potential safety critical system malfunctions, describing a mismatch between the applied light signals and the vehicles' trajectory, were examined within the laboratory study. Short video sequences, recorded from a pedestrians' perspective, displaying interactions with an approaching vehicle in a shared space setting were applied as study material. In the videos, different abstract light signals as potential means of communication were augmented at the interaction vehicle. According to the results, participants indicated to initially trust and accept the system. These ratings even increased after achieving interaction experience with the signals. Thus, the general positive impact of interaction experience on a system's assessment seems also applicable to the technology of light signals as potential means of communication in AVs. Participants also indicated to feel rather safe during encounters with the interaction vehicle including the light signals as means of communication. After experiencing system malfunctions, participants' system assessment declined regarding the indicated trust and acceptance ratings as well as the subjective feeling of safety. The results highlight the importance of an adequate system assessment enabling for a systems' usage to apply expected benefits (e.g., enhanced maneuver predictability of AVs due to additional light signals as means of communication) but also preventing from overreliance on a system in terms of safety (e.g., overreliance on AVs' light signals as means of communication but neglecting the vehicles' trajectories as communication signals).

Pedestrians ≥ 65 years represent particularly vulnerable road users due to several age-related declines. Therefore, this road user group might specifically benefit of additional communication signals in AVs, announcing prospective driving maneuvers in advance and supporting the predictability of interactions. Thus, differences in system assessment between younger (18 – 40 years) and elderly (≥ 65 years) participants were also investigated in the study of Paper III. The findings revealed that elderly participants consistently assessed the system

more positive than younger participants. After experiencing malfunctions, elderly participants adjusted their system assessment less than younger participants, which is worrisome in terms of traffic safety since elderly participants might be particularly affected by potential system malfunctions and an inappropriate system assessment (e.g., due to longer reaction times in case of unexpected AV trajectories while neglecting vehicle movements as communication signal).

Overall, the results of the conducted studies within this thesis highlight the requirement for a human-centered system development. Implementing specific driving parameters and investigating additional light signals as potential means of communication in AVs were specifically focused with regard to predictable and intuitive interactions in mixed road traffic in shared space settings. Specifically, the findings showed that there are various influencing factors on driving maneuver decisions that should be also considered in AVs' driving functions to provide predictable and intuitive interaction capabilities. Moreover, the findings revealed a general potential of additional light signals as means of communication in AVs to support predictable interactions in mixed road traffic. Various concepts of the human-machine interaction research might be also applicable for AVs and additional light signals as potential means of communication with surrounding road users in mixed road traffic. For instance, the positive influence of prior system knowledge and interaction experience was shown to be applicable to light signals as means of communication in AVs. Moreover, the findings highlighted that requirements of different user groups should be specifically considered when developing, evaluating and introducing AVs and additional light signals. Further research should consider additional traffic scenarios and influencing factors when investigating predictable and intuitive interactions in mixed road traffic. Moreover, requirements of different user groups should be respected in more detail within further studies. The thesis aimed on contributing to the research knowledge to support predictable and intuitive interactions in mixed road traffic. Practical implications derived from the findings might provide input for supporting a successful introduction and usage of AVs and additional light signals as potential means of communication.

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SYNOPSIS

1 INTRODUCTION

In recent years, there has been an increase of automated driving functions that are expected to provide several advantages such as enhancing road safety, traffic efficiency and supporting driver comfort (European Road Transport Research Advisory Council, 2017). For instance, in 2022 Mercedes-Benz (Mercedes-Benz Group AG, 2021) released their statutory approved *Drive Pilot*, an automated driving system capable of executing the longitudinal and lateral control of the vehicle in real road traffic (whereas currently merely applicable in highway settings with speed limits up to 60km/h such as traffic jams; Mercedes-Benz Group AG, 2021). In case of required takeovers, the system provides requests and takeover time to the driver (Mercedes-Benz Group AG, 2021). Thus, the automated driving functions can be categorized as vehicle automation Level 3 according to taxonomy of the Society of Automotive Engineers (SAE; SAE International, 2021). Therefore, the driver is allowed to engage in other tasks than driving and monitoring the system (SAE International, 2021), such as reading newspapers (Allgemeiner Deutscher Automobil-Club, 2023), which thus modifies the driver's role (Merat et al., 2012). Due to a potential driver's role shift by the introduction of such automated driving functions, the driver inside the vehicle might no longer be available as interaction partner for surrounding traffic participants in the currently established form (Schieben et al., 2019). Therefore, the previous example (i.e., *Drive Pilot* by Mercedes-Benz Group AG, 2021) might demonstrate that interactions between drivers and surrounding traffic participants might prospectively change (Schieben et al., 2019) with the introduction of automated vehicles (AVs; SAE Level 3 or higher; SAE International, 2021).

Generally, road traffic is a social system that requires a coordination of actions by various road users for safe, efficient and smooth interactions (Domeyer et al., 2020). Particularly shared spaces, such as parking areas, with a variety of different road users interacting (e.g., vehicles, pedestrians; Department for Transport, 2011), decreased statutory regulations (Straßenverkehrsordnung [StVO], 2021) and a low amount of road markings require a successful coordination of actions (Department for Transport, 2011). Implicit and explicit communication signals are applied by traffic participants (Dey & Terken, 2017; Rasouli et al., 2018) to announce, anticipate, predict and thus coordinate their movements when interacting (Schieben et al., 2019).

Successful interactions also need to be achieved in mixed road traffic, including AVs and surrounding manual road users as incidental users of AVs (Domeyer et al., 2020). However, potential challenges are hypothesized considering predictable and intuitive encounters in

mixed road traffic (Schieben et al., 2019; van Loon & Martens, 2015). More specifically, potential incompatibilities in driving behavior between AVs and manually driven vehicles are expected to cause challenges in anticipating and predicting prospective actions and thus the coordination in mixed road traffic (described as *compatibility issues* by van Loon & Martens, 2015) since there is currently a highly defensive driving style implemented in AVs (Nyholm & Smids, 2020; Stange, Kühn, et al., 2022b). Moreover, the transformation of interactions in mixed road traffic due to the vehicle automation as new team member (Schieben et al., 2019; Woods, 1996) is assumed to cause potential issues as the previously mentioned example of the Drive Pilot (Mercedes-Benz Group AG, 2021) considering a potential driver's role shift highlights (Schieben et al., 2019).

In the recent years there has been a rapidly growing body of human factors research investigating potential solutions for supporting interactions in mixed road traffic (e.g., Rouchitsas & Alm, 2019; Schaarschmidt et al., 2021; Schieben et al., 2019). This thesis aims on contributing to this field of research considering predictable and intuitive encounters in mixed road traffic within shared space settings comprising a particular requirement for interactions (e.g., parking areas; Department for Transport, 2011). Generally, interactions in road traffic are often coordinated by spatial and temporal gaps in traffic flow (Bengler et al., 2020; Summala, 2007). To achieve an increased predictability of prospective maneuvers during encounters and thus driving behavior compatibility between AVs and manually driven vehicles (van Loon & Martens, 2015) the behavior of an ideal manual driver might be used as a role model in AVs (Pillai, 2017). With regard to interactions in shared spaces, manual drivers' gap acceptance parameters (GA; Summala, 2007) in traffic flow for initiating parking maneuvers and coordinating actions during encounters were therefore further investigated and quantified to potentially providing a basis for intuitive AV driving functions (comparable to approaches by Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Moreover, to consider transformed interactions in mixed road traffic, additional communication signals as potential means of communication in AVs to substitute the driver-pedestrian interaction were examined (i.e., external human-machine interfaces, eHMIs; Bengler et al., 2020; Schieben et al., 2019).

The present cumulative dissertation consists of three peer-reviewed research articles that have been published in scientific journals (subsequently labeled Paper I to III). In the synopsis, an overview of previous research, theoretical concepts and a framework that connects the different papers of the thesis are introduced and implications from the results of the conducted studies of the papers are deduced. At the beginning, concepts considering interactions in manual road traffic, driving as joint activities and the significance of situation awareness in driving scenarios are considered (chapter 2). Then, communication in road traffic is respected in closer detail (chapter 3). The chapters 4 und 5 consider the topic of vehicle automation, the

requirements for predictable interactions between AVs and manual road users as well as a theoretical framework aiming to support successful interactions in mixed road traffic. The research objectives of the current dissertation are presented in chapter 6, followed by an overview of the applied methodology (chapter 7). In chapter 8 the main results are summarized and discussed. Potential implications are derived in chapter 9, a conclusion is presented in chapter 10. After the synopsis, the three research articles of the thesis are presented.

In the study presented in Paper I manual drivers' GA parameters for initiating parking actions when encountering upcoming interaction partners were assessed. The parameters could be used as a basic orientation in AVs' driving functions for coordinating actions with surrounding road users intuitively when initiating parking actions in shared spaces (comparable to the presented approach by Beggiato et al., 2017). The study presented in Paper II investigated eHMI signals as potential means of communication in AVs to support interactions with surrounding road users as incidental users. Paper III focusses on the effect of eHMI interaction experience and malfunctions on pedestrians' system assessment. Moreover, differences of younger and elderly participants' system assessment was investigated (Paper III).

Paper I

Hensch, A.-C., Beggiato, M., & Krems J. F. (2023). Drivers' gap acceptance during parking maneuvers as a basis for initiating driving actions in automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour, 92*, 133-142. https://doi.org/10.1016/j.trf.2022.11.008

Paper II

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems J. F. (2019). Effects of a light-based communication approach as an external HMI for automated vehicles - a wizard-of-oz study. *Transaction and Transport Sciences, 10*(2), 18-32. https://doi.org/10.5507/tots.2019.012

Paper III

Hensch, A.-C., Kreißig, I., Beggiato, M., & Krems, J. (2022). The effect of eHMI malfunctions on younger and elderly pedestrians' trust and acceptance of automated vehicle communication signals. *Frontiers in Psychology,* 13:866475. https://doi.org/10.3389/fpsyg.2022.866475

2 INTERACTIONS IN ROAD TRAFFIC

Road traffic is formally regulated by statutory regulations (e.g., Straßenverkehrsordnung for Germany; Straßenverkehrsordnung, 2021). It is generally characterized by a spatial co-presence of several traffic participants during encounters in an interactional space (Haddington & Rauniomaa, 2014). Since road traffic represents a highly dynamic social system, interdependencies between diverse traffic participants are resulting (Domeyer et al., 2020), potentially leading to uncertainties and ambiguities (FeldmanHall & Shenhav, 2019). Therefore, spatial and temporal interactions and coordination processes between different traffic participants (Domeyer et al., 2020) are required for managing such interdependencies in the spatial co-presence (Malone & Crowston, 1994), reducing uncertainties (FeldmanHall & Shenhav, 2019) and avoiding ambiguities and conflicts (Risser, 1988). In addition, these processes facilitate for a reciprocal error compensation of involved traffic participants (Renner & Johansson, 2006). Due to the highly dynamic character of road traffic scenes (Domeyer et al., 2020), such interactions between road users need to be conducted in short time intervals (Schaarschmidt et al., 2021).

2.1 Defining interactions in road traffic

Due to their complexity, interactions in road traffic are frequently investigated (e.g., vehicle-vehicle interactions; Risto et al. (2017); or vehicle-pedestrian interactions; Rasouli & Tsotsos (2020)). Numerous approaches considering the general concept of interactions can be found in the literature (for an overview see e.g., Markkula et al., 2020). With regard to interactions in road traffic, Markkula et al. (2020) suggested the following broad definition:

> A situation where the behaviour of at least two road users can be interpreted as being influenced by the possibility that they are both intending to occupy the same region of space at the same time in the near future (Markkula et al., 2020; p. 10).

A prominent approach considering interactions in road traffic with a specific focus on safety engineering aspects was developed by Hydén (1987). Different types of interactions are classified by their frequency of occurrence and the level of severity of events. Moreover, required compensational actions for avoiding conflicts or collisions are described by this approach. In conclusion, interactions in road traffic mainly focus on maintaining traffic safety due to collision avoidance according to this specific approach (Hydén, 1987).

Goffmann (1971) considered road traffic from a sociological perspective. According to this approach, the different involved traffic participants coordinate and adjust their maneuvers accordingly to avoid conflicts and maintain mobility. Following this approach, different road

users interact with each other for maintaining road safety but also for providing traffic efficiency (Goffmann, 1971).

Other authors analyzed interactions in road traffic by game-theoretic approaches (e.g., Millard-Ball, 2018) with a special focus on cooperative and competitive behavior of traffic participants during encounters (Millard-Ball, 2018). Cooperation requires sharing information, attitudes and beliefs between involved interaction partners (Deutsch, 2011). Thus, sharing information and attitudes to provide a certain amount of predictability should be respected as additional requirements for successful interactions in road traffic (Deutsch, 2011; Millard-Ball, 2018).

The different approaches do not necessarily contradict each other. Rather, diverse aspects of interactions in road traffic are specifically highlighted (Markkula et al., 2020). In summary, it might be concluded that successful interactions in road traffic exceed the mere purpose of conflict avoidance and movement in traffic (Markkula et al., 2020) and comprise safe, efficient but also transparent and predictable encounters in road traffic (Domeyer et al., 2020; Schaarschmidt et al., 2021).

2.2 Joint activities in road traffic

Given the required coordination of actions between different traffic participants (Clark, 1996), interactions in road traffic might be considered as *joint activities* (Klein et al., 2004), a concept originally established in the linguistics domain (Clark, 1996). For joint activities, several conditions need to be fulfilled (Klein et al., 2004): Participants' individual actions are required for being coordinated and participants need to commit to prevent from breakdowns of these joint activities by being cooperative (Clark, 1996). To prevent such breakdowns and reduce uncertainties when interacting, an *interpredictabliy* of actions is required. This implies the necessity to make own actions *observable* and thus predictable and also being able to predict actions of other participants (Klein et al., 2004). Therefore, a *common ground* comprising shared presumptions, convictions and body of knowledge about interactions is highly necessary in joint activities (Clark & Brennan, 1991). By establishing a common ground between participants (Clark & Brennan, 1991), interactions could be smoothed and coordination costs could be reduced (e.g., less required coordination time; Domeyer et al., 2020) allowing for shortened, economical interaction processes (Klein et al., 2004). In addition, the interaction participants need to be able to coordinate and influence their actions, which thus describes a *directability* of actions during joint activities (Klein et al., 2004). Overall, the interpredictablity of actions and a common ground of shared knowledge and presumptions between interaction participants is highly important since incorporating the potential to increase the predictability of encounters in road traffic (Clark & Brennan, 1991; Klein et al., 2004).

2.3 Situation awareness in road traffic

Obtaining correct mental representations, interpretations and predictions of a situation is also required to successfully coordinate encounters (Endsley, 1995). These aspects are generally described by the concept of *situation awareness* (SA), initially proposed in the aviation domain (Endsley, 1995). SA can be defined according to Endsley (1995) as "*the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future*" (Endsley, 1995, p. 36). The concept can be transferred to further human factors domains, such as road traffic (e.g., a driver's perspective; Krems & Baumann, (2009) or a pedestrian's perspective; Rodríguez Palmeiro et al. (2018)). Without adequate interpretations of road traffic scenes, conflicts or collapses of the interaction process might occur (Endsley, 1995). There are three sequential SA levels defined: For SA level one, situational features and objects (e.g., attributes, status and dynamics) need to be perceived. SA level two comprises the integration of the perceived elements to a mental representation of the specific traffic scene and the comprehension of the relevance of particular situational elements (Endsley, 1995). Since experienced drivers have a greater and more differentiated knowledge about traffic situations at their disposal, they are capable to identify and integrate relevant situational elements of a driving scene faster, with less mental effort and more reliable (Krems & Baumann, 2009). Besides experience as one individual factor, system factors influence SA, resulting decisions and performed actions. SA level three describes the capability for predicting and anticipating the development and future states of road traffic scenes (Endsley, 1995).

Predicting and anticipating the development of road traffic scenes and future actions of other road users is particularly important due to the spatial co-presence during encounters (Domeyer et al., 2020). The anticipation of future actions is, besides planning and executing these cognitive components, an aspect of the proactivity concept. Proactive behavior describes future-focused, deliberate actions and it is generally applied to reduce ambiguities and uncertainties by providing additional information of a situation (Grant & Ashford, 2008). Within the context of road traffic, anticipatory behavior supplies additional time and space within traffic scenes by identifying prospective actions a few seconds in advance in comparison to mere reactionary driving (Stahl et al., 2014). Therefore, maneuvers could be adapted accordingly (Stahl et al., 2014), facilitating for smoother interactions and reducing conflicts to provide traffic safety and efficiency when sharing spaces (Domeyer et al., 2020; Stahl et al., 2014). Anticipating and predicting the upcoming development of traffic scenarios represents a high-level cognitive competence of drivers (Baumann & Krems, 2007). Therefore, more experienced drivers show an increased amount of pre-event maneuvers compared to less experienced drivers (Stahl et al., 2014).

2.4 Shared spaces as interactional space for different traffic participants

Urban road traffic is particular complex, since diverse traffic participants need to interact successfully (@City, 2018). Particularly in *shared spaces*, a variety of different road users including vehicles and vulnerable road users (VRUs; Department for Transport, 2011; Holländer et al., 2021) are required to coordinate their actions (Brill et al., 2023). Thereby, the term VRUs comprises a heterogeneous group of different road users (i.e., pedestrians, cyclist and motorcyclist) that are notably vulnerable in case of collisions (Holländer et al., 2021).

However, there is currently no consistent definition for the term shared spaces (Brill et al., 2023; Moody & Melia, 2014). Rather, it is used as an umbrella term for a set of infrastructural design approaches (Kaparias et al., 2013; Uttley et al., 2020). In general, shared spaces mainly aim on calming traffic and enhancing VRUs' movement and comfort (Department for Transport, 2011). For instance, it could be shown that shared spaces have the potential to increase traffic efficiency since participants accepted smaller gaps in traffic flow within these settings (Woodman et al., 2019). Moreover, shared spaces aim on decreasing the speed and priority of vehicles to enhance traffic safety (Department for Transport, 2011). In addition, these settings are featured with a low amount of road markings (Department for Transport, 2011) and are characterized by low spatial distances between interaction partners (Lau et al., 2022). However, statutory regulations in Germany are rather undefined for shared spaces except from §1 StVO (Straßenverkehrsordnung, 2021):

> (1) Use of the road requires constant care and mutual respect. (2) A person using the road shall act in such a way as not to harm or endanger or, more than is unavoidable in the circumstances, to hinder or inconvenience any other person (Federal Ministry for Digital and Transport, n.d., §1, https://bmdv.bund.de/blaetterkatalog/catalogs/327056/pdf/complete.pdf).

Due to the low amount of statutory regulations (Brill et al., 2023), uncertainty during interactions is potentially introduced in shared spaces (Kaparias et al., 2012). This might lead to potentially ambiguous encounters of different road users (Brill et al., 2023), possibly resulting in space sharing conflicts (Markkula et al., 2020). Therefore, interactions are highly required in these settings to negotiate and coordinate prospective actions smoothly and in a common sense (Brill et al., 2023). Thus, a proactive and predictable interaction behavior becomes particularly important within shared spaces (Mertens et al., 2020).

Parking areas are a common, though currently under-investigated example for shared spaces when considering interaction research (Uttley et al., 2020). Therefore, interactions in parking areas, applied as infrastructural setting of shared spaces, are further considered in the current thesis.

3 COMMUNICATION IN ROAD TRAFFIC

To support a successful coordination of actions during encounters, communication between different road users is required (Hölzel, 2008), since displaying behavior provided by communication (Feltovich et al., 2004) announces prospective actions (Färber, 2016). The resulting predictive and anticipatory function of communication (Portouli et al., 2014) supports traffic flow and enables for a reciprocal error compensation of different involved participants by adapting maneuvers accordingly (Färber, 2016). Particularly in ambiguous scenarios, traffic participants use communication to announce upcoming actions proactively and therefore prevent from interferences during interactions (Färber, 2016).

However, due to the spatial separation of the different participants (e.g., drivers inside a vehicle and surrounding road users outside a vehicle) interactions and communication in road traffic is particularly challenging (Färber, 2016). Therefore, specific formal regulations are required as a basis for communication, such as road traffic regulations (e.g., for Germany the German Road Traffic Regulation; Straßenverkehrsordnung, 2021). These formal road traffic regulations are complemented by informal rules (Färber, 2016).

3.1 Models for describing communication in road traffic

Since the *Encoder-Decoder-Model* according to Shannon and Weaver (Shannon, 1948; Shannon & Waever, 1949) allows to classify distinct elements of a communication process, it can be used to some extent to describe the directed, short-term communication processes in road traffic (Schaarschmidt et al., 2021). According to the model (Shannon, 1948; Shannon & Waever, 1949), communication processes are initiated by a sender that encodes a message by a transmitter in form of signals. This transmitted message is sent over a noisy channel to a receiver. Finally, this transmitted message needs to be decoded by the receiver (Shannon, 1948; Shannon & Waever, 1949). For road traffic, sender and receiver in the model are different traffic participants with diverse options for sending communication signals (Schaarschmidt et al., 2021). Due to the previously mentioned spatial separation of the different traffic participants (Färber, 2016), messages are mainly communicated non-verbally (e.g., by motion parameters; Risto et al., 2017) and communication is frequently supported by technical devices (e.g., by the direction indicator of vehicles; Schaarschmidt et al., 2021). An additional challenge are potential errors that might occur during the transmission process that could inhibit feedback to the sender (i.e., noise influencing the communication; Shannon, 1948; Shannon & Waever, 1949), which highlights the requirement for conspicuous, distinct and intelligible communication signals in road traffic (Schaarschmidt et al., 2021) as well as shared knowledge by different traffic participants about applied signals (Röhner & Schütz, 2020).

However, since the Encoder-Decoder-Model (Shannon, 1948; Shannon & Waever, 1949) was primarily developed for describing the technical transmission of messages (i.e., sending and receiving messages), diverse aspects of interpersonal communication remain fairly disregarded within the model (Schaarschmidt et al., 2021). For instance, the general context of the overall communication situation (Schaarschmidt et al., 2021), the content of a sent message (Röhner & Schütz, 2020) and the interpretation of specific messages by the receiver of the message are not considered within the model (Schaarschmidt et al., 2021). Therefore, additional models also need to be respected for communication in road traffic that rather focus on the content of communicated messages (Schaarschmidt et al., 2021; e.g., the *Five Axioms of Communication* according to Watzlawick; Watzlawick (2016); *Four-Sides Communication Model* of Schulz von Thun (2010). For instance, these models emphasize the influence of previous experience on message decoding and interpretation (Schaarschmidt et al., 2021).

Regarding specific communication signals in road traffic, different classifications can be applied. For instance, there are classifications distinguishing between formality, modality or intentionality of applied signals (Schaarschmidt et al., 2021). The latter represents a commonly used taxonomy in human factors research considering communication in road traffic, leading to the distinction of implicit and explicit communication signals (e.g., Y. M. Lee et al., 2020; Markkula et al., 2020; Schieben et al., 2019).

3.2 Implicit communication in road traffic

Traffic participants predominantly use implicit signals for communicating and coordinating actions (for vehicle-pedestrian interaction see e.g., Dey & Terken, 2017; Rasouli et al., 2018; for vehicle-vehicle interaction see e.g., Imbsweiler et al., 2017) since these signals represent an important source of information when negotiating actions (Ackermann, Beggiato, Bluhm, et al., 2019; Dey & Terken, 2017; Harkin et al., 2023). Generally, implicit communication in road traffic can be defined according to Markkula et al. (2020) as *“A road user behaviour which affects own movement or perception, but which can at the same time be interpreted as signaling something to or requesting something from another road user*” (Markkula et al., 2020, p. 14).

For instance, positions (Himanen & Kulmala, 1988), movement gestures of traffic participants (Risto et al., 2017) and kinematics are applied as implicit communication signals in road traffic to anticipate and predict prospective actions (Risto et al., 2017). For instance, decelerating or maintaining speed is applied by drivers for signaling (not) giving priority to other traffic participants (e.g., Šucha et al., 2017; Várhelyi, 1998). Moreover, approach speeds of encountering traffic participants as motion parameters (Schneemann & Gohl, 2016) and thus resulting time gaps in traffic flow during interactions (Katz et al., 1975; Rasouli et al., 2017)

are used for coordinating actions (Bengler et al., 2020; Summala, 2007). Therefore, gaps in traffic flow might be applied as useful temporal and spatial parameters to understand maneuvering decisions in road traffic (Summala, 2007).

3.2.1 Gap acceptance for coordinating actions in road traffic

During interactions, people generally maintain specific thresholds of space and time to other entities (Hall, 1969). For the driving context it was described that road users move within particular safety zones of hypothetical spatial fields comprising specific hypothetical boundaries around their own entity (Gibson & Crooks, 1938). The capabilities of traffic participants to understand, predict and anticipate the prospective development of road traffic scenes and upcoming actions (Baumann & Krems, 2007; comparable to SA; Endsley, 1995) enables them to maintain such individual thresholds (Summala, 1988, 2007). Besides supporting road safety and efficiency, traffic participants' feeling of comfort might be supported by operating within these individual boundaries and thresholds (Stahl et al., 2014; Summala, 2007). Therefore, the concept of road users' individual safety margins was introduced by Summala (1988).

Time gaps in traffic flow and thus resulting safety margins to other traffic participants are used when coordinating interactions (Bengler et al., 2020; Summala, 2007). By adapting own maneuvers accordingly while initiating and conducting actions, additional time and space can be provided within road traffic scenes (Stahl et al., 2014). For instance, road users frequently need to decide accepting or rejecting a specific gap in traffic flow for initiating and conducting actions (Summala, 2007; e.g., crossing or turning actions due to potential space sharing conflicts; Markkula et al., 2020) that describes the individual gap acceptance behavior of individuals (GA; Summala, 2007).

Previous GA research primarily focusing on road safety (Hancock et al., 1991; Horswill et al., 2005; Y. M. Lee & Sheppard, 2017), identified several factors influencing selected gaps in traffic flow (Bottom & Ashworth, 1978; Y. M. Lee & Sheppard, 2017; Schleinitz et al., 2019). The size of approaching interaction partners were shown to impact GA for initiating driving actions (Hancock et al., 1991). Specifically, when encountering smaller interaction partners, smaller gaps were accepted for initiating driving maneuvers compared to encountering larger interaction partners (Alexander et al., 2002; Hancock et al., 1991; Robbins et al., 2018). For instance, it was reported by Hancock et al. (1991) that smaller gaps for initiating driving maneuvers were more frequently accepted when interacting with a motorcycle compared to larger vehicles such as trucks (Hancock et al., 1991), despite motorcycles represent a VRU with a particular risks in case of accidents (Holländer et al., 2021).

Since motion parameters are applied as important signals in road traffic (Risto et al., 2017), the approaching interaction partners' speed was also shown to influence GA when initiating maneuvers (Bottom & Ashworth, 1978; Schleinitz et al., 2019). Various studies from different road users' perspectives revealed a stable effect that smaller time gaps were accepted for initiating actions at higher speeds of the encountering interaction partner compared to lower speeds (for a drivers' perspective: Alexander et al., 2002; Bottom & Ashworth, 1978; Petzoldt, Schleinitz, et al., 2017; Schleinitz et al., 2019; for a pedestrians' perspective: Beggiato et al., 2017). The effect was also shown to be stable for various approaching interaction partners, such as vehicles of different sizes (Beggiato et al., 2017; Petzoldt, Ngoc, et al., 2017) or different two-wheelers (Schleinitz et al., 2019).

In addition, driver characteristics were also shown to influence GA parameters and resulting encounters between different road users (de Haan et al., 2022; Yan et al., 2007). Age was revealed to have an impact on accepted gaps in traffic flow leading to larger GA for initiating actions by older participants, representing more conservative decisions compared to younger participants (for a driver's perspective see de Haan et al., 2022; Yan et al., 2007; for a pedestrian's perspective see Beggiato et al., 2017; Oxley et al., 2005). The reported findings might be explained by participants' strategies to compensate for a decreased sensitivity for approach speed judgments of encountering interaction partners (Staplin, 1995) that were found from the fifth life decade (Scialfa et al., 1991). Moreover, drivers' sensation seeking, as a frequently examined personality trait in the context of driving (for an overview see Jonah, 1997), was revealed to impact preferred time gaps to surrounding road users, specifically resulting in smaller time headways to other road users for drivers scoring higher in sensation seeking (Heino et al., 1996). Since GA parameters represent individually preferred margins of space and time to surrounding traffic participants, they might be treated as one particular parameter of individual driving styles (Sagberg et al., 2015; Summala, 2007) that generally comprise preferences for specific parameters such as headway times and differ between individuals (Sagberg et al., 2015).

In short, accepted gaps in traffic flow are applied for coordinating actions during encounters (Summala, 2007). Previous research on safety aspects revealed that selected gaps are influenced by various factors (Hancock et al., 1991; Schleinitz et al., 2019). However, besides movements of traffic participants and gaps in traffic flow as a form of implicit communication (Y. M. Lee et al., 2020; Onkhar et al., 2022), explicit communication needs to be applied in several situations due to legal regulations (Straßenverkehrsordnung, 2021) or to resolve ambiguities if implicit communication exceeds its limits (Ackermann, Beggiato, Schubert, et al., 2019; Dey & Terken, 2017).

3.3 Explicit communication in road traffic

According to Markkula et al. (2020) explicit communication in road traffic can be defined as "*A road user behaviour which does not affect own movement or perception, but which can be interpreted as signaling something to or requesting something from another road user*" (Markkula et al., 2020, p. 15).

The application of explicit communication signals is to some extent legally regulated in road traffic regulations (for Germany: Straßenverkehrsordnung, 2021). For instance, in Germany the usage of the direction indicator for announcing prospective turning actions in road traffic is determined by these regulations (§9 StVO; Straßenverkehrsordnung, 2021). In addition, there are other explicit communication signals that are applied in road traffic such as gestures or eye contact between different traffic participants (Moore et al., 2019; Šucha et al., 2017).

In general, mutual eye contact between interaction partners represents an important communication signal (Argyle & Dean, 1965). It has the potential to signal mutual awareness between involved interaction partners (Argyle & Dean, 1965), to increase compliance (Kleinke, 1977), and provide feedback about applied behavior (Šucha et al., 2017). In the context of road traffic, eye contact is also discussed as an important communication signal (Rasouli et al., 2017; Šucha et al., 2017). It becomes particularly important during negotiations (Rasouli et al., 2017) between pedestrians and drivers in low-speed scenarios, including short distances, between the different interaction partners such as shared spaces (Lau et al., 2022). For instance, mutual eye contact was shown to increase the number of stoppings by drivers to let pedestrians cross the street (Guéguen et al., 2015). Moreover, eye contact was reported to increase pedestrians' perceived feeling of safety during crossing actions in front of vehicles, which is useful for comfortable interactions in road traffic (Onkhar et al., 2022). On the other hand it was argued that eye contact is not required for successful interactions, highlighting the importance of kinematics and movements (e.g., since in some scenarios achieving eye contact between traffic participants is not possible such as during bright sunlight that causes glare on the windshield of vehicles; Moore et al., 2019).

Additional communication signals explicitly showing a vehicle's deceleration action in form of a frontal brake light supplementing the vehicle's movement as implicit communication were investigated by Petzoldt et al. (2018). The signals aimed on potentially supporting pedestrians' road crossing actions when encountering vehicles. Due to the additional explicit signals, participants identified the vehicle's deceleration maneuvers easier and faster, which supported the decision process for their crossing actions. Thus, it might be concluded from the findings that explicit communication signals, as additional technology applied in vehicles, potentially

have the benefit to increase traffic safety and efficiency (Petzoldt et al., 2018). However, it is currently unclear whether such signals are comprehensively realizable in road traffic.

4 VEHICLE AUTOMATION

Vehicle automation is generally assumed to enhance traffic safety, its efficiency and driving comfort (SAE International, 2021). Therefore, an increasing amount of driving task components becomes automated and will be introduced into road traffic (Schieben et al., 2019).

System automation can be generally defined according to Parasuraman et al. (2000) as "*a device or system that accomplishes (partially or fully) a function that was previously, or conceivably could be, carried out (partially or fully) by a human operator"* (Parasuraman et al., 2000; p. 287). According to the given definition, automation should be seen as a continuum comprising a range of diverse automation levels (Parasuraman et al., 2000).

4.1 Levels of vehicle automation

Different taxonomies were established, comprising varying levels of automation (e.g., Sheridan & Verplank, 1978). One of the most commonly applied taxonomies regarding the driving task and enhanced automated driving functions in vehicles is the *J3016 standard* by the SAE (SAE International, 2021). The taxonomy defines six different levels of vehicle automation. Specifically, the different levels of automation are distinguishable regarding the lateral and longitudinal vehicle control, the defined fallback layer for conducting the driving task and the required supervision of the dynamic driving situation (SAE International, 2021).

SAE Level 0 (i.e., no driving automation) describes exclusively manual driving, however, safety features of the vehicles might be activated in this SAE level. In SAE Level 1 (i.e., driver assistance) lateral *or* longitudinal vehicle motion control (e.g., lane centering *or* adaptive cruise control) as one of the driving tasks, is performed by driving assistance. Meanwhile, the dynamic driving situation needs to be permanently supervised by the driver. In SAE Level 2, the driving assistance systems performs lateral *and* longitudinal vehicle control (i.e., partial driving automation). However, due to requested takeovers, the driver permanently needs to supervise the system and the dynamic driving situation and take over the driving task anytime if required in this SAE level (SAE International, 2021).

In the following levels of vehicle automation defined by the SAE (SAE International, 2021), automated driving functions are resulting due to the overall performance of the driving task by the vehicle automation including lateral and longitudinal control of the vehicle and the supervision of the dynamic driving scene. Particularly, in SAE Level 3 (i.e., conditional driving automation) the vehicle automation system acts within limited scenarios and conditions (i.e.,

operational design domains, ODDs; SAE International, 2021). Since there is the possibility of requested takeovers (i.e., the driving task is required to be continued by the manual driver) in cases when the automation functions exceed their limits, the manual driver acts as the fallback layer within this vehicle automation level. In SAE automation Level 4 and 5, there is no fallback layer in form of the manual driver required. More specifically, in SAE Level 4 (i.e., high driving automation), the vehicle automation is able to operate within certain ODDs. Whereas, AV functions are not restricted to certain ODDs in SAE Level 5 (i.e., full driving automation) and are supposed to operate under all conditions in road traffic (SAE International, 2021). In the current thesis the term *AV* (i.e., *automated vehicles*) comprises vehicles of SAE Level 3 or higher according to the taxonomy (SAE International, 2021).

Due to previously mentioned expected benefits of AVs (European Road Transport Research Advisory Council, 2017), these automation systems will be introduced in road traffic leading to a long transition period (Litman, 2019) comprising a variety of vehicles of different automation levels (i.e., manually driven vehicles up to SAE Level 2 coexisting with AVs SAE Level 3 or higher; SAE International, 2021). This coexistence of different traffic participants is described as mixed road traffic (Ioannou, 1998). To support successful interactions in mixed road traffic, the vehicle automation needs to interact with the driver or passenger(s) inside the vehicle and with surrounding traffic participants, such as pedestrians or manually driven vehicles (Bengler et al., 2020; Schieben et al., 2019). Due to legibility, the term *driver* will be applied in the following for the person in the current driver's seat regardless of the vehicles' automation level.

4.2 Challenges in automated driving

Despite assumed benefits of increased vehicle automation and automated driving (European Road Transport Research Advisory Council, 2017), several challenges of AVs are discussed considering the introduction of these vehicles into public road traffic (Schieben et al., 2019; van Loon & Martens, 2015). Besides potential challenges *inside* the vehicle due to increased automation mainly concerning the driver (e.g., required takeovers of the driving task by the manual driver in SAE Level 3; e.g., Brandenburg & Roche, 2020; Hergeth et al., 2016; SAE International, 2021), interactions with surrounding road users *outside* AVs might also face challenges in mixed road traffic (Habibovic et al., 2018). At present there are rarely AVs on public roads available (with a few exceptions e.g., autonomous shuttles that are currently operated in several pilot projects or model regions; Shuttle Modellregion Oberfranken (2020) or automated driving functions as mentioned in the introduction; Mercedes-Benz Group AG (2021)). Thus, surrounding road users' interaction experience as *incidental users* (Domeyer et al., 2020) with AVs in mixed road traffic is currently limited (Stange, 2021). Therefore, established interaction strategies from manual road traffic might be merely accessible for interactions (Stange, 2021).

To support successful, intuitive and predictable interactions in mixed road traffic, anticipated challenges during encounters between AVs and surrounding traffic participants as incidental users of this technology are currently discussed in human factors literature (Nyholm & Smids, 2020; Schieben et al., 2019; van Loon & Martens, 2015). Potential challenges, assumed to be particularly relevant during interactions in shared spaces, are elaborated in the following. For instance, AVs' highly defensive driving behavior as usually implemented in current studies (Stange, Kühn, et al., 2022b) or the transition of the drivers' role as interaction partner for surrounding road users are discussed as challenging in mixed road traffic (Schieben et al., 2019).

4.2.1 AVs' driving behavior during interactions

Since increased traffic safety is one of the main potentials assumed for automated driving (European Road Transport Research Advisory Council, 2017), AVs' driving behavior is currently implemented to be strictly rule-compliant (e.g., exactly obeying speed limits and maintaining large safety margins in traffic flow; deduced from expert interviews by Stange, Kühn, et al., 2022b) compared to manual drivers that may violate traffic rules to some extent and under specific circumstances (Nyholm & Smids, 2020). Such AV driving behavior potentially removes social behavior in mixed road traffic that would contribute to smooth interactions (Domeyer et al., 2020).

Previous studies implemented a highly defensive driving behavior in AVs to investigate potential consequences for interactions in mixed road traffic (Stange, Kühn, et al., 2022b). In particular, smooth acceleration and deceleration actions (Nyholm & Smids, 2020) or a highly conservative turning behavior at intersections including large required gaps in traffic flow was examined as AVs' driving behavior (Junghans et al., 2021). The defensive driving behavior implemented in AVs resulted in reduced traffic flow efficiency (Junghans et al., 2021) due to letting AVs rather act as an obstacle (Stange, Kühn, et al., 2022a). Moreover, frustration and thus aggressive behavior of manual drivers toward AVs was revealed leading to close, safety critical following distances in traffic flow (Stange, Kühn, et al., 2022a). Despite AVs' strictly rule-compliant behavior, manual drivers indicated reduced perceived feeling of safety and comfort (Stange, Kühn, et al., 2022a), potentially leading to mistrust during interactions with AVs showing such driving behavior (van Loon & Martens, 2015).

According to Nyholm and Smids (2020), these findings might be explained by the currently implemented diverging driving behavior of AVs compared to manually operated vehicles leading to compatibility issues of interaction capabilities. The experienced incompatibilities in driving behavior potentially restrict anticipating prospective maneuvers (Nyholm & Smids, 2020) and thus leading to participants' reduced comfort ratings during interactions (Stange,

Kühn, et al., 2022a). Particularly during the introduction of AVs and the long transition period (Litman, 2019), these issues are expected as challenging in literature with regard to successful interactions in mixed road traffic (Nyholm & Smids, 2020).

On the other hand, Stanton et al. (2020) found that participants were not able to distinguish between a manual driving mode and an automated driving mode of a vehicle when applying videos of lane change maneuvers recorded in real road traffic as study material. Besides the differences in investigated scenarios compared to Stange, Kühn, et al. (2022a), these findings might also highlight the significance of specifically implemented driving parameters in AVs (Stanton et al., 2020).

4.2.2 Interaction transformation in AVs

The increasing amount of vehicle automation is also assumed leading to new coordination and communication demands (Sarter et al., 1997; Schieben et al., 2019) due to changed interactions and transformed team compositions that might be considered as challenging in AVs (Schieben et al., 2019; Woods, 1996). In particular, interactions will prospectively transform from a dyadic relation in manual driving (i.e., comprising the driver of a vehicle and surrounding traffic participants) to a triadic constellation in automated driving (i.e., including the driver of a vehicle, surrounding traffic participants and the vehicle automation; which can be seen as a new team member; Schieben et al., 2019).

Whereas, the driver-AV communication remains to be meaningful to avoid contrary information communicated by the AV and the driver to surrounding traffic participants (e.g., due to mode confusion of the driver) to provide traffic safety and prevent discomfort of other road users (Schieben et al., 2019). The communication between AVs and surrounding traffic participants will also have a significant role since road traffic requires numerous interactions and drivers inside vehicles might be potentially distracted and thus no longer available as communication partner in AVs (Lagström & Lundgren, 2015; Schieben et al., 2019).

Since eye contact is discussed as an important communication signal between pedestrians and drivers (Šucha et al., 2017) in scenarios comprising low distances between the interaction partners (Lau et al., 2022), but might be impaired in automated driving due to driver inattention or absence, previous studies examined missing eye contact (Lagström & Lundgren, 2015; Rothenbücher et al., 2016). Generally, the results revealed that participants in the pedestrians' role would have preferred achieving eye contact with the driver of the interaction vehicle (Rodríguez Palmeiro et al., 2018). Beyond that, missing eye contact impaired interactions (Lagström & Lundgren, 2015; Rothenbücher et al., 2016) due to less perceived safety and comfort (Lagström & Lundgren, 2015) as well as reduced trust (Rothenbücher et al., 2016). In addition, traffic efficiency was also affected when the driver inside a vehicle was simulated to

be inattentive or absent and no eye contact was achieved. Specifically, more hesitant crossing decisions or a general diminished willingness by participants for crossing a street was reported (Lagström & Lundgren, 2015).

Therefore, interactions in AVs should be supported by communicating acknowledgement and compliance toward surrounding road users (Rothenbücher et al., 2016). In that regard, previous studies highlighted the vehicle behavior as an even more important source of information for prospective maneuvers if the driver was simulated to be absent or inattentive (Habibovic et al., 2018; Moore et al., 2019). This draws attention to the vehicles' movement as implicit communication that needs to be highly distinct, coherent and perceptible in AVs (Schaarschmidt et al., 2021). However, due to mentioned transformations considering the interaction constellation in AVs (Schieben et al., 2019), established forms of interpersonal communication between drivers and surrounding traffic participants in manual driving might need to be substituted or replaced by additional communication signals (e.g., in specific use cases if implicit communication exceed its limits such as in shared spaces; Ackermann, Beggiato, Schubert, et al., 2019; Schieben et al., 2019).

5 ENABELING AVS FOR PREDICTABLE INTERACTIONS IN MIXED ROAD TRAFFIC

Due to the previously mentioned exemplary challenges in AVs (Schieben et al., 2019; van Loon & Martens, 2015), appropriate solutions for successful interactions in mixed road traffic are required to support the usage and acceptance of this technology (Nyholm & Smids, 2020; Schieben et al., 2019). Prospective interactions in shared spaces need to be particularly considered (Schaarschmidt et al., 2021) due to rather undefined statutory regulations in these scenarios (Brill et al., 2023) and a diversity of different traffic participants interacting (Department for Transport, 2011) as incidental users of AVs (Domeyer et al., 2020).

There are various frameworks and models considering human-technology interactions due to the generally increasing amount of automation (Johnson et al., 2014; Tinga et al., 2023). For instance, frameworks focusing on human-robot interactions indicated that these interactions require transparent, predictable and directable actions when coordinating encounters (Johnson et al. (2014)); comparable to joint activities in human-human interactions; Klein et al. (2004)). Moreover, models with a focus on interactions *inside the vehicle* (i.e., between the vehicle automation and the driver) mainly focused on communication processes and shared SA, implying to provide information to the interaction partners as well as predicting and anticipating the prospective development of a scene (Tinga et al., 2023).

Given the requirements of previous frameworks and models (Johnson et al., 2014; Tinga et al., 2023), it might be concluded that successful interactions between AVs and *surrounding road users* also require predictable and intuitive actions that enable the involved traffic participants to establish joint activities (Klein et al., 2004) and adequate SA (Endsley, 1995) and therefore, apply a proactive interaction behavior during encounters (Mertens et al., 2020).

5.1 HMI framework in AVs

Bengler et al. (2020) developed a *human-machine interface (HMI) framework* for AVs as a methodological approach to consider potential interaction challenges due to increased vehicle automation (Figure 1). The framework describes a holistic HMI for AVs that combines several individual HMIs. These individual HMIs communicate information to various recipients and aim on supporting intuitive and predictable interactions in AVs and thus, the SA of involved manual road users (Bengler et al., 2020; comparable to human-technology team SA; Endsley, 2023).

In particular, the different HMIs included in the framework, influencing factors on the selection of the applied HMIs and specific information that should be communicated by the vehicle automation are mentioned within the framework. Since interactions between AVs, the driver inside the vehicle and surrounding road users are interdependent, the framework comprises a circular structure (Bengler et al., 2020). The different components of the framework are described in more detail in the following.

The selection and required information communicated by the individual HMIs are influenced by the vehicles' automation system including its current capabilities, the infrastructure (such as road type or traffic rules) and dynamic elements (i.e., addresses of HMI messages inside the vehicle, namely the driver and passengers, and surrounding traffic participants outside the vehicle). Moreover, the framework includes several internal HMIs communicating information to the driver and the passengers inside the vehicle. For instance, an automation HMI providing information about the automation system is defined within the framework (Bengler et al., 2020).

Since motion parameters are important for coordinating interactions during encounters in manual road traffic (e.g., GA parameters; Bengler et al., 2020; Summala, 2007), information communicated via the vehicle's dynamics are also considered in AVs and are labeled as *dynamic HMI* within the framework (dHMI; Bengler et al., 2020). To support successful interactions in mixed road traffic, AVs are required to directly communicate their intentions by vehicle dynamics but also need to be able to perceive and interpret dHMI information given by surrounding traffic participants and react accordingly (van Loon & Martens, 2015). Information provided by the dHMI are applicable for internal communication to the driver and

passengers as well as for the external communication to surrounding traffic participants around the AV (Bengler et al., 2020).

The *external HMI* (eHMI; Bengler et al., 2020) mainly communicates information to surrounding road users outside the AV. In manual road traffic, brake lights and direction indicators might be considered as current types of eHMIs that are legally required (Bengler et al., 2020). In AVs, additional eHMI signals could be applied to support interactions with surrounding road users if dHMI signals exceed their limits. Supplementary information about prospective driving actions might be provided by eHMIs considering intelligible and distinct communication signals (Ackermann, Beggiato, Schubert, et al., 2019). Moreover, eHMI signals might display the current automation status of an AV to surrounding road users or substitute the interaction with the former driver inside the vehicle. However, the selection and combination of different HMI types (e.g., dHMI and eHMI information) needs to be further investigated with regard to successful encounters in mixed road traffic (Bengler et al., 2020).

Since road traffic is a social system, there are frequent interactions between different road users (Domeyer et al., 2020). Therefore, the potential communication of AVs by dHMI and eHMI information as well as the combination of both HMIs with surrounding traffic participants in mixed road traffic is further elaborated in the following.

5.2 Dynamic human-machine interfaces (dHMIs)

5.2.1 Achieving interaction compatibility in mixed road traffic

Motion parameters are important communication signals in manual road traffic (Domeyer et al., 2020; Moore et al., 2019; Risto et al., 2017) since they support the prediction and anticipation of prospective actions and therefore, enable for a proactive behavior and successful interactions (Domeyer et al., 2020; Stahl et al., 2014). However, previous research highlighted several compatibility concerns related to an assumed and currently implemented highly defensive driving style of AVs (Stange, Kühn, et al., 2022b) and a thus diverging driving behavior compared to manual drivers potentially impairing successful interactions in mixed road traffic (van Loon & Martens, 2015).

Therefore, Nyholm and Smids (2020) presented and discussed several approaches to increase driving behavior compatibility in mixed road traffic, particularly when AVs are introduced to the market. The following approaches were suggested: Seeking merely for a collaboration between vehicle automation and manual drivers; adjusting manual driving behavior more toward artificial driving behavior, for instance by adjusting traffic regulations; or implementing established manual driving parameters in automated driving functions, providing established and intuitive interaction capabilities in AVs (Nyholm & Smids, 2020). To support predictable interactions in mixed road traffic, is seems not recommendable to introduce new,

potentially artificial driving patterns with AVs, since they are discussed as causing anticipated incompatibility issues when interacting with incidental users, potentially impairing a successful introduction of AVs (Nyholm & Smids, 2020; van Loon & Martens, 2015).

It was shown that human users apply social scripts of human-human interactions also to human-technology interactions (Li & Liu, 2023; Nass et al., 1996). Moreover, humans aim on reducing uncertainties during human-human interactions by achieving predictions about future behavior based on perceived similarities. These uncertainty reduction mechanisms relying on similarities of human-human interactions might be also applied for human-technology interactions (Berger & Calabrese, 1975). Applying existing interaction strategies of manual road traffic to AVs' driving functions would take advantage of such similarities concerning established knowledge and experiences during encounters (Domeyer et al., 2020; van Loon & Martens, 2015; Wilbrink et al., 2023). Therefore, a common ground for coordinating actions provided by shared expectations regarding interactions (Clark & Brennan, 1991; Shor, 1964) and thus lowered coordination costs and reduced surprises caused by automation (Klein et al., 2004) could be provided by this approach (e.g., van Loon & Martens, 2015). This in turn could be assumed to support traffic safety and efficiency when sharing spaces in mixed road traffic (Domeyer et al., 2020; Stahl et al., 2014).

According to van Loon and Martens (2015) two general aspects for achieving driving behavior compatibility between AVs and manual road users need to be considered: *Forward compatibility* describes a required concordant AV driving behavior compared to the applied behavior of manually driven vehicles, supporting the predictability of upcoming driving maneuvers conducted by AVs. Whereas, the feature of *backward compatibility* describes AVs' required capabilities for anticipating prospective actions of manual road users appropriately, derived from motion parameters of surrounding traffic participants such as lateral and longitudinal movements or positions (van Loon & Martens, 2015). Thus, upcoming AV maneuvers might be increasingly anticipated by surrounding traffic participants following the approach of applying currently established interaction capabilities from manual driving also in mixed road traffic (van Loon & Martens, 2015). This in turn would support a proactive behavior of manual traffic participants by adapting own maneuvers accordingly and therefore, providing additional time and space during encounters (Stahl et al., 2014). Moreover, by implementing manual driving parameters in AVs (Nyholm & Smids, 2020), comparable to experienced manual drivers (Krems & Baumann, 2009), would allow AVs to increasingly anticipate and predict prospective maneuvers and the development of road traffic scenes (van Loon & Martens, 2015). Therefore, AVs would be also enabled for a proactive driving behavior rather than a reactive behavior and could adapt own actions accordingly (Stahl et al., 2014). This approach would be particularly useful to ensure successful interactions with incidental users

of AVs, such as surrounding traffic participants (Domeyer et al., 2020). In summary, according to the literature it seems reasonable to build on existing and thus familiar interaction capabilities of manual road users and align AVs' driving behavior and interaction skills accordingly to manual road users in mixed road traffic that supports successful interactions (Nyholm & Smids, 2020; van Loon & Martens, 2015).

However, several constraints should be taken into account when implementing established interaction capabilities from manual driving in AVs. Manual drivers might engage in risky and potentially illicit driving maneuvers to some extent and under specific circumstances that is infeasible to be implemented in AVs (Nyholm & Smids, 2020). Therefore, the behavior of an ideal manual driver might be used as a role model in AVs (Pillai, 2017). A potential approach for applying established interaction capabilities in AVs would be to derive and quantify specific parameters of manual traffic participants in human user studies as a basic orientation for AVs' driving functions (Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Besides achieving behavior compatibility (van Loon & Martens, 2015), this approach (i.e., applied by Beggiato et al., 2017; Stange, Goralzik, et al., 2022) would counter the current disadvantages of deep learning mechanisms for AVs' driving parameters that lack the criteria of *observability, predictability and directability* (Johnson & Bradshaw, 2021; Klein et al., 2004).

5.2.2 Deriving gap acceptance parameters as a basis for AVs' driving functions

Since dHMI parameters work for both perspectives, as communication signals to the driver and passengers inside the vehicle and also to surrounding traffic participants (Bengler et al., 2020), various driving parameters, as dHMI parameters, were investigated for different perspectives considering intuitive and predictable interactions in AVs (e.g., Ackermann, Beggiato, Bluhm, et al., 2019; Bellem et al., 2018). For instance, acceleration (Bellem et al., 2018) and deceleration parameters (Stange, Goralzik, et al., 2022) were examined from a drivers' perspective with a focus on passenger comfort and perceived feeling of safety in AVs. In addition, pitch motion (Bindschädel et al., 2022) and deceleration parameters were assessed for prospectively coordinating encounters between AVs and surrounding road users (Ackermann, Beggiato, Bluhm, et al., 2019).

Previous studies aimed on quantifying and deriving specific parameters from manual driving that might be used as a basic orientation in specific AVs' driving functions (see e.g., Stange, Goralzik, et al. (2022) examining drivers' braking maneuvers onset times at intersections) to achieve interaction behavior compatibility with manual road users (van Loon & Martens, 2015). Since encounters in road traffic are frequently coordinated by gaps in traffic flow as spatial and temporal characteristics (Summala, 2007), Beggiato et al. (2017) investigated GA parameters from a pedestrians' perspective for crossing actions. The parameters could be

applied as an orientation for AVs' braking responses that should be initiated within a certain gap to intuitively communicate priority toward potentially crossing pedestrians (Beggiato et al., 2017).

A coordination of actions is particularly required in shared spaces (Brill et al., 2023). Therefore, GA parameters should be considered in further detail with regard to intuitive interactions in mixed road traffic within these settings (Beggiato et al., 2017). Besides pedestrians' GA, a deeper understanding of manual drivers' GA for initiating driving actions in shared spaces is also required for mixed road traffic (Hensch et al., 2021). However, previous GA research mainly focused on road safety aspects (Hancock et al., 1991). Different vehicle types as interaction partners were considered (e.g., passenger vehicle vs. motorcycle; Y. M. Lee & Sheppard, 2017; Robbins et al., 2018; different two-wheelers; Schleinitz et al., 2019). Since there is a high diversity of traffic participants that need to interact in shared spaces (Department for Transport, 2011), a variety of interaction partners should be also considered when focusing on drivers' GA in shared spaces for coordinating interactions in AVs. However, previous GA literature on safety aspects mainly considered higher speed levels of encountering traffic than common for shared spaces (e.g., 25mph/ about 40km/h vs. 55mph/ about 90km/h; Yan et al., 2007).

Overall, a deeper understanding of manual drivers' GA that might be applied in mixed road traffic as one specific parameter for coordinating interactions intuitively (Beggiato et al., 2017), such as initiating parking maneuvers, and potentially influencing factors need to be achieved. Manual drivers' GA parameters might be quantified and derived as a basic orientation for AVs' driving functions to support driving behavior compatibility and a proactive driving style, for instance by adapting own driving maneuvers accordingly (see Paper I of the current thesis; comparable approaches were presented by Beggiato et al. (2017); Stange, Goralzik, et al. (2022)).

5.3 External human-machine interfaces (eHMIs)

Shared spaces with a diversity of different road users interacting (Department for Transport, 2011) in low spatial distances (Lau et al., 2022) require for highly predictable encounters in mixed road traffic (Brill et al., 2023; Schaarschmidt et al., 2021). However, dHMI information are potentially ambiguous when exceeding their boundaries and might be insufficient in these settings (Schaarschmidt et al., 2021). Therefore, eHMI signals are discussed as a potential implementation in AVs to provide additional information if necessary and supplement or substitute communication if required (Ackermann, Beggiato, Schubert, et al., 2019; Schieben et al., 2019). Moreover, eHMIs might enhance the predictability of AVs' prospective driving actions for surrounding traffic participants (Habibovic et al., 2018) as incidental users of AVs

(Domeyer et al., 2020). Thus, these signals might have the potential to resolve ambiguities during encounters (Petzoldt et al., 2018) and support proactive interactions (Dey et al., 2022).

However, the introduction of new technologies, such as eHMIs, also entail new challenges that need to be considered (Ackermann, Beggiato, Schubert, et al., 2019; Sarter et al., 1997). Therefore, a fast growing body of human factors research considered eHMIs as potential means of communication in AVs (for an overview see e.g., Dey et al., 2020; Rouchitsas & Alm, 2019).

5.3.1 Specific implementation of eHMIs as means of communication in AVs

At the time when this thesis was prepared, there was merely a low number of particular legal regulations available for eHMI (for available *guidelines* and *checklists* see e.g., International Organization for Standardization [ISO], 2018; SAE International, 2018; Wilbrink et al., 2023). Therefore, investigated eHMI implementations are currently manifold (for an overview see e.g., Dey et al., 2020). For instance, investigated eHMI implementations differed regarding their communication modality (e.g., visual vs. auditory eHMIs; Mahadevan et al., 2018). Since, visual eHMIs were preferred over acoustic eHMI signals in user studies (Mahadevan et al., 2018) and represent the most commonly investigated form of eHMIs (Dey et al., 2020), this eHMI modality is also focused in the following sections.

There is currently only a small amount of particular legal regulations available for eHMIs (Wilbrink et al., 2023). If applied to vehicles, it is recommend to ensure the conspicuity of eHMI information from multiple directions around AVs and place the signals at an appropriate height (Eisma et al., 2019). Besides recommendations for the position of visual eHMIs, diverse conceptual implementations were investigated (Rouchitsas & Alm, 2019). For instance, anthropomorphic concepts (e.g., Chang et al., 2017), texts (e.g., Ackermann, Beggiato, Schubert, et al., 2019), symbols and icons (e.g., Clamann et al., 2017; Eisele & Petzoldt, 2022) or abstract light signals were assessed (e.g., Lau et al., 2021). Since LED light bands that display abstract light signals can be technically easily installed in vehicles, these signals have been considered as favorably for eHMI messages (Dey et al., 2020). Moreover, abstract light signals do not require specific language skills and are applicable in different contexts (e.g., for different user groups; Tabone et al., 2021). By implementing LED light bands all around the vehicle, eHMI signals' conspicuity from multiple directions around AVs might be provided (Eisma et al., 2019).

In addition, the perspectives of provided eHMI messages as potential means of communication in AVs are discussed in the literature (i.e., information about the AVs' status vs. provided instructions to surrounding road users; for an overview see Dey et al., 2020; Schieben et al., 2019). It should be considered that presenting AVs' status information requires

adequate SA of surrounding traffic participants since these information need to be interpreted in a first step and road users need to act accordingly considering these information (Dey et al., 2022; Endsley, 1995). Moreover, Ackermann, Beggiato, Schubert, et al. (2019) reported participants' preference towards instruction-based eHMI messages for surrounding road users compared to AVs' status information. However, Dey et al. (2022) argued that eHMI messages should comprise status information rather than instructions to other road users due to legal implications. Moreover, instructions to surrounding traffic participants are highly context and recipient dependent and therefore potentially ambiguous (Dey et al., 2022).

Various methodologies were applied to investigate eHMI implementations, such as monitor-based laboratory studies (e.g., Ackermann, Beggiato, Schubert, et al., 2019), virtual reality-based laboratory studies (e.g., Holländer et al., 2019) and field studies applying physical prototypes (e.g., Rothenbücher et al., 2016; for an overview see Rouchitsas & Alm, 2019). However, at the time of this thesis there were rarely field studies investigating physical eHMI prototypes that considered the assessment of technically easily installable but also abstract light signals by incidental users (Rouchitsas & Alm, 2019) in shared spaces that highly require interactions between different road users (Department for Transport, 2011). Therefore, the study of Paper II of the current thesis was conducted.

5.3.2 User assessment of eHMIs as additional means of communication in AVs

With regard to a human-centered development (ISO, 2019), previous studies revealed a generally positive impact of eHMIs on interactions between (simulated) AVs and surrounding VRUs (i.e., mainly pedestrians as investigated interaction partners; for an overview see Rouchitsas & Alm, 2019). Particularly, higher perceived feeling of safety (Böckle et al., 2017; de Clercq et al., 2019), increased ratings of trust (Faas, Mathis, et al., 2020) and acceptance toward AVs (Schindler et al., 2020) as important preconditions for a systems' usage and user reliance (Ghazizadeh et al., 2012; J. D. Lee & See, 2004) were indicated by participants when an eHMI was applied compared to conditions comprising exclusively vehicle movements (de Clercq et al., 2019; Faas, Mathis, et al., 2020; Schindler et al., 2020) as dHMI information (Bengler et al., 2020). Furthermore, interaction experience was revealed to positively impact eHMI assessment (e.g., increased ratings for feeling of safety or trust by increased experience; Faas, Kao, et al., 2020) as previously reported for interactions with AVs (Penmetsa et al., 2019) or technical systems in general (Cocron & Krems, 2013). The general effect of technology interaction experience on its assessment was shown to be stable for various user groups, such as different age groups (Hartwich et al., 2019). In addition, a higher traffic efficiency was reported when applying additional eHMI signals compared to baseline conditions covering only dHMI signals (e.g., reduced initiation times for crossing actions by participants; Faas, Mattes, et al., 2020). Overall, eHMIs could be considered as a promising

approach to increase the predictability of encounters in mixed road traffic between AVs and surrounding traffic participants as incidental users (Bengler et al., 2020; Schaarschmidt et al., 2021).

However, by applying eHMIs as additional means of communication in AVs, potential malfunctions resulting in unpredictable mismatches between provided eHMI messages und vehicle movements as dHMI information cannot fully be excluded (Holländer et al., 2019). Previous research reported declines of trust (Kaleefathullah et al., 2022) and perceived feeling of safety for eHMIs in case of system malfunctions (Holländer et al., 2019). Moreover, participants' perceived safety and confidence regarding AVs' prospective maneuvers was impaired when eHMI malfunctions occurred (Holländer et al., 2019). In addition, a habituation of eHMI signals was revealed, potentially impairing traffic safety in case of eHMI shortfalls due to longer identification times of merely dHMI signals (Petzoldt et al., 2018). Despite expected benefits for encounters, surrounding road users should be aware of potential eHMI malfunctions and act accordingly in such situations to provide road safety (Faas et al., 2021; Kaleefathullah et al., 2022).

Since elderly pedestrians (≥ 65 years) are over-represented in accident statistics, they need to be considered as particularly vulnerable road users (European Commission, 2023). Thus, elderly pedestrians might particularly benefit of potential advantages of AVs, such as increased road safety (Hensch et al., 2019). The application of eHMI signals as additional means of communication in AVs is generally assumed to support the predictability of AVs' prospective driving actions (Habibovic et al., 2018). These additional information might compensate for age-related declines of elderly to some extent (e.g., decreased walking speed during road crossing as revealed by Oxley et al. (2005); for an overview of age-related declines of elderly see Dunbar et al. (2004); Polders et al. (2015)). However, previous literature on different aspects of human-technology interaction reported ambiguous results concerning elderly users' attitude toward technology (e.g., Czaja et al., 2006; Hartwich et al., 2019). Specifically, lower usage rates (Tacken et al., 2005), less interest (Czaja et al., 2006) and reduced comfort compared to younger users were indicated by elderly when interacting with technology (Czaja & Sharit, 1998). Whereas, elderly users stated being more positive toward a technology (Hartwich et al., 2019; Rödel et al., 2014), were more likely to trust automated systems compared to younger users (for an overview see Schaefer et al., 2016) and stated a higher willingness to use a technology (Nordhoff et al., 2018). Therefore, this specific user group should be particularly considered with regard to eHMIs as potential means of communication in AVs (Schaarschmidt et al., 2021). Moreover, previous literature reported that elderly users were less sensitive and adjusted their trust in a technology less in case of system malfunctions compared to younger users (Ho et al., 2005). Given the previous findings

(Czaja et al., 2006; Hartwich et al., 2019; Ho et al., 2005), effects of potential eHMI malfunctions should be particularly investigated for this user group with regard to traffic safety (Schaarschmidt et al., 2021).

Currently, eHMI research rarely focused on elderly pedestrians as specific user group (as exception see Hensch et al., 2019; Othersen et al., 2018). Due to the previously reported general ambiguous attitude toward technology (Czaja et al., 2006; Hartwich et al., 2019), the marginal adaptation of system assessment ratings in case of malfunctions (Ho et al., 2005) and potentially resulting safety issues, elderly users' requirements with regard to eHMIs and potential system malfunctions should be investigated in closer detail (see Paper III of the current thesis; Schaarschmidt et al., 2021).

6 RESEARCH OBJECTIVES OF THE DISSERTATION

The different components of the dissertation project aimed on contributing to the research field considering intuitive and predictable interactions between AVs and surrounding manual road users in shared space settings, given the previously presented challenges that are assumed for mixed road traffic (Schieben et al., 2019; van Loon & Martens, 2015). Therefore, different forms of communication with surrounding road users were considered (i.e., dHMI and eHMI information). The research results might be respected to some extent when introducing and implementing a holistic HMI in AVs (Bengler et al., 2020).

Based on the above reported theoretical approaches and previous findings, the following general considerations were made with regard to predictable and intuitive interaction capabilities in AVs for mixed road traffic:

- Potential coordination capabilities of AVs are required to be intuitive and predictable for manual road users (Habibovic et al., 2018; Nyholm & Smids, 2020; van Loon & Martens, 2015), to support SA (Endsley, 1995) and a common ground for smoothly coordinating actions during encounters (Clark & Brennan, 1991).
- To substitute potentially lacking communication in automated driving and to support the predictability of AVs' prospective driving actions for surrounding road users, eHMI signals as additional means of communication in AVs might be applied in specific settings (Schieben et al., 2019).
- The requirements of specific user groups, such as incidental users with limited interaction experience considering AVs or elderly road users, should be considered when it comes to eHMIs as potential means of communication in AVs (Domeyer et al., 2020; Schaarschmidt et al., 2021).

Due to the mentioned considerations the following research objectives were examined within the current dissertation project:

6.1 Research objective 1: Examining and deriving manual drivers' gap acceptance parameters when initiating parking actions as a basic orientation for intuitively initiating parking maneuvers in AVs

For implementing intuitive and predictable interaction capabilities in AVs, manual driving parameters as dHMI parameters (Bengler et al., 2020) might be derived as a basic orientation for AVs' driving functions (e.g., Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Since shared spaces frequently require interactions between diverse traffic participants (Brill et al., 2023) and encounters between traffic participants are often coordinated by gaps in traffic flow (Bengler et al., 2020; Summala, 2007), it seems reasonable to further consider GA as an important parameter (Beggiato et al., 2017). However, at the beginning of the current dissertation project, GA research with a focus on AVs' driving parameters from a drivers' perspective was rather lacking since previous research mainly focused on safety aspects (e.g., Hancock et al., 1991). Therefore, the first research objective was to examine manual drivers' GA as a basic orientation for AVs' driving functions (comparable to approaches by Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Specifically, GA parameters for initiating parking actions while encountering different traffic participants approaching with various speeds in a shared space setting were collected. Since GA could be also seen as a parameter of individual driving styles (Summala, 2007), driver characteristics were also considered to be prospectively respected in selectable AV driving styles (Hensch et al., 2021). The revealed GA parameters might be used as a basis for intuitively initiating parking maneuvers in AVs and therefore supporting driving behavior compatibility with manual drivers (comparable to Beggiato et al., 2017; Stange, Goralzik, et al., 2022; van Loon & Martens, 2015). The results of the conducted study were reported in Paper I.

6.2 Research objective 2: Assessing abstract eHMI signals as additional means of communication in AVs by incidental users in a shared space setting

Additional eHMIs signals provided by technically easily installable LED light bands seem a promising approach for supporting the communication in AVs with surrounding road users (Dey et al., 2020). When the dissertation project was started, there were rarely field studies in shared space settings applying physical prototypes considering the assessment of abstract eHMI signals as means of communication in AVs by incidental users (Rouchitsas & Alm, 2019). Therefore, the second research objective focused on the assessment of abstract visual eHMI signals in AVs by pedestrians as incidental users without prior knowledge about applied

signals. A Wizard-of-Oz approach (Dahlbäck et al., 1993) was applied to simulate an AV with an eHMI in a shared space setting (comparable to e.g., Rothenbücher et al., 2016). Participants' system assessment, namely perceived feeling of safety during the interactions, the signals' intuitive comprehensibility, trust in, usefulness of the investigated signals and the general assessed usefulness of eHMI signals was examined after encounters with the interaction vehicle in the study of Paper II.

6.3 Research objective 3: Investigating participants' eHMI assessment considering interaction experience with the system and multiple malfunctions of the system

Interaction experience with eHMIs as technical systems was reported to influence the system assessment positively (Faas, Kao, et al., 2020). However, potential malfunctions of eHMIs, leading to contradicting information between eHMI and dHMI information, cannot be fully excluded if the systems are introduced to the market (Holländer et al., 2019). Therefore, an appropriate level of system assessment is required by surrounding road users to benefit from additional information provided by eHMI signals during encounters with AVs but also consider dHMI information in an appropriate manner in case of eHMI malfunctions (Faas et al., 2021). Therefore, the third research objective was to investigate the effect of eHMI interaction experience and multiple malfunctions on participants' system assessment. Specifically, perceived feeling of safety during the interactions, trust in (Jian et al., 2000) and acceptance of the system (i.e., usefulness and satisfaction; Van Der Laan et al., 1997) were repeatedly examined from a pedestrians' perspective in a recorded shared space scenario displaying encounters with an interaction vehicle including an augmented visual eHMI (Paper III).

6.4 Research objective 4: Examining differences in eHMI assessment between younger and elderly pedestrians

Elderly pedestrians are over-represented in accident statistics (European Commission, 2023) and thus might particularly benefit of additional information provided by eHMIs that potentially support the predictability of encounters with AVs (Habibovic et al., 2018). However, as previously reported, elderly users' attitude toward technology is rather ambiguous (Czaja et al., 2006; Hartwich et al., 2019). Currently, only little research on eHMIs respects potential requirements of elderly pedestrians as a specific user group (as exception see e.g., Othersen et al., 2018). Therefore, special consideration was given to differences in system assessment considering interaction experience and experienced eHMI malfunctions between younger (18 – 40 years) and elderly pedestrians (≥ 65 years) within the fourth research objective (Paper III).

6.5 Integration of conducted studies of the thesis into the HMI framework by Bengler et al. (2020)

Encounters between AVs and surrounding traffic participants as incidental users of the technology will frequently occur in mixed road traffic (Domeyer et al., 2020), particularly in shared spaces with a high demand for interactions (Brill et al., 2023). Therefore, dHMI and eHMI information as potential means of AVs' communication capabilities to surrounding road users should be specifically considered in these settings to increase the predictability of interactions (Bengler et al., 2020; Habibovic et al., 2018). When implementing a holistic HMI in AVs (including dHMI and eHMI), the requirements of manual road users should be respected (Bengler et al., 2020; Figure 1). Therefore, the present thesis particularly focused on GA parameters when initiating parking actions as a dHMI parameter that might be used as a basic orientation for intuitive AV driving functions (comparable to Stange, Goralzik, et al., 2022; Paper I; Figure 1); participants' assessment of abstract eHMI signals as potential means of communication in AVs without prior knowledge (Paper II; Figure 1); the effect of eHMI experience and eHMI malfunctions contradicting vehicle movements as dHMI information on younger and elderly participants' system assessment (Paper III; Figure 1).

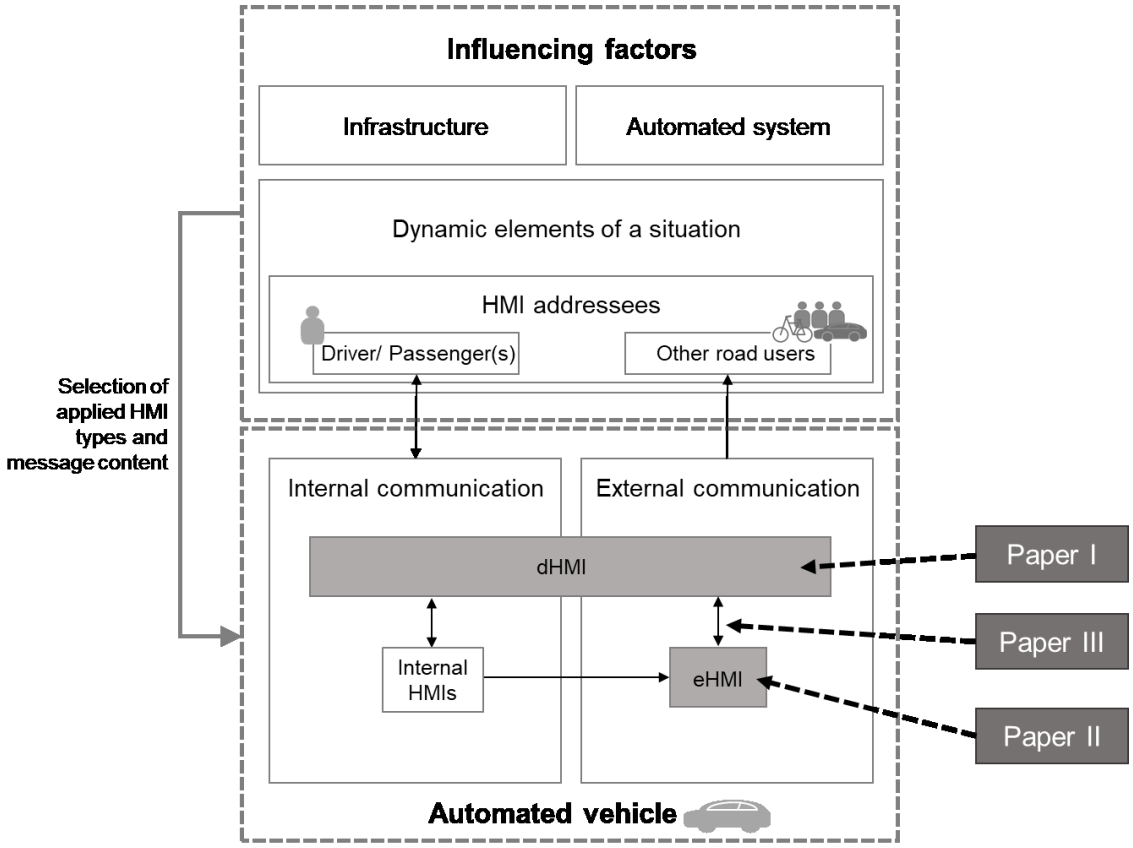
7 OVERVIEW OF THE APPLIED METHODOLOGY

The data of the current dissertation were collected within the projects InMotion (BMVI, Grand no. 16AVF2016A), @City-AF (BMWi, Grand no. 19A18003L) and the Collaborative Research Center "Hybrid Societies" (DFG, Project-ID 416228727 — SFB 1410; project D02 "Implicit driving cues") mainly focusing on interaction capabilities of AVs.

Overall, the thesis comprises three experimental studies using different methodologies. To derive manual drivers' GA parameters as dHMI information when initiating parking maneuvers in a shared space setting with different encountering interaction partners, a laboratory study was conducted (Paper I; research objective 1). The revealed parameters might be used as a basic orientation in AVs' driving functions for intuitively initiating parking maneuvers (for comparable approaches see Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Abstract eHMI signals as additional means of communication in AVs (Schieben et al., 2019) were investigated by a Wizard-of-Oz approach (Dahlbäck et al., 1993; Rothenbücher et al., 2016) encountering incidental users in a shared space setting (Paper II, research objective 2). Moreover, the effect of eHMI experience and malfunctions contradicting vehicle movements as dHMI information on younger and elderly pedestrians' system assessment was investigated in a further laboratory study (Paper III; research objectives 3 and 4).

Figure 1

Visualization of the HMI framework according to Bengler et al. (2020), including a classification of the journal papers of the present thesis



Note. Visualization of the HMI framework according to Bengler et al. (2020) comprising influencing factors on HMI selection and the different HMI types as suggested for AVs. Due to their potential for communicating with surrounding road users, the dHMI and eHMI are highlighted within the visualization since representing important concepts of the present thesis. A classification of the journal papers of the present thesis is added within the framework (adapted from Bengler et al. (2020); internal HMIs are adapted, highlights of eHMI, dHMI and icons of traffic participants and classification of the thesis' journal papers are added). From "From HMI to HMIs: Towards an HMI framework for automated driving," by K. Bengler, M. Rettenmaier, N. Fritz, and A. Feierle, 2020, *Information, 11*(2), p. 3 (https://doi.org/https://doi.org/10.3390/info11020061).

The method of the laboratory studies and the Wizard-of-Oz approach will be summarized in the following sections. Further details of the applied methods are described in the respective papers (Paper I-III).

7.1 Laboratory studies

Laboratory studies generally allow to systematically vary and control potentially influencing factors on assessed aspects. For the road traffic context, laboratory studies provide the

additional advantage of participants' safety. Moreover, laboratory studies are time and cost-efficient compared to other implementations such as field studies (Vollrath & Krems, 2011).

To provide a realistic impression of the respectively investigated scenarios despite the laboratory setting, video material displaying real-world road traffic scenarios was applied in the conducted studies of Paper I and Paper III of the current thesis (a comparable approach was applied by Beggiato et al., 2017).

For an exact control and manipulation of influencing factors (Vollrath & Krems, 2011), the study reported in Paper I investigated manual drivers' GA parameters in a laboratory approach. Participants' GA for initiating parking actions in a shared space setting with encountering interaction partners of different sizes, approaching with different low speeds and driver characteristics as influencing factors on GA were examined. The derived parameters might be used as a basic orientation for intuitive driving functions in AVs when initiating parking maneuvers (comparable to Beggiato et al., 2017). Generally, there is a broad research tradition for GA studies (Bottom & Ashworth, 1978; Gibbs, 1968; Hurst et al., 1968) primarily with a focus on road safety aspects (Hancock et al., 1991; Horswill et al., 2005; Y. M. Lee & Sheppard, 2017). GA in traffic flow is mainly investigated in intersection (i.e., for drivers' GA; Petzoldt, Schleinitz, et al., 2017; Schleinitz et al., 2019) or road crossing scenarios (i.e., for pedestrians' GA; Beggiato et al., 2017) due to overlapping trajectories of involved road users and a required coordination of actions (Wilbrink et al., 2018). Encountering traffic participants, representing the traffic flow, approach with a constant speed from a predetermined distance at the observer's point of view (i.e., the participant's perspective; Lee & Sheppard, 2017; Schleinitz et al., 2015). Indicating the individual accepted gaps for starting specific actions by pressing a button proved as beneficial tradeoff between level of empirical realism and participants' safety in GA studies (Schleinitz et al., 2015). Within the study of Paper I, participants were asked pressing a button to indicate the last acceptable moment for initiating a left-turn parking action in front of approaching traffic into an empty parking space. The applied methodology is described in detail in Paper I.

In previous research, eHMI signals and potential system malfunctions were also frequently investigated in laboratory settings to ensure participants' safety in case of the investigated eHMI malfunctions (Holländer et al., 2019; Kaleefathullah et al., 2022). Here several short video sequences were presented to the participants followed by a system assessment (Petzoldt et al., 2018). The study reported in Paper III of the current thesis applied a comparable approach for investigating the effect of eHMI experience and malfunctions on younger and elderly users' system assessment. The video sequences of the current study were recorded from a pedestrians' perspective and displayed encounters with an approaching interaction vehicle including an augmented eHMI in a shared space setting. The videos were

recorded in front of an empty parking space (i.e., the participants' perspective), which the participants were instructed intending to cross. After several video sequences displaying encounters with the interaction vehicle, participants' repeatedly assessed the system by questionnaires (i.e., during an initial measurement without interaction experience (t_0), after encountering a valid system (t_1) and after experiencing multiple system malfunctions (t_2)). The system's malfunctions, for instance, comprised an eHMI signal displaying that the vehicle would yield for the participants to cross the empty parking space in front of the vehicle despite initiating a parking action, which might have resulted in safety critical encounters in the field. The detailed methodology of the study is described in Paper III.

7.2 Wizard-of-Oz study

Wizard-of-Oz approaches represent a potential implementation to enhance the generalizability of research results in the field when investigating eHMIs as potential communication capabilities in AVs (for an overview see Fuest, 2021; Rouchitsas & Alm, 2019).

The Wizard-of-Oz approach is an established research method that has been previously applied in human-computer interaction research for developing and examining dialog systems (e.g., Dahlbäck et al., 1993). Thereby, a human investigator (i.e., the wizard) is hidden from the participants while performing the role of the technical system during the simulated human-computer interaction (Fraser & Gilbert, 1991). Thus, the approach enables to investigate a wide and flexible range of implementation alternatives of potential systems (Hoffman & Ju, 2014) in an early development phase of these systems (Habibovic et al., 2016). Moreover, applying a Wizard-of-Oz approach proved to be less expensive compared to actual prototypes of technical systems (Habibovic et al., 2016).

Due to the mentioned benefits, Wizard-of-Oz approaches also became popular in AV research (e.g., Rodríguez Palmeiro et al., 2018; Rothenbücher et al., 2016). Specifically, a driver of a manually operated vehicle is commonly hidden and covered by a seat suit, which lets the vehicle appear driverless and thus automated to surrounding traffic participants (e.g., Dey et al., 2019; Fuest et al., 2018; Rothenbücher et al., 2016). Since it was reported that the majority of surrounding road users not noticed the hidden driver of the vehicle, an AV simulation could be realizable by this approach (Rothenbücher et al., 2016). Thus, is seems reasonable to apply the Wizard-of-Oz approach when investigating prospective interactions in mixed road traffic between AVs and manual road users (e.g., implemented by Fuest et al., 2018; Rothenbücher et al., 2016). A Wizard-of-Oz study simulating an AV where the driver was covered by a seat suit was also conducted in the current dissertation project to investigate abstract eHMI signals as means of communication in AVs by incidental users in a shared space scenario (Paper II). Naïve participants as incidental users assessed different abstract

eHMI signals respectively that were presented by a light bar on the roof of the simulated AV. More details of the applied methodology is described in Paper II.

8 MAIN RESULTS AND DISCUSSION

The following chapter presents an overview of the main findings of the conducted studies of the current thesis. Revealed results are discussed considering the research objectives of the thesis. Selected methodological considerations and potential requirements for further research are also discussed in the following respective sections. Further details are presented in the respective Papers I to III of the thesis.

8.1 Main findings and discussion regarding gaps in traffic flow for coordinating encounters

8.1.1 Research objective 1: Manual drivers' gap acceptance as a basic orientation for AVs' driving functions when initiating parking maneuvers

To overcome assumed driving behavior compatibility issues between AVs and manually driven vehicles (e.g., due to a highly defensive driving style of AVs as currently implemented in research studies; Junghans et al., 2021; Nyholm & Smids, 2020; Stange, Kühn, et al., 2022b; van Loon & Martens, 2015), established interaction capabilities of manual drivers might serve as a role model (Pillai, 2017) and could be used as a basis for AVs' driving functions (Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Since interactions in manual road traffic are often coordinated by accepted gaps in traffic flow as dHMI information (Bengler et al., 2020; Summala, 2007), research objective 1 considered manual drivers' GA parameters in closer detail (Paper I).

Specifically, the study presented in Paper I aimed on examining and deriving manual drivers' GA parameters as a specific driving parameter that might be used as a basic orientation considering intuitive and predictable driving functions in AVs (for comparable approaches see Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Accepted gaps for initiating parking actions in a shared space setting when encountering different traffic participants were collected in a laboratory study applying video material recorded from a drivers' perspective. As situational factors, the effect of size and speed of approaching interaction partners were investigated. Moreover, the influence of driver characteristics, namely age and the personality trait sensation seeking, on GA was also examined within the study (Paper I).

The indicated gaps within the conducted study for initiating parking actions were generally sufficient in terms of traffic safety. When focusing on the revealed gaps, manual drivers indicated smaller GA when encountering smaller interactions partners in contrast to larger vehicles, which was also reported by previous GA studies rather focusing on safety aspects

(e.g., Hancock et al., 1991; Robbins et al., 2018). However, the absolute time differences in GA values between the investigated interaction partners were comparably small (i.e., less than one second). It should be respected that the smallest encountering interaction partner in the conducted study represented a motorcycle (i.e., a VRU) being rather fragile in case of accidents (Holländer et al., 2021). Thus, the results raised the question whether it is sufficient to consider the perspective of one interaction partner during encounters when investigating manual driving parameters as a basic orientation for AVs' driving functions. Rather, specifically for the investigated scenario and the parameter of accepted gaps when coordinating actions, the findings imply that the perspective of encountering interactions partners should be also respected when aiming on successful encounters and a comprehensive concept of successful interactions in mixed road traffic for all road users.

With regard to the approaching speed of encountering interaction partners, smaller temporal gaps were accepted at higher speeds of the upcoming vehicles. This was also revealed by previous findings considering GA with a focus on traffic safety (Bottom & Ashworth, 1978; Petzoldt, Schleinitz, et al., 2017; Schleinitz et al., 2019). It might be argued that AVs could use these smaller temporal accepted gaps for initiating maneuvers at higher approach speeds of encountering vehicles in terms of enhancing traffic efficiency and still provide intuitive driving behavior as common in manual road traffic (Paper I).

Moreover, there was an effect of driver characteristics on GA revealed. Particularly, older participants (≥ 45 years) indicated larger GA for initiating parking actions compared to younger participants (18 – 30 years), which is in line with previous GA research (Beggiato et al., 2017; Yan et al., 2007). In addition, the results revealed that drivers' scoring higher in sensation seeking preferred smaller time gaps during encounters compared to participants scoring lower in sensation seeking (comparably to Heino et al. (1996) for investigated time headways). Based on the results, it might be argued that driver characteristics and resulting preferences for driving parameters, such as GA as one specific parameter, should be also respected in AVs' driving functions to provide driving comfort (comparable to Bellem et al., 2018).

Overall, it can be concluded that there is no one specific time gap that is always considered as adequate in terms of intuitive and predictable maneuvering decisions when initiating parking maneuvers in front of encountering interaction partners (comparable to Beggiato et al. (2017) for participants' GA as a basis for intuitive AV braking parameters). Rather, various factors influenced manual drivers' maneuvering decisions. In order to provide a common ground when interacting (Clark & Brennan, 1991) and to prevent from potential compatibility issues with manual road users (van Loon & Martens, 2015), influencing factors on maneuvering decisions when initiating parking actions also need to be respected in AVs' driving parameters to provide successful encounters (Stange, Goralzik, et al., 2022).

Moreover, by equipping AVs with differentiated knowledge about influencing factors on manual drivers' decisions (Beggiato et al., 2017; comparable to experienced manual drivers; Krems & Baumann, 2009), the vehicles would be enabled to provide proactive encounters by anticipating prospective driving actions and adapting own maneuvers accordingly (Stahl et al., 2014; van Loon & Martens, 2015). Thus, the derived GA parameters of the study might be used as an orientation for one particular parameter in AVs' driving function (comparable to Stange, Goralzik, et al., 2022). It should be noted that additional factors potentially influencing GA and their specific impact as well as different traffic scenarios need to be further investigated to provide a comprehensive basis for intuitive and predictable driving functions in AVs (Paper I).

With regard to the applied method of a laboratory study presented in Paper I, it should be acknowledged that influencing factors were systematically controlled. However, since laboratory studies potentially suffer from low external validity due to artificial conditions (Vollrath & Krems, 2011), GA parameters as a basis for AVs' driving functions also need to be investigated in driving simulator and field studies that provide a higher external validity and a more realistic setting for real road traffic (Vollrath & Krems, 2011; Paper I).

8.2 Main findings and discussion regarding eHMIs as potential additional means of communication in AVs

Research objectives 2 to 4 considered eHMI signals as potential means of communication in AVs. The signals might provide an additional source of information aiming on supporting the predictability of maneuvers during interactions with AVs and the SA of surrounding traffic participants (Endsley, 1995; Habibovic et al., 2018). Particularly in shared spaces with few statutory regulations (Department for Transport, 2011) and a low amount of road markings (Moody & Melia, 2014), eHMIs might contribute to support predictable and successful encounters in mixed road traffic (Brill et al., 2023). The main findings of the studies reported in Paper II and III are highlighted and discussed in the following sections.

8.2.1 Research objective 2: Assessment of eHMI signals as potential means of communication in AVs by incidental users

Paper II focused on the assessment of abstract eHMI light signals as potential means of communication in AVs by participants without prior knowledge about the signals. Therefore, a Wizard-of-Oz approach was applied where a seat suit covered the driver of the test vehicle and thus simulated an AV (comparable to Rothenbücher et al., 2016). Since the vehicle moved within a shared space setting (i.e., scenario of a parking area), interactions with various pedestrians as incidental users of the eHMI and the simulated AV occurred, exceeding mere one-to-one encounters. To provide highly conspicuous signals, a light bar presenting different

eHMI signals was placed on the roof of the test vehicle (as recommended by Dey et al., 2020). Participants were asked to indicate their perceived feeling of safety during the interaction with the test vehicle. Moreover, the intuitive comprehensibility of the applied eHMI signals, trust, assessed usefulness of the investigated signals and the general usefulness of eHMI signals were evaluated by the participants (Paper II).

The findings of the study revealed that participants felt generally safe during encounters with the interaction vehicle mainly due to the rather defensive driving style and the large spatial distance to the vehicle. However, participants indicated a significantly lower perceived feeling of safety in the simulated AV condition (i.e., when the driver was covered by the seat suit and the vehicle appeared driverless), which was similarly reported by previous studies that simulated an absent or distracted driver (e.g., Lagström & Lundgren, 2015; Rodríguez Palmeiro et al., 2018). A possible explanation might be given by the missing eye contact, since generally signaling awareness and providing feedback to interaction partners (Argyle & Dean, 1965; Šucha et al., 2017), which could not be achieved in the simulated AV condition due to the absent (i.e., covered) driver in the current study (comparable to Lagström & Lundgren, 2015).

For substituting the missing interaction between drivers and surrounding road users and enhancing the predictability of prospective driving maneuvers, eHMIs as potential means of communication in AVs were applied in the study (as suggested by Schieben et al., 2019). However, the applied eHMI signals did not have an effect on participants' perceived feeling of safety. The findings might be explained since the investigated abstract eHMI signals were assessed as rather unintuitive without prior knowledge about their assigned meanings (as comparably mentioned by Schaarschmidt et al., 2021) and therefore, might not have contributed to increase the predictability of prospective maneuvers of the interaction vehicle and the overall traffic situation (as mentioned by Habibovic et al., 2018). In conducted interviews, participants' mainly stated being uncertain about the signals' assigned meanings, despite the signals were linked to situational context, such as the vehicles' movement (Paper II). The results are in contrast to Eisele and Petzoldt (2022) who found in their online study that additional contextual factors improved the intelligibility of investigated eHMI signals. However, Eisele and Petzoldt (2022) investigated icons as eHMI signals in contrast to the current study that applied abstract eHMI signals.

The low intuitiveness of the applied eHMI signals might have also impacted the assessed trust in and the perceived usefulness of the investigated signals that were only partially given in participants' evaluation (Paper II). However, applying text messages as more distinct eHMI signals as suggested by Ackermann, Beggiato, Schubert, et al. (2019) seems not recommendable due to the technical feasibility (i.e., large displays would be required for

presenting the messages; Clamann et al., 2017) and the accessibility of provided messages (i.e., language skills would be required for text messages; Tabone et al., 2021). On the other hand, a general application of eHMI signals in AVs was assessed as useful by incidental users of the current study (comparably reported by Schieben et al., 2019). These findings imply that eHMI signals might have the potential to be prospectively applied as means of communication in AVs (Paper II).

However, to ensure the benefit of abstract eHMI signals, it might be argued that previous information about signals' meanings need to be provided, comparable to assigned meanings for traffic signs in general (Schaarschmidt et al., 2021) since the mere context of a traffic situation revealed to be insufficient within the current study to deviate the signals' meanings (in contrast to Eisele & Petzoldt, 2022). This raises the question, how these signals would be evaluated given prior knowledge about their assigned meanings (as mentioned by Schaarschmidt et al. (2021) for traffic signs in general) and the development of eHMI assessment when achieving interaction experience with the system (as investigated by e.g., Faas, Kao, et al., 2020). Moreover, further research is needed to identify specific steps for calibrating an appropriate assessment of eHMI signals (Faas et al., 2021), such as perceived safety during interactions, trust and perceived usefulness of the abstract signals.

8.2.2 Research objective 3: Influence of system experience and malfunctions on eHMI assessment

Due to the results of the study reported in Paper II considering the low intuitiveness of abstract eHMI signals as means of communication, prior knowledge about eHMIs was provided to the participants before interacting with the system in the study of Paper III. Specifically, information about the general concept of eHMI, the applied eHMI signals and their respective meaning were given to the participants in the study (Paper III).

The study investigated the development of participants' system assessment due to interaction experience and the impact of multiple system malfunctions, implying a mismatch between vehicles' movement as dHMI information and provided eHMI signals (Hensch et al., 2022; Holländer et al., 2019). Multiple potentially ambiguous encounters with an interaction vehicle were assessed in the laboratory study. Short video sequences recorded in a parking area as a scenario of a shared space displayed interactions with an approaching vehicle including an eHMI implemented in the windshield. The material was recorded from a pedestrians' perspective. Participants assessed the system repeatedly, during an initial measurement without interaction experience (t_0), after encountering a valid system (t_1) and after experiencing multiple system malfunctions (t_2) and indicated their perceived feeling of safety during the

interactions (t_1 + t_2), trust (Jian et al., 2000; t_0 - t_2) and acceptance (i.e., usefulness and satisfaction according to Van Der Laan et al., 1997; t_0 - t_2) of the eHMI signals (Paper III).

According to the initial measurement when receiving prior information about eHMIs and the assigned signal meanings (i.e., t_0), participants indicated to trust and accept the system. After gaining interaction experience with the system (i.e., t_1), participants' trust and acceptance ratings (i.e., usefulness; Van Der Laan et al., 1997) toward the eHMIs increased in contrast to the initial measurement (t_0 vs. t_1). Moreover, participants indicated to feel rather safe during encounters when gaining interaction experience (t_1). The results are in line with Faas, Kao, et al. (2020) who applied a much longer time period of three weeks for achieving system experience in contrast to the study reported in Paper III that provided a shorter time period for gaining system experience. Since the results revealed a positive effect of interaction experience on participants' system assessment, training sessions or publicity campaigns considering AVs and eHMIs might be provided to prospectively support their introduction and successful interactions in mixed road traffic (Faas, Kao, et al., 2020). However, required durations for achieving sufficient system experience is needed to be further determined.

After experiencing multiple system malfunctions (e.g., displayed eHMI signal to let participants cross the empty parking space in front of the interaction vehicle but initiating of a parking action into this parking space; i.e., t_2), participants' system assessment declined in terms of reduced perceived feeling of safety during the interactions (t_1 vs. t_2). Moreover, reduced trust and acceptance ratings (i.e., usefulness and satisfaction; Van Der Laan et al., 1997) toward the eHMIs were indicated by the participants compared to valid system functions (t_1 vs. t_2). Thus, participants seemed to adapt their eHMI system assessment dynamically (e.g., by adjusting trust in the system; Hoff & Bashir, 2015). The system assessment should be calibrated appropriately to support an adequate system usage (Faas et al., 2021). The findings are consistent with previously reported results on single eHMI malfunctions for settings comprising higher initial speed levels of an interaction vehicle (Faas et al., 2021; Holländer et al., 2019). Despite interacting in a shared space as a low-speed setting (Department for Transport, 2011), participants seemed to be sensitive for dHMI information in case of eHMI malfunctions in the study of Paper III. Thus, it should be acknowledged that dHMI and eHMI information need to be consistent with each other to support traffic safety and to provide additional benefits when combining these HMIs in mixed road traffic (Bengler et al., 2020; Wilbrink et al., 2023).

The conducted laboratory study merely provided low external validity but ensured participants' safety (Vollrath & Krems, 2011) due to investigating system malfunctions (comparably to Kaleefathullah et al., 2022). However, despite applying video sequences in a laboratory study as material, eHMI interaction experience and malfunctions impacted participants' assessment of the system (i.e., regarding perceived feeling of safety, trust and acceptance; Paper III).

Other measures, such as crossing initiation measures, should be obtained in further studies in addition to the system assessment conducted by questionnaires (comparable to Holländer et al., 2019).

8.2.3 Research objective 4: Differences in eHMI assessment between younger and elderly pedestrians

Elderly pedestrians (i.e., ≥ 65 years) are particularly vulnerable road users (European Commission, 2023). Therefore, this user groups might especially benefit of additional information provided by eHMIs enhancing the predictability of maneuvers during interactions with AVs in mixed road traffic (Habibovic et al., 2018), since they might compensate for age-related declines such as decrements of psycho-motoric functions, cognitive and sensory abilities (for an overview of age-related declines see Dunbar et al., 2004; Polders et al., 2015). However, the requirements of this specific user group are currently rarely investigated in eHMI research (with exceptions of e.g., Hensch et al., 2019; Othersen et al., 2018). Therefore, the study reported in Paper III of the current thesis also considered differences in eHMI assessment between younger (18 – 40 years) and elderly participants (≥ 65 years) over different points of measurement (i.e., including different experiences when interacting with the system and system malfunctions; $t_0 – t_2$).

Elderly participants consistently assessed the system more positive across the different points of measurement regarding perceived feeling of safety during the interaction, trust and acceptance (i.e., usefulness; Van Der Laan et al., 1997) toward the system compared to younger participants (Paper III). The results corroborate previous findings considering human-technology interactions that showed a more positive attitude toward (Hartwich et al., 2019) and higher trust in technology by elderly users (Schaefer et al., 2016). Comparable findings considering elderly users' acceptance of eHMIs were previously revealed (Hensch et al., 2019). The application of eHMI signals might generally support anticipating and predicting prospective maneuvers in AVs (Habibovic et al., 2018) as well as proactive encounters offering additional time and space for conducting actions (Stahl et al., 2014). Therefore, it could be argued that the positive attitude of elderly toward eHMIs might be particularly useful since the increased predictability of AV maneuvers by eHMI signals (Habibovic et al., 2018) might compensate for elderly users' age-related declines (Dunbar et al., 2004; Polders et al., 2015).

However, elderly participants also consistently indicated more positive ratings when assessing the system despite experiencing malfunctions (i.e., t_2; with an exception of satisfaction ratings; Van Der Laan et al., 1997). It should be highlighted that elderly participants adjusted their system assessment less after experiencing malfunctions than younger participants. A stronger decline of acceptance ratings (i.e., usefulness and satisfaction; Van Der Laan et al., 1997)

after experiencing system malfunctions was obtained for younger participants in contrast to elderly participants, resulting in an even larger difference in ratings between the age groups (Paper III). The results are in line with previous findings that focused on elderly participants' trust adjustment and resulting overreliance on an automated decision aid in case of system malfunctions (Ho et al., 2005). In terms of traffic safety and potential interactions in mixed road traffic, the results are particularly worrisome since elderly pedestrians require even longer execution times for actions than younger pedestrians (e.g., during road crossings; Oxley et al., 2005; Stelmach & Nahom, 1992). Therefore, elderly pedestrians might be particularly affected by potential eHMI malfunctions and a rather inappropriate system assessment since fast reactions might be specifically necessary in case of misinterpretations or mismatches of eHMIs signals (e.g., by promptly clearing the interactional space in front of an AV).

Since differences in system assessment were revealed between elderly and younger participants when interacting with eHMIs as a form of technology (Paper III), further research should consider specific requirements of different user groups for interactions in closer detail (Schaarschmidt et al., 2021). For instance, children as a user group with potential specific requirements and resulting characteristics for eHMI interaction might be considered in further detail in prospective studies (Charisi et al., 2017; Schaarschmidt et al., 2021).

9 IMPLICATIONS

To benefit of potential advantages provided by increased automated driving functions (European Road Transport Research Advisory Council, 2017) and eHMIs as potential means of communication in AVs (Habibovic et al., 2018), these technologies need to be applied and used (J. D. Lee & See, 2004; SAE International, 2021). Therefore, the present thesis aimed on contributing to the field of research achieving a deeper understanding of interactions between AVs and manual road users, prospectively supporting successful encounters in mixed road traffic (for further research see e.g., Rouchitsas & Alm, 2019; Schaarschmidt et al., 2021; Schieben et al., 2019). Besides specific implications and requirements for further research within this field derived from the findings of the individual studies, overall theoretical and practical implications deduced from the results are elaborated in the following.

However, the following presented implications do not intend to represent an exhaustive list, rather specific aspects are highlighted. Since the research fields of AVs in general and eHMI signals as means of communication comprise highly practical considerations (Bengler et al., 2020), theoretical and practical implications are in some cases not clearly distinguishable from each other and might overlap, which is also reflected in the following presented implications.

9.1 Theoretical considerations

Considering the findings and the derived implications presented in Paper I to III, it seems reasonable to accompany the introduction of new technologies, here specifically AVs and eHMI as potential means of communication in automated driving, with user studies to apply a human-centered system development (comparable to ISO, 2019). Established theoretical concepts from different domains that focus on achieving a coordination during encounters between involved interaction partners (i.e., joint actions; Klein et al., 2004) and enhancing the predictability during interactions (i.e., SA; Endsley, 1995) might be also a helpful theoretical basis for successful encounters in mixed road traffic.

The HMI framework by Bengler et al. (2020) was developed to consider expected interaction requirements and challenges in AVs to achieve predictable encounters in mixed road traffic. According to the framework, these challenges should be countered by a holistic HMI comprising different individual HMIs that exchange information between AVs, the driver and passengers inside the vehicle and surrounding traffic participants. Therefore, the framework has the potential to provide a useful orientation for the research field (e.g., creating a common understanding of specific HMI terms, identifying addressees and interrelations of different HMIs to support interactions; Bengler et al., 2020). The present thesis focused on the dHMI and eHMI that should provide information to surrounding road users (Bengler et al., 2020) as incidental users of AVs since road traffic is a social system (Domeyer et al., 2020). However, the framework does not provide specific HMI parameter values, particular information about messages that need to be communicated (e.g., for eHMIs) or exact timings when coordinating different HMIs (Bengler et al., 2020). For instance with regard to eHMIs, additional guidelines and checklists need to be considered for an orientation (ISO 2018; SAE International, 2018; Wilbrink et al., 2023). Prospective research is required, for instance to determine particular parameter values of the different HMIs (e.g., GA when initiating parking actions from a driver's perspective as a specific dHMI parameter; Paper I).

Besides the HMI framework (Bengler et al., 2020), additional concepts could provide a theoretical basis for underlying mechanisms when coordinating interactions in mixed road traffic. The concept of joint activities (Klein et al., 2004), originally developed in the linguistics domain (Clark, 1996), might be a useful theoretical concept considering predictable interactions in mixed road traffic between AVs and manual road users. The concept generally aims on successfully coordinating actions (Klein et al., 2004) and minimizing coordination costs when interacting (Domeyer et al., 2020). Therefore, actions of the involved participants need to be interpredictable (i.e., making own actions predictable to others and being able to predict upcoming actions of others; Klein et al., 2004), which is supported by a common ground of mutual knowledge and presumptions about interactions (Clark & Brennan, 1991)

and the directability of these actions (Klein et al., 2004). Comparable criteria were also presented by frameworks considering successful human-robot interactions (e.g., Johnson et al., 2014). To achieve an interpredictablity of actions and a common ground during encounters in mixed road traffic, allowing for more economical interaction processes (Clark & Brennan, 1991; Klein et al., 2004), it is suggested to derive and implement established interaction capabilities from manual driving into AVs (for comparable approaches see Beggiato et al., 2017; Stange, Goralzik, et al., 2022). Therefore, the study of Paper I investigated manual drivers' GA for initiating parking actions in a shared space setting as a basic orientation for one specific parameter in AVs' driving functions (comparable to Beggiato et al. (2017) for pedestrians' GA). This approach could support achieving driving behavior compatibility in mixed road traffic (Nyholm & Smids, 2020; van Loon & Martens, 2015). Thus, the concept of joint activities (Klein et al., 2004) could provide a suitable rationale for implementing established interaction capabilities in AVs to support predictable and intuitive encounters in mixed road traffic (Schieben et al., 2019).

The concept of SA (Endsley, 1995), developed in the aviation domain, might be also helpful when considering successful interactions in mixed road traffic. The concept describes achieving mental representations, interpretations and predictions of highly dynamic scenes as also typical for road traffic (Endsley, 1995; Krems & Baumann, 2009) that are required to reduce conflicts or collapses of interaction processes. Situational features need to be perceived and interpreted to predict and anticipate the future development of a scene (Endsley, 1995). This in turn allows for a proactive interactional behavior of involved participants (Grant & Ashford, 2008). Focusing on driving behavior in mixed road traffic, implementing currently established interaction capabilities of manual driving in AVs would allow these vehicles to intuitively announce and making prospective driving actions predictable to surrounding traffic participants (Beggiato et al., 2017; comparable to forward compatibility according to van Loon & Martens, 2015). Moreover, prospective actions of surrounding road users could be anticipated more reliably by AVs (comparable to backward compatibility according to van Loon & Martens, 2015). These mechanisms could potentially provide additional time and space during interactions and could enable increased proactive encounters in mixed road traffic (Stahl et al., 2014).

The concept of SA (Endsley, 1995) might be also applied as a theoretical basis concerning the usage of eHMI signals as potential means of communication in AVs. Due to prospectively transformed interactions in AVs (Schieben et al., 2019), SA of surrounding road users could be restricted since specific information, such as eye contact with the driver, might no longer be enabled (Endsley, 1995; Schieben et al., 2019). Additional eHMI signals might substitute such missing information, provide information about the vehicles' automation status, increase

the predictability of prospective AV maneuvers during interactions and could support the SA of surrounding traffic participants (Endsley, 1995; Habibovic et al., 2018; Schieben et al., 2019). Therefore, prospective AV maneuvers might be increasingly anticipated by other road users (Habibovic et al., 2018), which could enable for proactive encounters (Dey et al., 2022). Hence, the concept of SA (Endsley, 1995) could also provide a theoretical basis to support the application of eHMI signals as potential means of communication in AVs that might improve the transparency and the predictability of prospective actions in mixed road traffic (Habibovic et al., 2018).

Overall, it can be concluded that there are several theoretical concepts that could provide a theoretical orientation for increasing the predictability and intuitiveness of interactions in mixed road traffic (i.e., joint activities; Klein et al. (2004) or SA; Endsley (1995)).

However, additional cognitive demands due to the added signals and their potential consequences also need to be respected (Sarter et al., 1997) with regard to eHMIs as potential means of communication in AVs. The complexity of visual demanding traffic situations (Horberry et al., 2006) might be even increased when providing additional information by visual eHMI signals in road traffic scenes, particularly if interactions exceed the one-to-one interaction (Holländer et al., 2022; i.e., ironies of automation; Bainbridge, 1983). Therefore, a tradeoff between providing additional information by eHMIs thus increasing the predictability of a traffic situation (Habibovic et al., 2018) and displaying too much signals, potentially causing an information overload of involved traffic participants needs to be considered (Tabone et al., 2021). Moreover, it has to be noted that new technologies, such as eHMIs, lead to new cognitive demands due to novel kinds of errors (Sarter et al., 1997; e.g., eHMI malfunctions that contradict vehicles' movements as dHMI information; Holländer et al., 2019).

9.2 Practical implications

Several practical implications derived from the findings of the conducted studies (Paper I to III) and based on the previously considered theoretical aspects are presented in the following.

There is no one fits all implementation for gap selection in traffic flow when initiating parking actions and thus coordinating interactions in shared spaces.

When investigating manual drivers' accepted gaps as a basic orientation to support AVs' driving behavior compatibility for initiating parking actions (for comparable approached see Beggiato et al. (2017); Stange, Goralzik, et al. (2022)), there is no one specific time gap that is considered as always appropriate for starting parking maneuvers in shared spaces when encountering other road users (comparable to Beggiato et al. (2017) for pedestrians' GA during road crossing actions). Rather, several aspects such as situational factors and personal driver characteristics need to be respected (Paper I). AVs should to be aware of these

situational factors for their maneuvering decisions to act intuitively according to human users' expectations and apply a predictable driving behavior for surrounding manual road users when initiating parking actions (i.e., forward compatibility; van Loon & Martens, 2015). Moreover, implementing these parameters as knowledge in AVs' driving functions (Beggiato et al., 2017) comparable to experienced manual drivers (Krems & Baumann, 2009) would enable AVs to anticipate driving maneuvers of surrounding road users more reliably and could support increased proactive encounters in mixed road traffic (Endsley, 1995; i.e., backward compatibility; van Loon & Martens, 2015). Since the dHMI also operates to the driver and passengers inside a vehicle (Bengler et al., 2020), revealed differences in driving styles due to personal characteristics (Sagberg et al., 2015) might be also implemented in AVs (Bellem et al., 2018). This could be achieved by selectable driving style profiles as a form of customization accounting for individual preferences of driving styles (Terken & Pfleging, 2020) as, for instance, currently available for adaptive cruise control settings comprising different configurations of following time to traffic ahead (for an overview see e.g., Raju et al., 2022). GA values could represent one particular parameter of these driving profiles in AVs (Hensch et al., 2021). Overall, derived parameters of manual drivers could provide a basic orientation for predictable and intuitive driving functions in AVs (comparable to Beggiato et al. (2017); Stange, Goralzik, et al. (2022)) and might have the potential to increase AVs' driving behavior compatibility in mixed road traffic (Nyholm & Smids, 2020; van Loon & Martens, 2015).

There is a general potential of eHMI signals as additional means of communication in AVs.

In AVs, eHMI signals are discussed as a useful communication solution to provide additional information during interactions (Dey et al., 2022; Schieben et al., 2019) and supporting the predictability of AVs' prospective driving actions for surrounding road users (Habibovic et al., 2018) if implicit communication exceeds their limits (Ackermann, Beggiato, Schubert, et al., 2019). Both studies on eHMIs of the current dissertation project (Paper II and III) revealed by different approaches and for different age groups of potential users that eHMIs were generally assessed as a useful means of communication potentially applied in AVs. However, additional user groups such as cyclists and their system assessment need to be investigated in further detail (see e.g., Kaß et al., 2020).

For instance, an external labeling of AVs by eHMIs comparable to driving school vehicles is currently prominently discussed and recommend (Wilbrink et al., 2023; for further information that are recommended to be communicated by eHMIs see Schieben et al.; 2019). Proving AVs' status information might support surrounding road users to anticipate prospective, potentially incompatible, driving maneuvers of AVs and adapt own movements accordingly, which could support traffic safety (Schaarschmidt et al., 2021). Moreover, a labeling would be

also helpful for achieving explicit interaction experience with AVs that was shown to positively influence the system assessment (Paper III; Faas, Kao, et al., 2020).

Prior information about abstract eHMI signals as means of communication in AVs and system experience is required when applied to mixed road traffic.

Despite being linked to the vehicles' movements, abstract light signals that might be technically easily installable in AVs (Dey et al., 2020) were assessed as unintuitive without prior knowledge about their assigned meanings (Paper II). Therefore, a learning process of the eHMI signals' meanings might be required as with traffic signs in general, to fully exploit the expected potential of eHMIs (Schaarschmidt et al., 2021), supporting predictability of AVs' prospective maneuvers and proactive encounters in mixed road traffic (Habibovic et al., 2018). Thus, it seems reasonable to provide prior information about the signals' meanings if introduced to road traffic (Schaarschmidt et al., 2021). For instance, information about eHMI signals might be provided by publicity campaigns, school education or information material specifically developed for particular user groups, such as children (e.g., comparable to Stiftung für Prävention der AXA (n.d.)). Moreover, as recommended by the ISO (2018) and Wilbrink et al. (2023), a harmonization and standardization of applied eHMI signals among manufactures, enabling for a simplified identification of signals and their respective meanings, appears useful (Wilbrink et al., 2023).

Consistent information need to be provided when combining eHMI and dHMI signals in a holistic HMI.

To benefit of additional eHMI information in terms of traffic safety and predictable interactions (Habibovic et al., 2018; Tabone et al., 2021), the applied signals need to be consistent with provided dHMI information such as vehicle movements (Bengler et al., 2020). Potential inconsistencies or mismatches between provided eHMI und dHMI information might result in ambiguities during interactions (Holländer et al., 2019). Therese ambiguities could lead to an reduced system assessment (Paper III) potentially impairing its usage (Faas et al., 2021) and even in safety critical encounters (Kaleefathullah et al., 2022). However, further research is required to determine the exact coordination, synchronization and specific timings between HMI types with regard to a holistic HMI (as also mentioned by Bengler et al., 2020) to consider traffic efficiency but also prevent from confusion due to premature announcements of maneuvers (Fuest, 2021).

An adequate system assessment is necessary to benefit from eHMI signals in AVs.

Since the introduction of new technologies leads to novel demands such as different kinds of errors (Sarter et al., 1997), it seems reasonable to calibrate an adequate system assessment that matches the capabilities and limitations of a system considering interaction safety but also

its efficiency (Kraus et al., 2020). An adequate system assessment in terms of eHMIs would enable potential users to apply expected benefits of this technology and could prevent from safety critical incidents in case of malfunctions by considering other information sources such as dHMI signals. Whereas, an inappropriate system assessment would either lead to an reduced willingness to apply the provided eHMI information and thus not fully benefiting of the system advantages or neglecting other information such as vehicles' movements as dHMI signals in case of system malfunctions (Paper III; Faas et al., 2021; J. D. Lee & See, 2004). Providing prior information about the system and its functions including capabilities and potential limitations could support achieving an adequate system assessment (Faas et al., 2021). Moreover, trainings and interaction experience (Paper III; Faas, Kao, et al., 2020) might enable for calibrating an appropriate system assessment (J. D. Lee & See, 2004). For instance, guided (error) trainings could provide knowledge and skills considering the system, potentially increasing interaction performance (Noble et al., 2020).

The requirements of specific user groups need to be considered in system development and further eHMI research.

In particular, the results of the thesis revealed that elderly participants consistently indicated a more positive eHMI assessment regarding perceived feeling of safety, trust and acceptance of the system, compared to younger users (Paper III). The results were even found despite system malfunctions (comparable to results for malfunctions of other technical systems revealed by Ho et al., 2005), considering mismatches between eHMI and dHMI information, potentially resulting in safety critical events when applied to real road traffic (Paper III; Holländer et al., 2019). Therefore, it can be concluded that diverse user groups need to be taken closer into account to consider specific requirements when interacting with eHMIs (Schaarschmidt et al., 2021), to achieve an adequate system assessment and prevent from potentially safety critical interactions (Faas et al., 2021). Recently, little eHMI research focused on the requirements of children (as exception see e.g., Charisi et al., 2017; Deb et al., 2020) or elderly (as exception see e.g., Othersen et al., 2018) as particularly vulnerable road user groups (European Commission, 2023). However, the development of technical systems should aim on predictability and observability but also in responsibility (Meyer et al., 2023). Therefore, further eHMI research should consider these user groups in more detail. For instance, specific trainings when interacting with eHMIs as means of communication in AVs for different user groups might be possible if these systems are implemented in mixed road traffic (for instance comparable to currently offered smartphone training courses specifically for elderly users; Technische Universität Chemnitz, 2023).

10 CONCLUSION

The thesis aimed on contributing to the existing research body enabling for predictable, intuitive and thus successful interactions between different traffic participants in mixed road traffic (e.g., findings reported in Paper I were respected in eHMI and dHMI principles by Wilbrink et al. (2023); results of Paper II were considered in an eHMI review by Rouchitsas and Alm (2019)). Specifically, dHMI und eHMI as potential means of communication in AVs (Bengler et al., 2020) were considered in closer detail within the current thesis. Parking areas as a currently under-investigated example for shared space (Uttley et al., 2020) with a high demand for coordinating actions between road users (Brill et al., 2023) were respected as settings within the current work.

Since gaps in traffic flow represent an important aspect of dHMI parameters (Bengler et al., 2020) when coordinating interactions (Summala, 2007), manual drivers' GA for initiating parking actions was investigated and derived in closer detail within the present thesis (Paper I) to be potentially applied as a role model (Pillai, 2017) that could provide a basic orientation for intuitive and predictable driving functions in AVs (i.e., initiating parking maneuvers; comparable to Beggiato et al. (2017); Stange, Goralzik, et al. (2022)). The findings suggested that there is no one fits all implementation for selecting gaps in traffic flow (comparable to Beggiato et al., 2017). Rather, manual drivers' GA for initiating parking actions was influenced by diverse aspects that should be also implemented in AVs to provide intuitive encounters in mixed road traffic (Hensch et al., 2021). The findings highlight the importance of prospectively investigating various manual driving parameters and potentially influencing factors in closer detail if applied as a basis in AVs' driving functions to provide driving behavior compatibility in mixed road traffic (van Loon & Martens, 2015).

Moreover, eHMI signals as additional means of communication in AVs, potentially enhancing the predictability of prospective AV maneuvers (Habibovic et al., 2018) were investigated within the current thesis (Paper II and III). The findings of the studies revealed that eHMIs have the potential to support prospective interactions in mixed road traffic since being evaluated as generally useful (Paper II). However, abstract eHMI signals were assessed as unintuitive without prior knowledge about the signals' meanings, implying the requirement for providing prior information (Schaarschmidt et al., 2021) and a prospective standardization and harmonization of applied signals among manufactures (Paper II; ISO, 2018; Wilbrink et al., 2023). Moreover, the results also indicated that eHMI assessment could be supported by interaction experience (Paper III), which highlights the significance of interaction trainings or publicity campaigns considering this potential means of communication (Faas, Kao, et al., 2020). To support the expected benefits, eHMI and dHMI information are required to act in

line with each other (Bengler et al., 2020; Tabone et al., 2021). It can be also suggested for introducing and implementing eHMIs as potential means of communication in AVs that specific requirements of different user groups need to be respected (Paper III; Schaarschmidt et al., 2021).

The current findings might be used as an initial point for further research in the field. For instance, additional scenarios and parameters as well as the requirements of specific user groups (Schaarschmidt et al., 2021) should be considered in more detail in future research when investigating eHMI signals and dHMI parameters as part of a holistic HMI in AVs (Bengler et al., 2020). Overall, it could be shown that established mechanisms considering human-technology interactions, such as the positive impact of interaction experience on system assessment (Cocron & Krems, 2013; Faas, Kao, et al., 2020), are also applicable to the technology of eHMIs. Moreover, novel demands arising with the new technology (Sarter et al., 1997), here specifically AVs and eHMIs as additional means of communication in mixed road traffic, were identified requiring a human-centered development to derive appropriate strategies for a successful system integration (ISO, 2019). The derived practical implications of the thesis might provide some input for supporting a successful introduction of AVs and eHMIs as potential means of communication.

11 REFERENCES

@City: Automatisiertes Fahren in der Stadt. (2018). *„@City: Automatisiertes Fahren in der Stadt [@City: Automated driving in cities]“:* @City: Automatisiertes Fahren in der Stadt. https://www.atcity-online.de/

Ackermann, C., Beggiato, M., Bluhm, L. F., Löw, A., & Krems, J. F. (2019). Deceleration parameters and their applicability as informal communication signal between pedestrians and automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*, *62*(April), 757–768. https://doi.org/10.1016/j.trf.2019.03.006

Ackermann, C., Beggiato, M., Schubert, S., & Krems, J. F. (2019). An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Applied Ergonomics*, *75*, 272–282. https://doi.org/10.1016/j.apergo.2018.11.002

Alexander, J., Barham, P., & Black, I. (2002). Factors influencing the probability of an incident at a junction: Results from an interactive driving simulator. *Accident Analysis and Prevention*, *34*(6), 779–792. https://doi.org/10.1016/S0001-4575(01)00078-1

Allgemeiner Deutscher Automobil-Club (2023, September 05). „*Autonomes Fahren Level 3: Freihändig durch den Stau [Autonomous driving level 3: Hands free through the traffic jam]“:* Allgemeiner Deutscher Automobil-Club. https://www.adac.de/rund-ums-fahrzeug/ausstattung-technik-zubehoer/autonomes-fahren/technik-vernetzung/autonomes-fahren-staupilot-s-klasse/

Argyle, M., & Dean, J. (1965). Eye-Contact, distance and affiliation. *Sociometry*, *28*(3), 289–304. https://doi.org/10.2307/2786027

Bainbridge, L. (1983). Ironies of Automation. *Automatica*, *19*(6), 775–779. https://doi.org/https://doi.org/10.1016/B978-0-08-029348-6.50026-9

Baumann, M. R., & Krems, J. F. (2007). Situation awareness and driving: A cognitive model. In Cacciabue. P.C. (Ed.), *Modelling driver behaviour in automotive environments: Critical issues in driver interactions with intelligent transport systems* (pp. 253–265). Springer. https://doi.org/https://doi.org/10.1007/978-1-84628-618-6_14

Beggiato, M., Witzlack, C., Springer, S., & Krems, J. F. (2017). The right moment for braking as informal communication signal between automated vehicles and pedestrians in crossing situations. In N. Stanton (Ed.), *Advances in Human Aspects of Transportation. AHFE 2017. Advances in Intelligent Systems and Computing, vol 597* (pp. 1072-1081).

Springer. https://doi.org/10.1007/978-3-319-60441-1

Bellem, H., Thiel, B., Schrauf, M., & Krems, J. F. (2018). Comfort in automated driving: An analysis of preferences for different automated driving styles and their dependence on personality traits. *Transportation Research Part F: Traffic Psychology and Behaviour*, *55*(May), 90–100. https://doi.org/10.1016/j.trf.2018.02.036

Bengler, K., Rettenmaier, M., Fritz, N., & Feierle, A. (2020). From HMI to HMIs: Towards an HMI framework for automated driving. *Information*, *11*(2), 61. https://doi.org/https://doi.org/10.3390/info11020061

Berger, C. R., & Calabrese, R. J. (1975). Some Explorations in Initial Interaction and Beyond: Toward a Developmental Theory of Interpersonal Communication. *Human Communication Theory*, *1*, 99–112. https://doi.org/https://doi.org/10.1111/j.1468-2958.1975.tb00258.x

Bindschädel, J., Krems, I., & Kiesel, A. (2022). Active vehicle pitch motion for communication in automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *87*(May), 279–294. https://doi.org/https://doi.org/10.1016/j.trf.2022.04.011

Böckle, M.-P., Brenden, A. P., Klingegård, M., Habibovic, A., & Bout, M. (2017). SAV2P: Exploring the impact of an interface for shared automated vehicles on pedestrians' experience. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct (AutomotiveUI '17)*, *Oldenburg, Germany* (pp. 136–140). https://doi.org/10.1145/3131726.3131765

Bottom, C. G., & Ashworth, R. (1978). Factors affecting the variability of driver gap-acceptance behaviour. *Ergonomics*, *21*(9), 721–734. https://doi.org/10.1080/00140137808931774

Brandenburg, S., & Roche, F. (2020). Behavioral changes to repeated takeovers in automated driving : The drivers ' ability to transfer knowledge and the effects of takeover request process. *Transportation Research Part F: Psychology and Behaviour*, *73*(August), 15–28. https://doi.org/https://doi.org/10.1016/j.trf.2020.06.002

Brill, S., Payre, W., Debnath, A., Horan, B., & Birrell, S. (2023). External human–machine interfaces for automated vehicles in shared spaces: A review of the human–computer interaction literature. *Sensors*, *23*(9), 4454. https://doi.org/10.3390/s23094454

Chang, C.-M., Toda, K., Sakamoto, D., & Igarashi, T. (2017). Eyes on a car: an interface design for communication between an autonomous car and a pedestrian. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17)*, *Oldenburg, Germany* (pp. 65–73). https://doi.org/10.1145/3122986.3122989

Charisi, V., Habibovic, A., Andersson, J., Li, J., & Evers, V. (2017). Children's views on identification and intention communication of self-driving vehicles. *Proceedings of the 2017 Conference on Interaction Design and Children (IDC '17)*, *Stanford, CA, USA* (pp. 399–404). https://doi.org/https://doi.org/10.1145/3078072.3084300

Clamann, M., Aubert, M., & Cummings, M. L. (2017). *Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles. Transportation Research Board 96th Annual Meeting (No. 17-02119), Washington, DC, USA* (p. 13). https://hal.pratt.duke.edu/sites/hal.pratt.duke.edu/files/u10/Clamann_etal_TRB2016.pdf

Clark, H. H. (1996). *Using language*. Cambridge University Press. https://doi.org/10.2277/0521561582

Clark, H. H., & Brennan, S. E. (1991). Grounding in communication. In L. B. Resnick, J. M. Levine, & S. D. Teasley (Eds.), *Perspectives on socially shared cognition* (pp. 127–149). American Psychological Association. https://doi.org/10.1037/10096-006

Cocron, P., & Krems, J. F. (2013). Driver perceptions of the safety implications of quiet electric vehicles. *Accident Analysis and Prevention*, *58*, 122–131. https://doi.org/https://doi.org/10.1016/j.aap.2013.04.028

Czaja, S. J., Charness, N., Fisk, Arthur, D., Hertzog, C., Nair, S. N., Rogers, W. A., & Sharit, J. (2006). Factors predicting the use of technology: Findings from the center for research and education on aging and technology enhancement (create). *Psychology and Aging*, *21*(2), 333–352. https://doi.org/https://doi.org/10.1037/0882-7974.21.2.333

Czaja, S. J., & Sharit, J. (1998). Age differences in attitudes toward computers. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*, *53*(5), 329–340. https://doi.org/10.1093/geronb/53B.5.P329

Dahlbäck, N., Jönsson, A., & Ahrenberg, L. (1993). Wizard of Oz studies — why and how. *Knowledge-Based Systems*, *6*(4), 258–266. https://doi.org/10.1145/169891.169968

de Clercq, K., Dietrich, A., Núñez Velasco, J. P., de Winter, J., & Happee, R. (2019). External human-machine interfaces on automated vehicles: Effects on pedestrian crossing decisions. *Human Factors*, 1–18. https://doi.org/10.1177/0018720819836343

de Haan, T., Stuiver, A., Lorist, M. M., & de Waard, D. (2022). Other road users' adaptations to increase safety in response to older drivers' behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour*, *84*(December), 277–286. https://doi.org/https://doi.org/10.1016/j.trf.2021.12.009

Deb, S., Carruth, D. W., Fuad, M., Stanley, L. M., & Frey, D. (2020). Comparison of child and adult pedestrian perspectives of external features on autonomous vehicles using virtual reality experiment. In N. A. Stanton (Ed.), *Advances in Human Factors of Transportation: Proceedings of the AHFE 2019 International Conference on Human Factors in Transportation* (pp. 145–156). Springer International Publishing. https://doi.org/10.1007/978-3-030-20503-4

Department for Transport. (2011). *Shared space*. https://nacto.org/docs/usdg/shared_space_department_transport.pdf

Deutsch, M. (2011). Cooperation and competition. In P. T. Coleman (Ed.), *Conflict, interdependence, and justice: The intellectual legacy of Morton Deutsch* (pp. 23–40). Springer Science + Business Media. https://doi.org/10.1007/978-1-4419-9994-8_2

Dey, D., Ackermans, S., Martens, M., Pfleging, B., & Terken, J. (2022). Interactions of automated vehicles with road users. In A. Riener, M. Jeon, & I. Alvarez (Eds.), *User Experience Design in the Era of Automated Driving* (Vol. 980, pp. 533–581). Springer International Publishing. https://doi.org/10.1007/978-3-030-77726-5_20

Dey, D., Habibovic, A., Löcken, A., Wintersberger, P., Pfleging, B., Riener, A., Martens, M., & Terken, J. (2020). Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives*, *7*. https://doi.org/10.1016/j.trip.2020.100174

Dey, D., Martens, M., Eggen, B., & Terken, J. (2019). Pedestrian road-crossing willingness as a function of vehicle automation, external appearance, and driving behaviour. *Transportation Research Part F: Traffic Psychology and Behaviour*, *65*(August), 191–205. https://doi.org/10.1016/j.trf.2019.07.027

Dey, D., & Terken, J. (2017). Pedestrian interaction with vehicles: Roles of explicit and implicit communication. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '17)*, *Oldenburg, Germany* (pp. 109–113). https://doi.org/https://doi.org/10.1145/3122986.3123009

Domeyer, J. E., Lee, J. D., & Toyoda, H. (2020). Vehicle automation-other road user communication and coordination: Theory and mechanisms. *IEEE Access*, *8*, 19860–19872. https://doi.org/10.1109/ACCESS.2020.2969233

Dunbar, G., Holland, C. A., & Maylor, E. A. (2004). *Older pedestrians: a critical review of the literature*. Department for Transport. https://publications.aston.ac.uk/id/eprint/24396/1/Older_pedestrians.pdf

Eisele, D., & Petzoldt, T. (2022). Effects of traffic context on eHMI icon comprehension. *Transportation Research Part F: Traffic Psychology and Behaviour*, *85*(February), 1–12. https://doi.org/https://doi.org/10.1016/j.trf.2021.12.014

Eisma, Y. B., van Bergen, S., ter Brake, S. M., Hensen, M. T. T., Tempelaar, W. J., & de Winter, J. C. F. (2019). External human-machine interfaces: The effect of display location on crossing intentions and eye movements. *Information*, *11*(1), 13. https://doi.org/10.3390/info11010013

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors*, *37*(1), 32–64. https://doi.org/https://doi.org/10.1518/001872095779049543

Endsley, M. R. (2023). Supporting human-AI teams:Transparency, explainability, and situation awareness. *Computers in Human Behavior*, *140*, 107574. https://doi.org/https://doi.org/10.1016/j.chb.2022.107574

European Commission. (2023). *Facts and figures seniors. European road safety observatory.* https://road-safety.transport.ec.europa.eu/system/files/2023-03/ERSO_annual_report_20220509.pdf

European Road Transport Research Advisory Council. (2017). *Automated driving roadmap*. https://www.ertrac.org/wp-content/uploads/2022/07/ERTRAC_Automated_Driving_2017.pdf

Faas, S. M., Kao, A. C., & Baumann, M. (2020). A longitudinal video study on communicating status and intent for self-driving vehicle - pedestrian interaction. *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20), Honolulu, HI, USA* (pp. 1–14). https://doi.org/https://doi.org/10.1145/3313831.3376484

Faas, S. M., Kraus, J., Schoenhals, A., & Baumann, M. (2021). Calibrating pedestrians' trust in automated vehicles. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*, *Yokohama, Japan* (pp. 1–17). https://doi.org/10.1145/3411764.3445738

Faas, S. M., Mathis, L.-A., & Baumann, M. R. (2020). External HMI for self-driving vehicles: Which information shall be displayed? *Transportation Research Part F: Traffic Psychology and Behaviour*, *68*(January), 171–186. https://doi.org/https://doi.org/10.1016/j.trf.2019.12.009

Faas, S. M., Mattes, S., Kao, A. C., & Baumann, M. (2020). Efficient paradigm to measure street-crossing onset time of pedestrians in video-based interactions with vehicles. *Information*, *11*(7), 360. https://doi.org/10.3390/INFO11070360

Färber, B. (2016). Communication and communication problems between autonomous vehicles and human drivers. In M. Maurer, C. J. Gerdes, B. Lenz, & H. Winner (Eds.), *Autonomous Driving* (pp. 125–144). Springer. https://doi.org/10.1007/978-3-662-48847-8

Federal Ministry for Digital and Transport. (n.d.). *German road traffic regulations*. https://bmdv.bund.de/blaetterkatalog/catalogs/327056/pdf/complete.pdf [01.11.2023]

FeldmanHall, O., & Shenhav, A. (2019). Resolving uncertainty in a social world. *Nature Human Behaviour*, *3*, 426–435. https://doi.org/https://doi.org/10.1038/s41562-019-0590-x

Feltovich, P. J., Bradshaw, J. M., Jeffers, R., Suri, N., & Uszok, A. (2004). Social order and adaptability in animal and human cultures as analogues for agent communities: Toward a policy-based approach. In A. Omicini, P. Petta, & J. Pitt (Eds.), *Engineering Societies in the Agents World IV. ESAW 2003. Lecture Notes in Computer Science(), vol 3071.* (pp. 21–48). Springer. https://doi.org/https://doi.org/10.1007/978-3-540-25946-6_2

Fraser, N. M., & Gilbert, G. N. (1991). Simulating speech systems. *Computer Speech and Language*, *5*(1), 81–99. https://doi.org/https://doi.org/10.1016/0885-2308(91)90019-M

Fuest, T. (2021). *Comparison of methods to evaluate the influence of an automated vehicle's driving behavior on pedestrians: Wizard of Oz, virtual reality, and video setups* [Doctoral dissertation, Technische Universität München]. https://d-nb.info/1248306783/34

Fuest, T., Michalowski, L., Traris, L., Bellem, H., & Bengler, K. (2018). Using the driving behavior of an automated vehicle to communicate intentions - A Wizard of Oz Study. *21st International Conference on Intelligent Transportation Systems (ITSC)*, *Maui, HI, USA* (pp. 3596–3601). https://doi.org/10.1109/ITSC.2018.8569486

Ghazizadeh, M., Lee, J. D., & Boyle, L. N. (2012). Extending the technology acceptance model to assess automation. *Cognition, Technology and Work*, *14*, 39–49. https://doi.org/10.1007/s10111-011-0194-3

Gibbs, W. L. (1968). Driver gap acceptance at intersections. *Journal of Applied Psychology*, *52*(3), 200–204. https://doi.org/https://doi.org/10.1037/h0025887

Gibson, J. J., & Crooks, L. E. (1938). A theoretical field-analysis of automobile-driving. *The American Journal of Psychology*, *51*(3), 453–471. https://doi.org/https://doi.org/10.2307/1416145

Goffmann, E. (1971). *Relations in public : microstudies of the public order*. Basic Books.

Grant, A. M., & Ashford, S. J. (2008). The dynamics of proactivity at work. *Research in Organizational Behavior*, *28*, 3–34. https://doi.org/10.1016/j.riob.2008.04.002

Guéguen, N., Meineri, S., & Eyssartier, C. (2015). A pedestrian's stare and drivers' stopping behavior: A field experiment at the pedestrian crossing. *Safety Science*, *75*, 87–89. https://doi.org/10.1016/j.ssci.2015.01.018

Habibovic, A., Andersson, J., Nilsson, M., Lundgren, V. M., & Nilsson, J. (2016). Evaluating interactions with non-existing automated vehicles: Three Wizard of Oz approaches. *2016 IEEE Intelligent Vehicles Symposium (IV)*, *Gothenburg, Sweden* (pp. 32–37). https://doi.org/10.1109/IVS.2016.7535360

Habibovic, A., Lundgren, V. M., Andersson, J., Klingegård, M., Lagström, T., Sirkka, A., Fagerlönn, J., Edgren, C., Fredriksson, R., Krupenia, S., Saluäär, D., & Larsson, P. (2018). Communicating intent of automated vehicles to pedestrians. *Frontiers in Psychology*, *9:1336*. https://doi.org/10.3389/fpsyg.2018.01336

Haddington, P., & Rauniomaa, M. (2014). Interaction between road users: Offering space in traffic. *Space and Culture*, *17*(2), 176–190. https://doi.org/https://doi.org/10.1177/1206331213508498

Hall, E. T. (1969). *The hidden dimension*. Doubleday Anchor Books.

Hancock, P. A., Caird, J. K., & Shekhar, S. (1991). Factors influencing drivers' left turn decisions. *Proceedings of the Human Factors 35th Annual Meeting*, *35*(15), 1139–1143. https://doi.org/https://doi.org/10.1177/154193129103501525

Harkin, A. M., Harkin, K. A., & Petzoldt, T. (2023). What to rely on – Implicit communication between pedestrians and turning automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour*, *98*(January), 297–317. https://doi.org/https://doi.org/10.1016/j.trf.2023.08.004

Hartwich, F., Witzlack, C., Beggiato, M., & Krems, J. F. (2019). The first impression counts – A combined driving simulator and test track study on the development of trust and acceptance of highly automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *65*(August), 522–535. https://doi.org/10.1016/j.trf.2018.05.012

Heino, A., Van Der Molen, H. H., & Wilde, G. J. S. (1996). Differences in risk experience between sensation avoiders and sensation seekers. *Personality and Individual Differences*, *20*(1), 71–79. https://doi.org/10.1016/0191-8869(95)00152-V

Hensch, A.-C., Beggiato, M., Schömann, M. X., & Krems, J. F. (2021). Different types, different

speeds – The effect of interaction partners and encountering speeds at intersections on drivers ' gap acceptance as an implicit communication signal in automated driving. In H. Krömker (Ed.), *HCI in Mobility, Transport, and Automotive Systems. HCII 2021. Lecture Notes in Computer Science, vol 12791.* (pp. 517–528). Springer. https://doi.org/https://doi.org/10.1007/978-3-030-78358-7_36

Hensch, A.-C., Kreißig, I., Beggiato, M., & Krems, J. F. (2022). The Effect of eHMI malfunctions on younger and elderly pedestrians' trust and acceptance of automated vehicle communication signals. *Frontiers in Psychology*, *13:866475*. https://doi.org/https://doi.org/10.3389/fpsyg.2022.866475

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems, J. F. (2019, October 2-4). *Steady, flashing, sweeping – An exploratory evaluation of light signals as an eHMI in automated driving* [Poster presentation]. Annual Meeting of the Human Factors and Ergonomic Society Europe Chapter, Nantes, France. doi:10.13140/RG.2.2.33925.29922

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems, J. F. (2020). How should Automated Vehicles communicate ? – Effects of a light-based communication approach in a Wizard-of-Oz study. In N. Stanton (Ed.), *Advances in Human Factors of Transportation. AHFE 2019. Advances in Intelligent Systems and Computing, vol 964*. (pp. 79-91). Springer. https://doi.org/https://doi.org/10.1007/978-3-030-20503-4_8

Hergeth, S., Lorenz, L., & Krems, J. F. (2016). Prior familiarization with takeover requests affects drivers' takeover performance and automation trust. *Human Factors*, *59*(3), 457–470. https://doi.org/https://doi.org/10.1177/0018720816678714

Himanen, V., & Kulmala, R. (1988). An application of logit models in analysing the behaviour of pedestrians and car drivers on pedestrian crossings. *Accident Analysis and Prevention*, *20*(3), 187–197. https://doi.org/https://doi.org/10.1016/0001-4575(88)90003-6

Ho, G., Wheatley, D., & Scialfa, C. T. (2005). Age differences in trust and reliance of a medication management system. *Interacting with Computers*, *17*(6), 690–710. https://doi.org/https://doi.org/10.1016/j.intcom.2005.09.007

Hoff, K. A., & Bashir, M. (2015). Trust in automation: Integrating empirical evidence on factors that influence trust. *Human Factors*, *57*(3), 407–434. https://doi.org/10.1177/0018720814547570

Hoffman, G., & Ju, W. (2014). Designing robots with movement in mind. *Journal of Human-Robot Interaction*, *3*(1), 91–122.

https://doi.org/https://doi.org/10.5898/JHRI.3.1.Hoffman

Holländer, K., Colley, M., Rukzio, E., & Butz, A. (2021). A taxonomy of vulnerable road users for HCI based on a systematic literature review. *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (CHI '21)*, *Yokohama, Japan* (pp. 1–13). https://doi.org/https://doi.org/10.1145/3411764.3445480

Holländer, K., Hoggenmüller, M., Gruber, R., Völkel, S. T., & Butz, A. (2022). Take it to the curb: Scalable communication between autonomous cars and vlnerable road users through curbstone displays. *Frontiers in Computer Science*, *4:844245*. https://doi.org/https://doi.org/10.3389/fcomp.2022.844245

Holländer, K., Wintersberger, P., & Butz, A. (2019). Overtrust in external cues of automated vehicles: An experimental investigation. *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '19)*, *Utrecht, Netherlands* (pp. 211–221). https://doi.org/10.1145/3342197.3344528

Hölzel, A. (2008). *Unterscheidung von formeller und informeller Kommunikation im Straßenverkehr [Distinction of formal and informal communication in traffic]* [Diploma thesis, Universität Wien]. https://core.ac.uk/download/pdf/11583874.pdf

Horberry, T., Anderson, J., Regan, M. A., Triggs, T. J., & Brown, J. (2006). Driver distraction: The effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance. *Accident Analysis and Prevention*, *38*(1), 185–191. https://doi.org/10.1016/j.aap.2005.09.007

Horswill, M. S., Helman, S., Ardiles, P., & Wann, J. P. (2005). Motorcycle accident risk could be inflated by a time to arrival illusion. *Optometry and Vision Science*, *82*(8), 740–746. https://doi.org/10.1097/01.opx.0000175563.21423.50

Hurst, P. M., Perchonok, K., & Sequin, E. L. (1968). Vehicle kinematics and gap acceptance. *Journal of Applied Psychology*, *52*(4), 321–324. https://doi.org/https://doi.org/10.1037/h0026043

Hydén, C. (1987). *The development of a method for traffic safety evaluation: The Swedish Traffic Conflicts Technique.* No. 70, Bulletin Lund Institute of Technology.

Imbsweiler, J., Palyafári, R., Puente León, F., & Deml, B. (2017). Untersuchung des Entscheidungsverhaltens in kooperativen Verkehrssituationen am Beispiel einer Engstelle [Investigation of decision behavior in cooperative traffic situations by the example of a bottleneck scenario]. *At-Automatisierungstechnik*, *65*(7), 477–488. https://doi.org/https://doi.org/10.1515/auto-2016-0127

Ioannou, P. (1998). *Evaluation of mixed automated/ manual traffic*. University of Southern California: California PATH Research Report (UCB-ITS-PRR-98-13). https://escholarship.org/uc/item/246977zg#main

International Organization for Standardization (ISO). (2019). *Ergonomics of human-system interaction — Part 210: Human-centred design for interactive systems; ISO 9241-210:2019.* International Organization for Standardization. https://cdn.standards.iteh.ai/samples/77520/8cac787a9e1549e1a7ffa0171dfa33e0/ISO-9241-210-2019.pdf [01.11.2023]

International Organization for Standardization (ISO). (2018). *Road Vehicles - Ergonomic aspects of external visual communication from automated vehicles to other road users; ISO/TR 23049:2018*. International Organization for Standardization. https://www.iso.org/standard/74397.html [01.11.2023]

Jian, J.-Y., Bisantz, A. M., & Drury, C. G. (2000). Foundations for an empirically determined scale of trust in automated systems. *International Journal of Cognitive Ergonomics*, *4*(1), 53–71. https://doi.org/10.1207/S15327566IJCE0401_04

Johnson, M., & Bradshaw, J. M. (2021). The role of interdependence in trust. In C. Nam & J. Lyons (Eds.), *Trust in Human-Robot Interaction* (pp. 379–403). Elsevier. https://doi.org/10.1016/b978-0-12-819472-0.00016-2

Johnson, M., Bradshaw, J. M., Feltovich, P. J., Jonker, C. M., & Riemsdijk, M. B. Van. (2014). Coactive design: Designing support for interdependence in joint activity. *Journal of Human-Robot Interaction*, *3*(1), 43–69. https://doi.org/10.5898/JHRI.3.1.Johnson

Jonah, B. A. (1997). Sensation seeking and risky driving: A review and synthesis of the literature. *Accident Analysis and Prevention*, *29*(5), 651–665. https://doi.org/10.1016/S0001-4575(97)00017-1

Junghans, M., Krauns, F., Sonka, A., Böhm, M., & Dotzauer, M. (2021). Comparison of safety and kinematic patterns of automated vehicles turning left in interaction with oncoming manually driven vehicles. *Transactions on Transport Sciences*, *2*(3), 55–66. https://doi.org/10.5507/tots.2021.003

Kaleefathullah, A. A., Merat, N., Lee, Y. M., Eisma, Y. B., Madigan, R., Garcia, J., & Winter, J. de. (2022). External human–machine interfaces can be misleading: An examination of trust development and misuse in a CAVE-based pedestrian simulation environment. *Human Factors*, *64*(6), 1070–1085. https://doi.org/https://doi.org/10.1177/0018720820970751

Kaparias, I., Bell, M., Dong, W., Sastrawinata, A., Singh, A., Wang, X., & Mount, B. (2013).

Analysis of pedestrian-vehicle traffic conflicts in street designs with elements of shared space. *Transportation Research Record*, *2393*, 21–30. https://doi.org/https://doi.org/10.3141/2393-03

Kaparias, I., Bell, M. G. H., Miri, A., Chan, C., & Mount, B. (2012). Analysing the perceptions of pedestrians and drivers to shared space. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(3), 297–310. https://doi.org/https://doi.org/10.1016/j.trf.2012.02.001

Kaß, C., Schoch, S., Naujoks, F., Hergeth, S., Keinath, A., & Neukum, A. (2020). A methodological approach to determine the benefits of external HMI during interactions between cyclists and automated vehicles: A bicycle simulator study. In H. Krömker (Ed.), *HCI in Mobility, Transport, and Automotive Systems. Driving Behavior, Urban and Smart Mobility. HCII 2020. Lecture Notes in Computer Science(), vol 12213*. (pp. 211–227). Springer. https://doi.org/10.1007/978-3-030-50537-0_16

Katz, A., Zaidel, D., & Elgrishi, A. (1975). An experimental study of driver and pedestrian interaction during the crossing conflict. *Human Factors*, *17*(5), 514–527. https://doi.org/10.1177/001872087501700510

Klein, G., Feltovich, P. J., Bradshaw, J. M., & Woods, D. D. (2004). Common ground and coordination in joint activity. *Organizational Simulation*, *53*, 139–184.

Kleinke, C. L. (1977). Compliance to requests made by gazing and touching experimenters in field settings. *Journal of Experimental Social Psychology*, *13*(3), 218–223. https://doi.org/https://doi.org/10.1016/0022-1031(77)90044-0

Kraus, J., Scholz, D., Stiegemeier, D., & Baumann, M. R. (2020). The more you know: Trust dynamics and calibration in highly automated driving and the effects of take-overs, system malfunction, and system transparency. *Human Factors*, *62*(5), 718–736. https://doi.org/10.1177/0018720819853686

Krems, J. F., & Baumann, M. R. (2009). Driving and situation awareness: A cognitive model of memory-update processes. In M. Kurosu (Ed.), *Human Centered Design. HCD 2009. Lecture Notes in Computer Science, vol 5619.* (pp. 986-994). Springer. https://doi.org/10.1007/978-3-642-02806-9_113

Lagström, T., & Lundgren, V. M. (2015). *AVIP - Autonomous vehicles interaction with pedestrians - An investigation of pedestrian-driver communication and development of a vehicle external interface* [Master thesis, Chalmers University of Technology]. https://publications.lib.chalmers.se/records/fulltext/238401/238401.pdf

Lau, M., Jipp, M., & Oehl, M. (2021). Investigating the interplay between eHMI and dHMI for

automated buses: How do contradictory signals influence a pedestrian's willingness to cross? *Proceedings of the 13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, *Leeds, United Kingdom* (pp. 152–155). https://doi.org/https://doi.org/10.1145/3473682.3480284

Lau, M., Jipp, M., & Oehl, M. (2022). Toward a holistic communication approach to an automated vehicle's communication with pedestrians: Combining vehicle kinematics with external human-machine interfaces for differently sized automated vehicles. *Frontiers in Psychology*, *13:882394*. https://doi.org/https://doi.org/10.3389/fpsyg.2022.882394

Lee, J. D., & See, K. A. (2004). Trust in automation: Designing for appropriate reliance. *Human Factors*, *46*(1), 50–80. https://doi.org/10.1518/hfes.46.1.50_30392

Lee, Y. M., Madigan, R., Giles, O., Garach-Morcillo, L., Markkula, G., Fox, C., Camara, F., Rothmueller, M., Vendelbo-Larsen, S. A., Rasmussen, P. H., Dietrich, A., Nathanael, D., Portouli, V., Schieben, A., & Merat, N. (2020). Road users rarely use explicit communication when interacting in today's traffic: implications for automated vehicles. *Cognition, Technology and Work*, *23*, 367–380. https://doi.org/10.1007/s10111-020-00635-y

Lee, Y. M., & Sheppard, E. (2017). Differences in gap acceptance for approaching cars and motorcycles at junctions : What causes the size-arrival effect? *Transportation Research Part F: Traffic Psychology and Behaviour*, *50*(October), 50–54. https://doi.org/https://doi.org/10.1016/j.trf.2017.07.006

Li, T., & Liu, P. (2023). Etiquette equality or inequality? Drivers' intention to be polite to automated vehicles in mixed traffic. In V. G. Duffy, S. J. Landry, J. D. Lee, & N. A. Stanton (Eds.), *Human-Automation Interaction. Automation, Collaboration, & E-Services, vol 11* (pp. 57–73). Springer. https://doi.org/https://doi.org/10.1007/978-3-031-10784-9_3

Litman, T. (2019). *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning.* Victoria Transport Policy Institute. https://www.vtpi.org/avip.pdf

Mahadevan, K., Somanath, S., & Sharlin, E. (2018). Communicating awareness and intent in autonomous vehicle-pedestrian interaction. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18), Montreal, QC, Canada* (pp. 1-12). https://doi.org/10.1145/3173574.3174003

Malone, T. W., & Crowston, K. (1994). The interdisciplinary study of coordination. *ACM Computing Surveys (CSUR)*, *26*(1), 87–119.

https://doi.org/https://doi.org/10.1145/174666.174668

Markkula, G., Madigan, R., Nathanael, D., Portouli, E., Lee, Y. M., Dietrich, A., Billington, J., Schieben, A., & Merat, N. (2020). Defining interactions: a conceptual framework for understanding interactive behaviour in human and automated road traffic. *Theoretical Issues in Ergonomics Science*, *21*(6), 728–752. https://doi.org/10.1080/1463922X.2020.1736686

Merat, N., Jamson, A. H., Lai, F. C., & Carsten, O. (2012). Highly automated driving, secondary task performance, and driver state. *Human Factors*, *54*(5), 762–771. https://doi.org/10.1177/0018720812442087

Mercedes-Benz Group AG (2021, July 29). *"Easy Tech: Conditionally Automated Driving with the DRIVE PILOT":* Mercedes-Benz Group AG. https://group.mercedes-benz.com/company/magazine/technology-innovation/easy-tech-drive-pilot.html

Mertens, J. C., Knies, C., Diermeyer, F., Escherle, S., & Kraus, S. (2020). The need for cooperative automated driving. *Electronics*, *9*(5), 754. https://doi.org/https://doi.org/10.3390/electronics9050754

Meyer, S., Mandl, S., Gesmann-Nuissl, D., & Strobel, A. (2023). Responsibility in hybrid societies: Concepts and terms. *AI Ethics*, *3*, 25–48. https://doi.org/https://doi.org/10.1007/s43681-022-00184-2

Millard-Ball, A. (2018). Pedestrians, autonomous vehicles, and cities. *Journal of Planning Education and Research*, *38*(1), 6–12. https://doi.org/https://doi.org/10.1177/0739456X16675674

Moody, S., & Melia, S. (2014). Shared space – research, policy and problems. *Proceedings of the Institution of Civil Engineers*, *167*(6), 384–392. https://doi.org/https://doi.org/10.1680/tran.12.00047

Moore, D., Currano, R., Strack, G. E., & Sirkin, D. (2019). The case for implicit external human-machine interfaces for autonomous vehicles. *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '2019)*, *Utrecht, Netherlands* (pp. 295–307). https://doi.org/10.1145/3342197.3345320

Nass, G., Fogg, B. J., & Moon, Y. (1996). Can computers be teammates ? *International Journal of Human-Computer Studies*, *45*(6), 669–678. https://doi.org/https://doi.org/10.1006/ijhc.1996.0073

Noble, A. M., Klauer, S. G., Machiani, S. G., & Manser, M. P. (2020). Importance of training

for automated, connected, and intelligent vehicle systems. In D. L. Fisher, W. J. Horrey, J. D. Lee, & M. A. Reagan (Eds.), *Handbook of human factors for automated, connected, and intelligent vehicles* (1st ed., pp. 395–420). CRC Press.

Nordhoff, S., de Winter, J., Madigan, R., Merat, N., van Arem, B., & Happee, R. (2018). User acceptance of automated shuttles in Berlin-Schöneberg: A questionnaire study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*(October), 843–854. https://doi.org/https://doi.org/10.1016/j.trf.2018.06.024

Nyholm, S., & Smids, J. (2020). Automated cars meet human drivers: responsible human-robot coordination and the ethics of mixed traffic. *Ethics and Information Technology*, *22*, 335–344. https://doi.org/10.1007/s10676-018-9445-9

Onkhar, V., Bazilinskyy, P., Dodou, D., & de Winter, J. C. F. (2022). The effect of drivers' eye contact on pedestrians' perceived safety. *Transportation Research Part F: Traffic Psychology and Behaviour*, *84*(January), 194–210. https://doi.org/https://doi.org/10.1016/j.trf.2021.10.017

Othersen, I., Conti-Kufner, A. S., Dietrich, A., Maruhn, P., & Bengler, K. (2018). Designing for automated vehicle and pedestrian communication: Perspectives on eHMIs from older and younger persons. In D. De Waard, K. Brookhuis, D. Coelho, S. Fairclough, D. Manzey, A. Naumann, L. Onnasch, S. Röttger, A. Toffetti, & R. Wiczorek (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference* (pp. 135–148). Online. https://www.hfes-europe.org/technology-ageing-society

Oxley, J. A., Ihsen, E., Fildes, B. N., Charlton, J. L., & Day, R. H. (2005). Crossing roads safely: An experimental study of age differences in gap selection by pedestrians. *Accident Analysis and Prevention*, *37*(5), 962–971. https://doi.org/10.1016/j.aap.2005.04.017

Parasuraman, R., Sheridan, T. B., & Wickens, C. D. (2000). A model for types and levels of human interaction with automation. *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans.*, *30*(3), 286–297. https://doi.org/10.1109/3468.844354

Penmetsa, P., Adanu, E. K., Wood, D., Wang, T., & Jones, S. L. (2019). Perceptions and expectations of autonomous vehicles – A snapshot of vulnerable road user opinion. *Technological Forecasting and Social Change*, *143*, 9–13. https://doi.org/10.1016/j.techfore.2019.02.010

Petzoldt, T., Ngoc, Q. H.-S., & Bogda, K. (2017). Time to arrival estimates, (pedestrian) gap

acceptance and the size arrival effect. *Driving Assessment Conference, Vermont, USA* (pp. 44–50). https://doi.org/10.17077/drivingassessment.1613

Petzoldt, T., Schleinitz, K., & Banse, R. (2018). Potential safety effects of a frontal brake light for motor vehicles. *IET Intelligent Transport Systems*, *12*(6), 449–453. https://doi.org/10.1049/iet-its.2017.0321

Petzoldt, T., Schleinitz, K., Krems, J. F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science*, *92*, 283–289. https://doi.org/10.1016/j.ssci.2015.07.021

Pillai, A. (2017). *Virtual reality based study to analyse pedestrian attitude towards autonomous Vehicles* [Master thesis, Aalto University]. https://core.ac.uk/download/pdf/132598629.pdf

Polders, E., Brijs, T., Vlahogianni, E., Papadimitriou, E., Yannis, G., Leopold, F., Durso, C., & Diamandouros, K. (2015). *Eldersafe risk and countermeasures for road traffic of elderly in europe.* European Comission. https://road-safety.transport.ec.europa.eu/system/files/2021-07/eldersafe_final_report.pdf

Portouli, E., Nathanael, D., & Marmaras, N. (2014). Drivers' communicative interactions: on-road observations and modelling for integration in future automation systems. *Ergonomics*, *57*(12), 1795–1805. https://doi.org/https://doi.org/10.1080/00140139.2014.952349

Raju, N., Schakel, W., Reddy, N., Dong, Y., & Farah, H. (2022). Car-following properties of a commercial adaptive cruise control system: A pilot field test. *Transportation Research Record*, *2676*(7), 128–143. https://doi.org/10.1177/03611981221077085

Rasouli, A., Kotseruba, I., & Tsotsos, J. K. (2017). Agreeing to cross: How drivers and pedestrians communicate. *IEEE Intelligent Vehicles Symposium (IV)*, *Los Angeles, CA, USA* (pp. 264–269). https://doi.org/https://doi.org/10.1109/IVS.2017.7995730

Rasouli, A., Kotseruba, I., & Tsotsos, J. K. (2018). Understanding pedestrian behavior in complex traffic scenes. *IEEE Transactions on Intelligent Vehicles*, *3*(1), 61–70. https://doi.org/10.1109/tiv.2017.2788193

Rasouli, A., & Tsotsos, J. K. (2020). Pedestrians : A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems*, *21*(3), 900–918. https://doi.org/10.1109/TITS.2019.2901817

Renner, L., & Johansson, B. (2006). Driver coordination in complex traffic environments. *Proceedings of the 13th Eurpoean Conference on Cognitive Ergonomics: Trust and*

Control in Complex Socio-Technical Systems (ECCE '06), *Zurich, Switzerland* (pp. 35–40). https://doi.org/https://doi.org/10.1145/1274892.1274899

Risser, R. (1988). *Kommunikation und Kultur des Strassenverkehrs [Communication and culture on road traffic]*. Bundesanstalt für Straßenwesen (BASt).

Risto, M., Emmenegger, C., Vinkhuyzen, E., Cefkin, M., & Hollan, J. (2017). Human-vehicle interfaces: The power of vehicle movement gestures in human road user coordination. *Driving Assessment Conference*, 186–192. https://doi.org/10.17077/drivingassessment.1633

Robbins, C. J., Allen, H. A., & Chapman, P. (2018). Comparing drivers' gap acceptance for cars and motorcycles at junctions using an adaptive staircase methodology. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*(October), 944–954. https://doi.org/10.1016/j.trf.2018.07.023

Rödel, C., Stadler, S., Meschtscherjakov, A., & Tscheligi, M. (2014). Towards autonomous cars: The effect of autonomy levels on Acceptance and User Experience. *Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '14)*, *Seattle, WA, USA* (pp. 1–8). https://doi.org/https://doi.org/10.1145/2667317.2667330

Rodríguez Palmeiro, A., van der Kint, S., Vissers, L., Farah, H., de Winter, J. C., & Hagenzieker, M. (2018). Interaction between pedestrians and automated vehicles: A Wizard of Oz experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*(October), 1005–1020. https://doi.org/10.1016/j.trf.2018.07.020

Röhner, J., & Schütz, A. (2020). *Psychologie der Kommunikation [Psychology of communication]*. Springer. https://doi.org/https://doi.org/10.1007/978-3-662-61338-2

Rothenbücher, D., Li, J., Sirkin, D., Mok, B., & Ju, W. (2016). Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. *25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, *New York, NY, USA* (pp. 795–802). https://doi.org/10.1109/ROMAN.2016.7745210

Rouchitsas, A., & Alm, H. (2019). External human–machine interfaces for autonomous vehicle-to-pedestrian communication: A review of empirical work. *Frontiers in Psychology*, *10:2757*. https://doi.org/10.3389/fpsyg.2019.02757

SAE International. (2021). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles; J3016.* SAE International. https://saemobilus.sae.org/content/J3016_202104/ [01.11.2023]

SAE International. (2018). *Automated driving system (ADS) marker lamp; J3134.* SAE International. https://saemobilus.sae.org/content/J3134_201905/ [01.11.2023]

Sagberg, F., Selpi, Bianchi Piccinini, G. F., & Engström, J. (2015). A review of research on driving styles and road safety. *Human Factors*, *57*(7), 1248–1275. https://doi.org/10.1177/0018720815591313

Sarter, N. B., Woods, D. D., & Billings, C. E. (1997). Automation surprises. In G. Salvendy (Ed.), *Handbook of Human Factors & Ergonomics,* vol 2 (pp. 1926–1943). Wiley.

Schaarschmidt, E., Yen, R., Bosch, R., Zwicker, L., Schade, J., & Petzoldt, T. (2021). *Grundlagen zur Kommunikation zwischen automatisierten Kraftfahrzeugen und Verkehrsteilnehmern [Fundamentals of communication between automated vehicles and road users].* Bundesanstalt für Straßenwesen (BASt). https://bast.opus.hbz-nrw.de/opus45-bast/frontdoor/deliver/index/docId/2497/file/F138_barrFrei.pdf

Schaefer, K. E., Chen, J. Y. C., Szalma, J. L., & Hancock, P. A. (2016). A meta-analysis of factors influencing the development of trust in automation: Implications for understanding autonomy in future systems. *Human Factors*, *58*(3), 377–400. https://doi.org/10.1177/0018720816634228

Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., & Merat, N. (2019). Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology and Work*, *21*(1), 69–85. https://doi.org/10.1007/s10111-018-0521-z

Schindler, J., Herbig, D. L., Lau, M., & Oehl, M. (2020). Communicating issues in automated driving to surrounding traffic. In N. S. Stephanidis C., Antona M. (Eds.), *HCI International 2020 – Late Breaking Posters. HCII 2020. Communications in Computer and Information Science, vol 1294.* (pp. 619–626). Springer. https://doi.org/10.1007/978-3-030-60703-6

Schleinitz, K., Petzoldt, T., & Gehlert, T. (2019). Drivers' gap acceptance and time to arrival judgements when confronted with approaching bicycles, e-bikes, and scooters. *Journal of Transportation Safety and Security*, *12*(1), 3–16. https://doi.org/10.1080/19439962.2019.1591551

Schleinitz, K., Petzoldt, T., Krems, J., & Gehlert, T. (2015). *Geschwindigkeitswahrnehmung von einspurigen Fahrzeugen [Speed perception of single lane vehicles].* Gesamtverband der Deutschen Versicherungswirtschaft e. V., Unfallforschung der Versicherer.
https://www.udv.de/resource/blob/79762/0b6b40ef012a7efd6a70acee16a8c946/33-

geschwindigkeitswahrnehmung-von-einspurigen-fahrzeugen-data.pdf

Schneemann, F., & Gohl, I. (2016). Analyzing driver-pedestrian interaction at crosswalks: A contribution to autonomous driving in urban environments. *IEEE Intelligent Vehicles Symposium (IV)*, *Gothenburg, Sweden* (pp. 38–43). https://doi.org/10.1109/IVS.2016.7535361

Schulz von Thun, F. (2010). *Miteinander reden: 1 - Störungen und Klärungen: Allgemeine Psychologie der Kommunikation [Talking with each other: 1 - Disturbances and clarifications disruptions and clarifications: General psychology of communication]* (61st ed.). Rowohlt Taschenbuch Verlag.

Scialfa, C. T., Guzy, L. T., Leibowitz, H. W., Garvey, P. M., & Tyrrell, R. A. (1991). Age differences in estimating vehicle velocity. *Psychology and Aging*, *6*(1), 60–66. https://doi.org/10.1037/0882-7974.6.1.60

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal*, *27*, 379–423. https://doi.org/10.1016/s0016-0032(23)90506-5

Shannon, C. E., & Waever, W. (1949). *The mathematical theory of communication*. University of Illinios Press. https://doi.org/10.1109/TMAG.1987.1065451

Sheridan, T. B., & Verplank, W. L. (1978). *Human and computer control of undersea teleoperators.* Massachusetts Institute of Technology. https://www.academia.edu/45510118/Human_and_Computer_Control_of_Undersea_Teleoperators

Shor, R. E. (1964). Shared patterns of nonverbal normative expectations in automobile driving. *The Journal of Social Psychology*, *62*(1), 155–163. https://doi.org/https://doi.org/10.1080/00224545.1964.9919512

Shuttle Modellregion Oberfranken (SMO) (2023, April). "*Shuttle Modellregion Oberfranken (SMO) [Shuttle model region Oberfranken (SMO)]":* Shuttle Modellregion Oberfranken (SMO). https://www.shuttle-modellregion-oberfranken.de/

Stahl, P., Donmez, B., & Jamieson, G. A. (2014). Anticipation in driving: The role of experience in the efficacy of pre-event conflict cues. *IEEE Transactions on Human-Machine Systems*, *44*(5), 603–613. https://doi.org/10.1109/THMS.2014.2325558

Stange, V. (2021). *Human driver and passenger reactions to highly automated vehicles in mixed traffic on highways and in urban areas* [Doctoral dissertation, Technischen Universität Carolo-Wilhelmina zu Braunschweig]. https://leopard.tu-braunschweig.de/receive/dbbs_mods_00069676

Stange, V., Goralzik, A., Ernst, S., Steimle, M., Maurer, M., & Vollrath, M. (2022). Please stop now, automated vehicle! – Passengers aim to avoid risk experiences in interactions with a crossing vulnerable road user at an urban junction. *Transportation Research Part F: Traffic Psychology and Behaviour*, *87*(May), 164–188. https://doi.org/10.1016/j.trf.2022.04.001

Stange, V., Kühn, M., & Vollrath, M. (2022a). Manual drivers' experience and driving behavior in repeated interactions with automated Level 3 vehicles in mixed traffic on the highway. *Transportation Research Part F: Traffic Psychology and Behaviour*, *87*(May), 426–443. https://doi.org/10.1016/j.trf.2022.04.019

Stange, V., Kühn, M., & Vollrath, M. (2022b). Safety at first sight? – Manual drivers' experience and driving behavior at first contact with Level 3 vehicles in mixed traffic on the highway. *Transportation Research Part F: Traffic Psychology and Behaviour*, *87*(May), 327–346. https://doi.org/https://doi.org/10.1016/j.trf.2022.04.004

Stanton, N. A., Eriksson, A., Banks, V. A., & Hancock, P. A. (2020). Turing in the driver's seat: Can people distinguish between automated and manually driven vehicles? *Human Factors and Ergonomics in Manufacturing*, *30*, 418–425. https://doi.org/https://doi.org/10.1002/hfm.20864

Staplin, L. (1995). Simulator and field measures of driver age differences in left-turn gap judgments. *Transportation Research Record*, *1485*, 49–55. https://onlinepubs.trb.org/Onlinepubs/trr/1995/1485/1485-007.pdf

Straßenverkehrsordnung (StVO). (2021). https://www.stvo.de/strassenverkehrsordnung [01.11.2023]

Stelmach, G. E., & Nahom, A. (1992). Cognitive-motor abilities of the elderly driver. *Human Factors*, *34*(1), 53–65. https://doi.org/10.1177/001872089203400107

Stiftung für Prävention der AXA (n.d.). *„Mit Max sicher im Strassenverkehr [Safe in road traffic with Max]":* AXA Stiftung Prävention. https://www.stiftung-praevention.ch/max-der-dachs

Šucha, M., Dostal, D., & Risser, R. (2017). Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis and Prevention*, *102*, 41–50. https://doi.org/10.1016/j.aap.2017.02.018

Summala, H. (1988). Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. *Ergonomics*, *31*(4), 491–506. https://doi.org/https://doi.org/10.1080/00140138808966694

Summala, H. (2007). Towards understanding motivational and emotional factors in driver behaviour: Comfort through satisficing. In P. C. Cacciabue (Ed.), *Modelling driver behaviour in automotive environments: Critical issues in driver interactions with intelligent transport systems* (pp. 189–207). Springer. https://doi.org/10.1007/978-1-84628-618-6

Tabone, W., de Winter, J., Ackermann, C., Bärgman, J., Baumann, M., Deb, S., Emmenegger, C., Habibovic, A., Hagenzieker, M., Hancock, P. A., Happee, R., Krems, J., Lee, J. D., Martens, M., Merat, N., Norman, D., Sheridan, T. B., & Stanton, N. A. (2021). Vulnerable road users and the coming wave of automated vehicles: Expert perspectives. *Transportation Research Interdisciplinary Perspectives*, *9*(March), 100293. https://doi.org/10.1016/j.trip.2020.100293

Tacken, M., Marcellini, F., Mollenkopf, H., Ruoppila, I., & Széman, Z. (2005). Use and acceptance of new technology by older people. Findings of the international MOBILATE survey: 'Enhancing mobility in later life.' *Gerontechnology*, *3*(3), 126–137. https://doi.org/https://doi.org/10.4017/gt.2005.03.03.002.00

Technische Universität Chemnitz (2023, October 18). *„Kursbereich: Smartphone/ Tablet & PC [Courses for smart phone/ tablet & pc]": Seniorenkolleg an der TU Chemnitz*. https://www.tu-chemnitz.de/seniorenkolleg/smartphone.html

Terken, J., & Pfleging, B. (2020). Toward shared control between automated vehicles and users. *Automotive Innovation*, *3*(1), 53–61. https://doi.org/10.1007/s42154-019-00087-9

Tinga, A. M., Petermeijer, S. M., Reus, A. J. C. De, Jansen, R. J., & Waterschoot, B. M. Van. (2023). Assessment of the cooperation between driver and vehicle automation: A framework. *Transportation Research Part F: Psychology and Behaviour*, *95*(May), 480–493. https://doi.org/https://doi.org/10.1016/j.trf.2023.04.002

Uttley, J., Lee, Y. M., Madigan, R., & Merat, N. (2020). Road user interactions in a shared space setting: Priority and communication in a UK car park. *Transportation Research Part F: Traffic Psychology and Behaviour*, *72*(July), 32–46. https://doi.org/https://doi.org/10.1016/j.trf.2020.05.004

Van Der Laan, J. D., Heino, A., & De Waard, D. (1997). A simple procedure for the assessment of acceptance of advanced transport telematics. *Transportation Research Part C: Emerging Technologies*, *5*(1), 1–10. https://doi.org/10.1016/S0968-090X(96)00025-3

van Loon, R. J., & Martens, M. H. (2015). Automated driving and its effect on the safety ecosystem: How do compatibility issues affect the transition period? *Procedia*

Manufacturing, *3*, 3280–3285. https://doi.org/10.1016/j.promfg.2015.07.401

Várhelyi, A. (1998). Drivers' speed behaviour at a zebra crossing: A case study. *Accident Analysis and Prevention*, *30*(6), 731–743. https://doi.org/10.1016/S0001-4575(98)00026-8

Vollrath, M., & Krems, J. (2011). *Verkehrspsychologie: Ein Lehrbuch für Psychologen, Ingenieure und Informatiker [Traffic psychology: a textbook for psychologist, engineers and computer scientist]* (M. Hasselhorn, H. Heuer, & F. Rösler, Eds.). Kohlhammer.

Watzlawick, P. (2016). *Man kann nicht nicht kommunizieren: Das Lesebuch [One cannot not communicate: The textbook]*. Hogrefe.

Wilbrink, M., Cieler, S., Weiß, S. L., Beggiato, M., Joisten, P., Feierle, A., & Oehl, M. (2023). Principles for external human–machine interfaces. *Information*, *14*(8), 463. https://doi.org/10.3390/info14080463

Wilbrink, M., Schieben, A., Kaup, M., Willrodt, J.-H., Weber, F., & Lee, Y. M. (2018). *Preliminary interaction strategies for the interACT automated vehicles*. German Aerospace Center. https://www.interact-roadautomation.eu/wp-content/uploads/interACT_WP4_D4.1_Preliminary_Human_Vehicle_Interaction_Strategies_v1.0_draftWebsite.pdf

Woodman, R., Lu, K., Higgins, M. D., Brewerton, S., Jennings, P. A., & Birrell, S. (2019). Gap acceptance study of pedestrians crossing between platooning autonomous vehicles in a virtual environment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *67*(November), 1–14. https://doi.org/https://doi.org/10.1016/j.trf.2019.09.017

Woods, D. D. (1996). Decomposing automation: Apparent simplicity, real complexity. In R. Parasuraman & M. Mouloua (Eds.), *Automation and Human Performance: Theory and Applications* (pp. 3–17). CRC Press. https://doi.org/10.1201/9781315137957

Yan, X., Radwan, E., & Guo, D. (2007). Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis and Prevention*, *39*(4), 843–852. https://doi.org/10.1016/j.aap.2006.12.006

PAPER I

DRIVERS' GAP ACCEPTANCE DURING PARKING MANEUVERS AS A BASIS FOR INITIATING DRIVING ACTIONS IN AUTOMATED VEHICLES

Citation:

Hensch, A.-C., Beggiato, M., & Krems J. F. (2023). Drivers' gap acceptance during parking maneuvers as a basis for initiating driving actions in automated vehicles. *Transportation Research Part F: Traffic Psychology and Behaviour, 92*(January), 133-142. https://doi.org/10.1016/j.trf.2022.11.008

This article was published in Research Part F: Traffic Psychology and Behaviour, 92, Ann-Christin Hensch, Matthias Beggiato, Josef F. Krems, Drivers' gap acceptance during parking maneuvers as a basis for initiating driving actions in automated vehicles, 133-142, Copyright Elsevier (2023).

DRIVERS' GAP ACCEPTANCE DURING PARKING MANEUVERS AS A BASIS FOR INITIATING DRIVING ACTIONS IN AUTOMATED VEHICLES

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Abstract

As a social system, traffic requires the coordination between different involved road users, particularly in shared spaces (e.g., parking areas) with fewer statutory regulations and hence more ambiguous encounters. By anticipating the development of driving scenes and adapting own driving actions, drivers maintain individually varying safety margins, such as accepted time gaps, to surrounding traffic participants. However, drivers' gap acceptance (GA) was shown to be influenced by situational factors and driver characteristics. In order to apply expectable interactions in mixed traffic, involving manual and automated vehicles (AVs), intuitive gaps in traffic flow need to be selected by AVs when initiating parking actions. Derived time gaps of manual drivers could provide a basic orientation for intuitive driving functions in AVs. Thus, the current experimental study assessed manual drivers' GA in a parking area scenario. Real-world video material was used to investigate the effects of interaction partners, their encountering speeds and drivers' age and sensation seeking on GA. In the study, 42 participants (including two age groups: 18–30 years vs ≥ 45 years) indicated their GA when initiating a left-turn parking maneuver in front of approaching vehicles. The study examined three interaction partners (motorcycle, passenger car, truck), each approaching at six different speed levels (10–35 km/h). The results revealed that selected time gaps increased as vehicle size increased, with the largest GA for the truck and the smallest gaps for the motorcycle. Moreover, time gaps decreased at higher approaching speeds of the interaction partners. In addition, older participants selected more conservative gaps and participants with higher sensation seeking scores accepted lower time gaps to initiate a parking maneuver. The results of the current study revealed that there is no one single time gap that is always considered as appropriate to initiate parking actions. For intuitive interaction capabilities in AVs and to support smooth encounters in mixed traffic, the speed of the approaching interaction partners should be considered as an essential situational factor when initiating parking maneuvers. To consider individual driving style preferences (e.g., due to driver age) and support user

acceptance, selectable driving style profiles should be available in AVs as a form of customization.

Keywords: gap acceptance, situation awareness, vehicle size, vehicle speed, driver age, automated vehicles

1 Introduction

Traffic as a social system requires the coordination and interaction between different participants to provide road safety, traffic efficiency, as well as the comfort of involved traffic participants (Domeyer et al., 2020). The traffic participants use various information from the driving scene to anticipate and thus coordinate prospective movements (e.g., deceleration maneuvers; Wilde, 1976). In addition, different implicit and explicit communication signals are applied to announce upcoming actions and to enhance predictability for other traffic participants (Schieben et al., 2019). The coordination between different traffic participants is particularly required during turning maneuvers (Hancock et al., 1991). For example, road users need to select appropriate gaps in traffic flow, which present a period of time upon the arrival of an interaction partner at an intersection, for conducting their turning maneuvers (Parkin et al., 2016).

For safe and smooth interactions between different traffic participants, drivers need to correctly perceive, understand and integrate relevant information of the driving scene. Due to the highly dynamic character of traffic scenes, drivers also need to predict and anticipate the development of these scenes which enables them to adapt their own maneuvers accordingly (Baumann & Krems, 2007). These processes are integrated in Endsley's concept of situation awareness (SA; Endsley, 1995). The involved traffic participants are required to achieve correct SA to avoid conflicts or collapses of the interaction process. Generally, three SA levels are distinguished to achieve a highly developed mental model of a situation. SA level one involves perceiving relevant elements of the situation. The second SA level describes the integration of situational elements and comprehension of the significance of respective elements (Endsley, 1995). For instance, experienced drivers are able to identify and integrate relevant situational elements of a driving scene faster and easier due to a greater and more differentiated knowledge of traffic situations (Krems & Baumann, 2009). Level three, the highest SA level, comprises anticipating and predicting the development of a driving scene (Endsley, 1995), which depicts a highly important cognitive competence of drivers (Baumann & Krems, 2007). Anticipating upcoming movements of surrounding traffic participants enables drivers to adapt their own maneuvers and provide smooth interactions that exceed the mere principle of accident avoidance (Stahl et al., 2014).

The anticipation of prospective actions represents, besides the planning and execution of these cognitive components, one aspect of proactive behavior. In general, proactive behavior describes deliberate, future-focused actions and is increasingly shown in ambivalent situations to resolve ambiguities (Grant & Ashford, 2008). For the context of transport, this form of behavior supports traffic safety and efficiency as it provides additional time and space during driving actions (Stahl et al., 2014). Therefore, it might be particularly important in shared

spaces, comprising decreased statutory regulations and thus ambiguous encounters. The coordination of different interaction partners is here for instance required when entering a parking space due to potentially conflicting trajectories (Hamilton-Baillie, 2008).

People maintain specific thresholds between themselves and other entities when interacting (Hall, 1969). Summala (2007) introduced the concept of individual safety margins, which includes thresholds of space and time, for the driving context. Due to drivers' capabilities for understanding and anticipating the development of the scenes, individual safety margins are maintained while initiating and conducting driving maneuvers. Thus, drivers adapt their own driving actions to obtain individual safety margins to surrounding traffic participants. For instance, drivers need to decide whether to accept or reject a gap in traffic flow (Summala, 2007), which depicts drivers' individual gap acceptance behavior (GA). Generally, the concept of gap acceptance comprises drivers' (or pedestrians') accepted time gaps to conduct an action in traffic flow (e.g., turning or crossing actions). GA is typically assessed in driving simulator, test track or lab studies; whereas indicating the accepted time gaps by pressing a button proved as beneficial tradeoff between participants' safety and level of realism. Thereby, the encountering interaction partners approach from a predetermined distance with a constant speed at the observer's point of view (Lee & Sheppard, 2017; Schleinitz et al., 2015). However, drivers' accepted time gaps were shown to be influenced by various situational factors and driver characteristics (e.g., Petzoldt, 2016; Yan et al., 2007). For instance, the size of the approaching interaction partner was revealed to influence selected time gaps for initiating a driving maneuver. Larger gaps were required when interacting with larger interaction partners (Hancock & Caird, 1993). One explanation is given by the so-called size-arrival effect (initially described for rather artificial material by DeLucia, 1991) that describes the general phenomenon that larger objects are judged to arrive earlier at an observer's position than smaller objects. In the driving context, the effect would result in increasingly conservative time gaps that are selected to initiate driving maneuvers when confronted with larger interaction partners (DeLucia, 1991). For instance, Hancock et al. (1991) reported a decreased tendency to accept time gaps for left-turn maneuvers in front of trucks as larger interaction partners compared to passenger cars or motorcycles as smaller interaction partners. Given an equal distance to the approaching interaction partners, participants judged a turning maneuver as safer when confronted with motorcycles compared to approaching passenger cars (Lee & Sheppard, 2017). Moreover, smaller gaps were accepted on average in front of approaching motorcycles compared to passenger cars (Robbins et al., 2018). On the other hand, according to the phenomenon of the size speed bias (Leibowitz, 1985), larger objects appear to move slower than smaller ones, despite moving at the same speed. For the context of road traffic this implies that larger vehicles need to travel much faster than smaller vehicles to be

perceived as approaching with the same speed (Petzoldt, 2016). In that regard, Clark et al. (2013) argued that misjudging a larger vehicle's speed could thus influence selected gaps (i.e., GA) to initiate turning maneuvers in front of approaching interaction partners. Since diverse phenomena regarding the effect of the interaction partners' size on drivers' GA were reported in previous literature (i.e., size-arrival effect; DeLucia, 1991 vs. size speed bias; Leibowitz, 1985) there is no hypothesis for this factor introduced subsequently.

The approaching speed of an interaction partner was identified as an additional factor influencing GA and the resulting encounters between different traffic participants. A stable effect could be shown that smaller time gaps were accepted to initiate a driving maneuver during higher speeds of the approaching interaction partner (Petzoldt et al., 2017). In particular, the effect could be shown for a variety of approaching interaction partners, such as passenger cars (Beggiato et al., 2018) as well as different two-wheelers (Hensch et al., 2021; Schleinitz et al., 2020). The presented findings are the basis for the first hypothesis (H1) that is subsequently introduced.

Besides situational factors, including size and speed of interaction partners, driver characteristics and individual driving style preferences should also be taken into account when considering encounters between different traffic participants. Driving styles are generally described as stable aspects of behavior and vary between individuals or groups of individuals. For instance, driving styles incorporate preferences for headway times or speeds (for an overview see Sagberg et al., 2015). Thus, GA as available time gaps to surrounding traffic participants, can be considered as one specific parameter of individually varying driving styles (Summala, 2007). Drivers' age was revealed to influence GA as a parameter of individual driving styles. Specifically it was reported that older participants selected larger time gaps to initiate a maneuver in front of approaching interaction partners, reflecting more conservative decisions, compared to younger participants (for a pedestrian's perspective see Beggiato et al., 2018; for a driver's perspective see Yan et al., 2007). These findings could be explained by employing strategies to compensate for a decreased sensitivity of speed judgements that were shown from the fifth decade of life (Scialfa et al., 1991). The presented research results are the basis for H2 that is introduced afterwards. Beyond drivers' age, sensation seeking is a frequently investigated personality trait in the driving context and was shown to influence individual driving styles (for an overview see Jonah, 1997). Generally, sensation seeking incorporates the need for new, diverse and complex experiences and sensations (Zuckerman, 1994). Regarding driving style, a positive relation between sensation seeking and a high speed driving behavior was shown (Taubman-Ben-Ari et al., 2004). Considering specific driving parameters, Heino et al. (1996) reported reduced time headways to surrounding traffic participants for higher sensation seekers during a free following task on motorways. Since

increased sensation seeking is related to a dynamic driving style (Taubman-Ben-Ari et al., 2004), it might also result in smaller accepted time gaps to other traffic participants when initiating parking actions during encounters in shared spaces. The findings are the basis for H3, which is introduced afterwards. Thus, besides situational factors, personal characteristics represent essential aspects influencing specific driving parameters, such as drivers' gap acceptance (Yan et al., 2007).

Recently, there has been an increase of automated driving functions, offering the advantages of enhanced road safety, traffic efficiency and driving comfort (SAE, 2018). To support user acceptance of automated vehicles (AVs; SAE Level 3 or higher; SAE, 2018), their interaction capabilities should be designed transparent and predictable to provide intuitive and expectable encounters in mixed traffic, involving manual and automated vehicles (Habibovic et al., 2018; van Loon & Martens, 2015). Without suitable interaction capabilities, AVs' driving maneuvers might be perceived as artificial and unexpected by human users in- and outside the vehicle (Schieben et al., 2019). That in turn could reduce traffic safety (Stange et al., 2022), traffic flow, user acceptance and thus the usage of those technologies (Schieben et al., 2019). The transfer and hence the implementation of established interaction capabilities from manual driving to AVs could provide a common ground between AVs, manual drivers and surrounding traffic participants by incorporating mutual knowledge and assumptions about potential encounters (Clark & Brennan, 1991). Implementing differentiated knowledge in AVs, as experienced human drivers have at their disposal, would enable AVs to identify and encode relevant situational information faster and more reliable (Krems & Baumann, 2009; comparable with SA level two, Endsley, 1995). That in turn would increasingly enable AVs to anticipate the prospective development of driving scenes. Therefore, AVs would be able to adapt their own driving actions and thereby provide additional time and space within driving scenes (e.g., by (non–) initiating driving maneuvers), which could support proactive interactions in mixed traffic (Stahl et al., 2014; comparable with SA level three, Endsley, 1995). However, to provide intuitive interactions in mixed traffic, which meet the expectations of human user in- and outside the vehicle, AVs need to consider various influencing factors for their maneuvering decisions comparable to human drivers (Domeyer et al., 2020). Therefore, a deeper understanding of potentially influencing factors and specific effects on manual drivers' maneuvering decisions during interactions is required. Moreover, it seems reasonable to quantify and derive specific parameters of manual driving that could be used as a basic orientation for configuring AVs' driving functions and thus support expectable interactions in mixed traffic (see for comparable approaches: Beggiato et al. (2018) considering pedestrians' GA during crossing actions as a basis for AVs' braking maneuvers; Stange et al. (2022) considering drivers' braking maneuver onset times at intersections). Manual drivers' GA

parameters for initiating parking actions could be used as a basis in AVs' driving functions to provide intuitive interactions in shared spaces (Hensch et al., 2021).

1.1 Objectives of the study

The present study assessed manual drivers' accepted time gaps for initiating parking actions in a shared space setting, where the coordination of actions is particularly important due to ambiguous encounters. The quantified time gaps provide information about initiating driving maneuvers to support expectable interactions between different traffic participants. The derived time gap parameters from manual drivers for initiating parking actions could prospectively be used as a basic orientation for intuitive interaction capabilities in AVs. Therefore, (a) situational (i.e., the size and approaching speed of interaction partners) and (b) driver characteristics (i.e., drivers' age and sensation seeking scores) as potentially influencing factors on accepted time gaps were investigated in the current study. The study manipulated three interaction partners of different sizes (i.e., motorcycle, passenger car, truck) approaching the observer's point of view with different speed levels that were investigated in a high level of detail (10/ 15/ 20/ 25/ 30/ 35 km/h). It is assumed that the interaction partners' size influences drivers' accepted time gaps. However, due to conflicting theories regarding the effect of the size of the interaction partner on drivers' GA (i.e., size-arrival effect vs size speed bias) there is no hypothesis introduced. Moreover, the following hypotheses were derived from previous research results and are subsequently investigated: Regarding the approaching speeds of the interaction partner, it is predicted that smaller time gaps would be selected with higher approaching speed levels of the respective interaction partner (H1). Moreover, the effects of drivers' age and sensation seeking are assessed in the study. Concerning drivers' age, larger accepted time gaps are expected for older drivers compared to younger drivers (H2). In addition, it is hypothesized that drivers scoring higher in sensation seeking will accept smaller time gaps when interacting with the approaching interaction partners compared to drivers scoring lower in sensation seeking (H3).

2 Materials and method

2.1 Participants

In total, $N = 42$ participants (22 women, 20 men) across two age groups contributed to the study. Detailed sample characteristics are provided in Table 1. All participants held a valid drivers' license, which was a precondition to contribute to the study, given the study assessed drivers' gap acceptance. The participants indicated an average annual mileage of $M = 11538.10$ km ($SD = 11629.78$ km).

Table 1

Overview of the sample's characteristics

Age group	*n*	n_{female}	n_{male}	M_{age}	SD_{age}	Min_{age}	Max_{age}
18 - 30 years	22	12	10	23.82	3.11	19	29
≥ 45 years	20	10	10	56.40	7.74	47	81

2.2 Research design

The current monitor-based study investigated participants' accepted time gaps when initiating a parking action in front of different interaction partners approaching at various speeds from a drivers' perspective. A 3 × 6 × 3 × 2 mixed factor design was applied. Three interaction partners were investigated (Fig. 1): A motorcycle (Piaggio Zip 50), a passenger car (Smart Electric Drive) and a truck (Ford Transit). Each interaction partner approached at six different speeds that were manipulated in a high level of detail and are typical in parking areas as shared spaces: 10/ 15/ 20/ 25/ 30/ 35 km/h. All speed levels were manipulated experimentally by accelerating or decelerating the video footage. The vehicle type and speed levels were applied as within-subject factors. In order to stabilize the results, each condition was presented three times in an overall randomized order, resulting in a total of 54 trials. Participants' age group (18–30 years vs ≥ 45 years) served as the between-subjects factor. In order to evaluate behavioral differences between the age groups, that were shown from the fifth decade of life (Scialfa et al., 1991), a middle category was not included in the study. Participants' sensation seeking scores were applied as a covariate. Participants' indicated GA served as the dependent variable in the current study. In particular, the latest moments for initiating left-turn parking maneuvers in front of oncoming vehicles were indicated by the participants. This approach was selected as a tradeoff to collect time gap parameters comprising safety margins toward oncoming traffic participants maintaining drivers' comfort and acceptance but also preventing from a highly defensive driving style that might restrict traffic flow.

2.3 Apparatus and material

2.3.1 Video material and simulation

The study included real-world video material displaying different approaching interaction partners from a drivers' perspective in a parking area as a shared space setting. The videos were recorded by a GARMIN VIRB Ultra 30 (1920x1080 pixels, 100 fps) in the parking area of Chemnitz University of Technology, Germany. The material displayed the perspective of an

onward left-turn parking maneuver into an empty parking space from a drivers' point of view (i.e., ego-vehicle). The ego-vehicle was placed with a lateral distance of 3.7 m and a longitudinal distance of 0.5 m from the empty parking space to provide an unobstructed view and a natural position to park in the space (Fig. 1a). Due to oncoming interaction partners (i.e., motorcycle, passenger car, truck) a hypothetical overlap of the ego-vehicle's and the approaching vehicles' trajectory was implied (Fig. 1b-d). The interaction vehicles approached from a distance of about 90 m to the ego-vehicle and were all driven by the same trained researcher to control for driving style and with a constant speed of approximately 15 km/h (i.e., no deceleration or acceleration). To determine post-hoc the exact speed in each recorded video sequence, unobtrusive markers were placed along the route. The final video material exclusively displayed the respective approaching vehicles without other moving objects. To investigate the effect of different speed levels on participants' GA, the approaching speed of the interaction partners was manipulated by accelerating or decelerating the video playback-rate. The manipulation of the playback-rate (i.e., the varied approach speed) resulted in video durations of approximately 9 to 32 s.

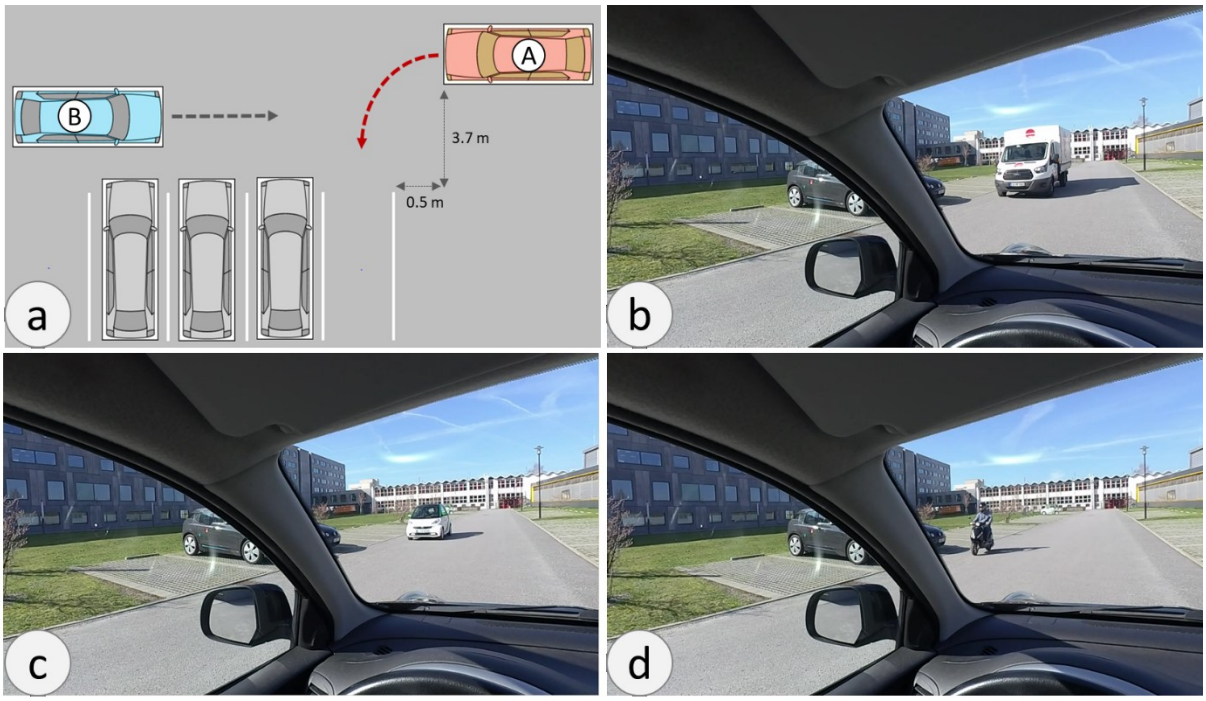
To achieve full experimental control, the pre-recorded video material was presented in a simulation environment that allowed for standardized instructions, a randomized order of the experimental trials and a logging of exact time gaps. Moreover, using the simulation environment allowed for controlling additional potentially influencing factors on GA, such as timings, lighting conditions or perspectives of the driving scene, by keeping them constant (Beggiato et al., 2017). The simulation environment was programmed in LabVIEW (National Instruments, 2015) and was presented on a 17″ Full HD screen to the participants.

2.3.2 Questionnaires

Besides the sociodemographic information comprising participants' age, gender and annual mileage driven, a standardized questionnaire was applied to determine participants' sensation seeking. Therefore, the Brief Sensation Seeking Scale (BSSS) by Hoyle et al. (2002) was used. The scale includes eight items that were averaged into one overall sensation seeking score. Participants indicated their agreement to the items on a 5-point Likert scale from [1] "strongly disagree" to [5] "strongly agree". Cronbach's alpha was determined to be at an acceptable level (α = 0.70; Field, 2009).

Figure 1

Recorded scenario of the current study and screenshot examples of the applied video material



Note. a) Recorded left-turn parking scenario of the study resulting in a hypothetical overlap of the ego-vehicle's (A) and approaching vehicles' (B) trajectories. Vehicle (A) displays the participants' perspective that need to anticipate the prospective development of the driving scene and that hypothetically initiates a left-turn maneuver in front of different approaching interaction partners that are illustrated as vehicle (B). (b - d) Examples of the applied video material displaying the investigated interaction partners: b) truck, c) passenger car and d) motorcycle.

2.4 Procedure

Participants were first welcomed and informed about the scope of the study before informed consent was obtained. To standardize the data collection, participants received written instructions that were provided in the simulation environment. However, participants always had the opportunity to ask questions if needed. Participants were instructed to indicate the latest moment they would select to initiate an onward left-turn parking maneuver into the empty parking space in front of the oncoming traffic participants (i.e., subsequent onset times for initiating the maneuver would have been considered as too late by the participants). The participants indicated the respective time gaps by pressing the enter key. They experienced five test trials, in which the video material was presented in the entire duration, to become acquainted with the simulation environment and the investigated interaction partners. Afterwards, 36 randomized experimental trials including data collection of time gaps were conducted. Participants then filled out sociodemographic and personality questionnaires and

conducted 18 additional experimental trials of GA collection. To prevent participant fatigue during the experimental trials, the videos were stopped when the respective gap per trial was indicated and the next trial followed. Moreover, the experimental trials of GA collection were separated to 36 and additional 18 trials. Participants received a monetary compensation of 10€ for contributing to the study that lasted approximately 60 min.

2.5 Data preparation

The indicated GA values were calculated as the time interval (in seconds) between the respective moments of participants' button presses (i.e., the latest onset time to initiate a parking action) and the hypothetical moment of collision between the approaching interaction vehicle and the ego-vehicle. Outliers in the GA data were identified using boxplots for all 54 single experimental trials across all participants. Extreme outliers (i.e., more than three interquartile ranges over the third or under the first quartile) were excluded from further analysis. Thus, 10 GA values were excluded, resulting in 2258 remaining GA values for further analysis. Afterwards, the mean GA of the respective three repetitions per condition was calculated.

3 Results

In the study, vehicle size and speed levels of the approaching interaction partners served as within-subject factors to investigate the effect on drivers' GA, whereas participants' age groups formed the between-subjects factor and participants' sensation seeking scores were applied as a covariate in the conducted repeated measures ANOVAs and ANCOVAs. The participants' GA served as the dependent variable. Since the assumption of sphericity (Mauchly's test) was violated for the factor approaching speed (Greenhouse-Geisser $\varepsilon \leq 0.75$), the Greenhouse-Geisser corrected *F*-values and degrees of freedom are reported for the ANOVA and ANCOVA results that include this factor. Table 2 provides a general overview of the study's results.

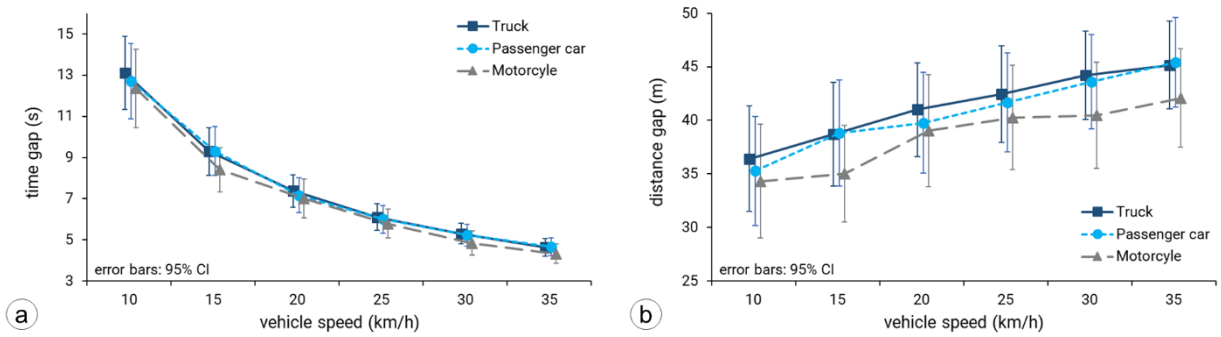
3.1 The effect of situational factors on GA

Generally, participants selected the smallest time gaps (in seconds) when encountering the motorcycle as the smallest interaction partner ($M = 7.13$, $SD = 2.91$), followed by the passenger car ($M = 7.52$, $SD = 2.82$). The largest time gaps were selected when interacting with the truck ($M = 7.64$, $SD = 2.69$). A statistically significant main effect for the factor vehicle size was found in the repeated measures ANOVA that was conducted for the GA values (Table 2). Post-hoc comparisons (Bonferroni-corrected) revealed statistically significant differences in GA between the truck and the motorcycle ($p < .001$) as well as between the

passenger car and the motorcycle (p = .018). Moreover, there was a significant main effect for the factor approaching speed (Table 2) such that participants accepted smaller time gaps at higher speed levels compared to the lower investigated speed levels (Fig. 2a). Bonferroni-corrected pairwise comparisons revealed significant differences between all investigated speed levels (p < .001). However, when considering the distance of selected gaps (in meters), participants selected longer distance gaps at higher speeds for initiating parking actions compared to lower investigated speed levels (Fig. 2b). The analysis did not show a significant interaction between vehicle size and approaching speed for GA (Table 2).

Figure 2

a) Selected time gaps in seconds by interaction partner and speed of the approaching vehicles; b) selected distance gaps in meters by interaction partner and speed of the approaching vehicles



3.2 The effect of driver characteristics on GA

The data revealed statistically significant differences in selected time gaps between the investigated age groups (Table 2). In general, older participants selected larger time gaps in front of the approaching interaction partners (M = 8.93, SD = 2.78) compared to younger participants (M = 6.06, SD = 1.97). In addition, the analysis revealed a significant interaction between vehicle speed and participants' age groups (Table 2). The differences between the age groups decreased with increasing approaching speed of the interaction partners. Specifically, the data showed a larger difference in GA between the age groups during lower speed levels compared to higher investigated speed levels (Fig. 3). However, there was no significant interaction between the size of the approaching interaction partner and participants' age groups (Table 2).

Additionally, there was a significant main effect of sensation seeking scores on GA revealed (Table 2). In particular, participants with higher sensation seeking scores accepted

smaller time gaps in front of the approaching interaction partners (*M* = 6.32, *SD* = 2.37) than participants with lower sensation seeking scores (*M* = 8.64, *SD* = 2.72). The analysis also revealed a significant interaction between vehicle speed and participants' sensation seeking scores (Table 2). To visualize the differences, a median split was applied to the sensation seeking scores (cut-off value = 3.13), creating two distinct groups of *high sensation seeking scores* and *low sensation seeking scores* (Fig. 4). The differences in time gaps between the sensation seeking groups decreased with increased speed levels of the approaching interaction partners. Again, no significant interaction between vehicle size and sensation seeking scores was revealed (Table 2).

Figure 3

Selected time gaps in seconds across age groups and approaching speed of the interaction partners

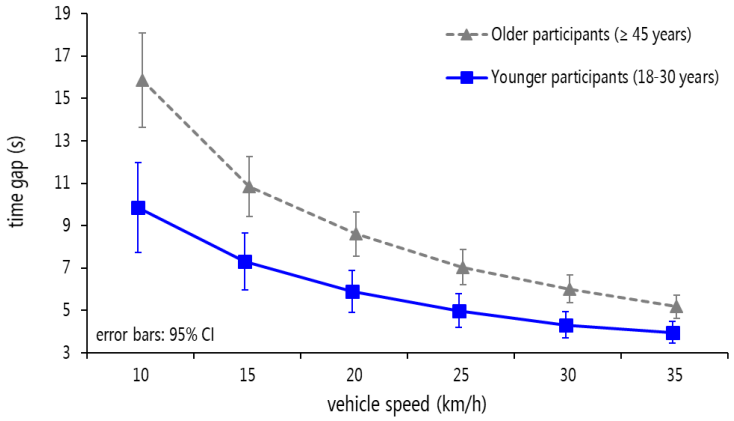
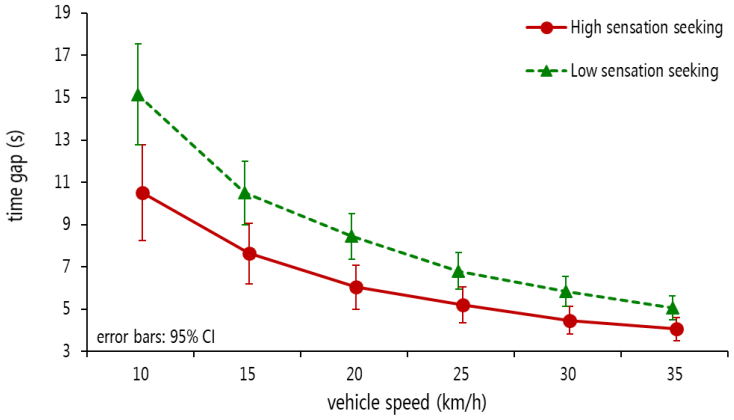


Figure 4

Selected time gaps in seconds across sensation seeking scores and approaching speed of the interaction partners



Note. High sensation seeking: *N* = 22 (*M* = 3.62, *SD* = 0.41); low sensation seeking: *N* = 20 (*M* = 2.48, *SD* = 0.36).

Table 2

ANOVA and ANCOVA results showing the main effects and interactions across vehicle size, approaching speed, age groups and sensation seeking scores on GA

Main and interaction effects	ANOVA		
	F	*p*	η^2_p
Vehicle size	***F*(2, 82) = 10.00**	**< .001**	**.196**
Speed[a]	***F*(1.11, 45.32) = 126.18**	**< .001**	**.755**
Age group	***F*(1, 40) = 16.07**	**< .001**	**.287**
Sensation seeking	***F*(1, 40) = 9.78**	**.003**	**.197**
Vehicle size x speed[a]	*F*(4.54, 186.24) = 1.28	.276	.030
Vehicle size x age group	*F*(2, 80) = 2.21	.116	.052
Vehicle size x sensation seeking	*F*(2, 80) = 1.08	.345	.026
Speed x age groups[a]	***F*(1.15, 46.14) = 18.44**	**< .001**	**.316**
Speed x sensation seeking[a]	***F*(1.12, 44.64) = 6.27**	**.013**	**.135**

Note. $N = 42$. Statistically significant results are highlighted in bold.

[a]Greenhouse-Geisser-corrected *F*-values and degrees of freedom are reported.

4 Discussion

The current study aimed at assessing and quantifying drivers' GA when initiating parking actions in a shared space setting using real-world video material. Anticipating the development of driving scenes supports drivers to adapt their own maneuvers faster and more adequately (Endsley, 1995; Stahl et al., 2014). For instance, it enables drivers maintaining individual safety margins to other traffic participants by adapting own driving actions (i.e., accepting or rejecting gaps in traffic flow by (non–) initiating driving actions; Summala, 2007). Since shared spaces frequently comprise ambiguous encounters, coordinating driving actions is particularly required in these settings (Hamilton-Baillie, 2008). Accepted gaps in traffic flow were shown to be influenced by situational factors and personal characteristics (e.g., Petzoldt, 2016; Yan et al., 2007). Therefore, participants indicated their accepted time gaps to initiate parking actions in front of different upcoming interaction partners approaching at different speed levels in the current study. Moreover, the study addressed effects of driver characteristics (i.e., age

and sensation seeking scores) on GA. The results revealed that there is no one single time gap that is always appropriate when initiating parking maneuvers. In fact, the results showed that manual drivers' accepted gaps were influenced by the approaching vehicle's size and speed, as well as by drivers' personal characteristics. To provide proactive encounters in mixed traffic and meet human drivers expectations, AVs need to be aware and consider those factors for their maneuver decisions (e.g., when initiating parking actions). Therefore, the identified time gap parameters for initiating parking actions could prospectively provide a basic orientation for intuitive interaction capabilities in AVs' driving functions, which could thus support traffic flow as well as comfort and acceptance of human users in- and outside the vehicle (see Stange et al. (2022) for a comparable approach considering drivers' braking maneuver onset times at intersections).

Generally, participants indicated safe gaps for initiating parking maneuvers in front of oncoming traffic despite being instructed to report the latest onset times within the current study. The approach was selected to support user comfort and acceptance but also traffic flow. The findings imply that participants generally aimed to avoid risky driving maneuvers by maintaining safety margins to other traffic participants, which is in line with previous findings (see e.g., Stange et al. (2022) for latest acceptable onset times of braking maneuvers at intersections).

In detail, the current study identified larger time gaps to initiate parking maneuvers when encountering larger vehicles, thus resulting in the most conservative time gaps. Participants selected the largest time gaps when interacting with the truck as the largest investigated vehicle. Despite the motorcycle presented a vulnerable road user with a particular risk in accidents, participants selected the smallest time gaps during these encounters since the motorcycle also presented the smallest interaction partner within the study. The results corroborate previous studies (Lee & Sheppard, 2017; Robbins et al., 2018) and are explainable by the size-arrival effect, stating that larger objects (i.e., larger interaction partners in the current study) are assumed to arrive earlier at the observer's position, resulting in larger accepted time gaps, than smaller interaction partners (DeLucia, 1991). However, the absolute differences of the selected time gaps between the vehicles were relatively small (i.e., below one second) despite being statistically significant.

There was a clear trend of smaller accepted time gaps at higher approaching speeds of the interaction partners, which corroborates previous studies and supports the assumptions (Petzoldt et al., 2017; Schleinitz et al., 2020; H1). However, the findings also showed that larger distance gaps were selected at higher approaching speeds of the interaction partners, which might indicate that participants considered the interaction partner's distance rather than the time-to-arrival when selecting gaps for initiating turning maneuvers (Law et al., 1993).

Another potential explanation might be provided by a combined model where both, the interaction partners' distance within a specific threshold and, beyond that, the approach speed are considered when selecting gaps in traffic flow (Summala, 2007). However, the assumed model, boundaries and specific parameter values would need to be investigated in further research. When considering the specific findings of the current study as a basic orientation for AVs' driving functions, it seems insufficient for AVs to operate within one single time gap value for all speeds when initiating parking actions to provide intuitive interactions with manual traffic participants (Hensch et al., 2021). Rather, AVs should apply varying GA parameters, depending on the approaching vehicles' speed, when initiating parking actions. Based on the results it might be argued that AVs could initiate parking maneuvers with smaller temporal safety margins at higher speeds of approaching interaction partners, but still provide intuitive encounters that support user acceptance and traffic flow.

Besides situational factors, driver characteristics influenced accepted time gaps to the approaching traffic participants as one specific parameter of individual driving styles. In particular, driver age influenced GA such that older participants tended to select larger time gaps to initiate a parking maneuver in front of approaching traffic than younger participants. The results support H2 and corroborate previous studies considering GA (Beggiato et al., 2018; Yan et al., 2007). Although previous research mainly compared the GA of participants older than 65 years to accepted time gaps of under 30 year-old participants (Yan et al., 2007), the current study depicted a similar trend for participants ≥ 45 years, which also resulted in larger time gaps for older participants. Drivers' sensation seeking was identified as an additional influencing factor on accepted time gaps. Smaller GA to initiate a parking action in front of the approaching traffic was accepted by participants scoring higher in sensation seeking than by lower sensation seekers, which supports H3. Comparable results were shown by Heino et al. (1996), who reported reduced time headways for high sensation seekers compared to low sensation seekers during a free following task on motorways. The findings indicate that AVs should consider the variability of human drivers' GA when initiating driving actions to support user acceptance. Therefore, selectable driving style profiles could be implemented in AVs as a form of customization. The profiles could be selected due to drivers' preferences (Terken & Pfleging, 2020) comparable to adaptive cruise control systems where various settings concerning the following time to traffic ahead are available (Raju et al., 2022). The revealed GA parameters for initiating parking actions could provide a first orientation for one specific parameter of different driving styles in AVs. For instance, a dynamic driving style profile, including smaller time gaps, and a defensive driving style profile, including larger time gaps, could be provided in AVs' driving functions (Hensch et al., 2021).

It should be acknowledged that the applied video-material and the participants' task to indicate their accepted time gaps by pressing the enter key is potentially lacking realism to actual traffic scenarios. However, the implementation was seen as beneficial tradeoff between participants' safety and empirical realism (Schleinitz et al., 2015). Moreover, the current study's findings are in line with the results of previous test track and field studies that considered specific influencing factors on accepted time gaps (see Petzoldt et al. (2017) for the impact of bicycle speed on accepted time gaps; see Heino et al. (1996) for the impact of participants' sensation seeking scores on time headways during a free following task). It should be also considered that the present study aimed at assessing manual drivers' GA as a basis for initiating driving actions in one specific driving scenario (i.e., onward-parking scenario). Although the current study examined the effect of situational and driver characteristics on GA, an understanding of additional influencing factors on manual drivers' decisions for specific driving maneuvers is required. Future studies should therefore examine additional speeds and age groups to those considered in the current study to increase the explanatory power of the results. Moreover, additional scenarios and perspectives need to be considered to comprehensively quantify parameters of manual drivers' interaction behavior that could provide a basic orientation for intuitive interaction capabilities in AVs. For instance, accepted gaps for initiating parking actions also need to be investigated from the perspective of oncoming traffic participants, particularly if these road users are VRUs.

The current study's findings imply that AVs should be equipped with differentiated knowledge about relevant situational aspects of driving scenes and influencing factors on human drivers maneuver decisions. Differentiated knowledge could support AVs to anticipate and predict the prospective development of driving scenes more reliably, which might be comparable to experienced human drivers (Krems & Baumann, 2009) and would thereby enable AVs to adapt their own driving behavior accordingly (Stahl et al., 2014). Thus, this knowledge could provide proactive encounters in mixed traffic and could support user acceptance and traffic flow (Schieben et al., 2019). The derived time gap values of the current study could provide a basic orientation for AVs' driving functions to support intuitive interactions in mixed traffic. Thus, AVs would be enabled to provide proactive encounters, for instance by maintaining specific safety margins to oncoming traffic when initiating parking maneuvers in shared spaces. Moreover, AVs should be also able to consider individually varying driver behavior (Hensch et al., 2021). Therefore, selectable driving style profiles as a form of customization might be provided in AVs, comparable to selectable adaptive cruise control settings (Raju et al., 2022; Terken & Pfleging, 2020).

5 Conclusion

Particularly in shared spaces including ambiguous encounters and diverse traffic participants, the coordination of actions is highly relevant (Hamilton-Baillie, 2008). Anticipating the prospective development of driving scenes enables drivers to adapt their own actions increasingly adequate and therefore supports proactive interactions with surrounding traffic participants (Endsley, 1995; Stahl et al., 2014). To support intuitive and proactive interactions in mixed traffic, user acceptance and thus the intention to use automated driving functions (Domeyer et al., 2020), established interaction capabilities from manual driving could be implemented as knowledge in AVs (Beggiato et al., 2018). Therefore, derived GA values from manual drivers could provide a basic orientation for one specific parameter of AVs' driving functions (Hensch et al., 2021). To meet the requirements of human users in- and outside the vehicle, the findings of the current study imply that there is no one single time gap that is always appropriate to initiate parking actions. However, situational factors (e.g., approaching vehicles' size and speed) and driver characteristics (e.g., age) were shown to influence the accepted time gaps of manual drivers when initiating parking actions. It can be argued that AVs should consider the approaching speed of the oncoming interaction partners as an essential situational factor when initiating parking actions. Moreover, selectable driving style profiles as a form of customization should be available in AVs for respecting individual driver preferences (Terken & Pfleging, 2020).

Funding

The research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation – [Project-ID 416228727 – SFB 1410]) and by the German Federal Ministry of Economics and Technology (BMWi; Project "@City-AF" – [Grant No 19A18003L]).

CRediT authorship contribution statement

Ann-Christin Hensch: Formal analysis, Investigation, Writing – original draft, Visualization. **Matthias Beggiato:** Conceptualization, Methodology, Software, Investigation, Writing – original draft, Writing – review & editing, Supervision. **Josef F. Krems:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

6 References

Baumann, M. R., & Krems, J. F. (2007). Situation awareness and driving: A cognitive model. In P. C. Cacciabue (Ed.), *Modelling driver behaviour in automotive environments: Critical issues in driver interactions with intelligent transport systems* (pp. 253–265). London: Springer.

Beggiato, M., Witzlack, C., & Krems, J. F. (2017). Gap acceptance and time-to-arrival estimates as basis for informal communication between pedestrians and vehicles. *AutomotiveUI 2017 - 9th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, Proceedings*, 50–57. https://doi.org/10.1145/3122986.3122995

Beggiato, M., Witzlack, C., Springer, S., & Krems, J. F. (2018). The right moment for braking as informal communication signal between automated vehicles and pedestrians in crossing situations. In N. Stanton (Ed.), *Advances in Human Aspects of Transportation. AHFE 2017. Advances in Intelligent Systems and Computing* (pp. 1072–1081). Springer. https://doi.org/10.1007/978-3-319-93885-1

Clark, H. E., Perrone, J. A., & Isler, R. B. (2013). An illusory size-speed bias and railway crossing collisions. *Accident Analysis and Prevention, 55*, 226–231. https://doi.org/10.1016/j.aap.2013.02.037

Clark, H. H., & Brennan, S. E. (1991). Grounding in communication. In S. D. T. L. B. Resnick, & J. M. Levine (Eds.), *Perspectives on socially shared cognition* (pp. 127–149). American Psychological Association.

DeLucia, P. R. (1991). Pictorial and motion-based information for depth perception. *Journal of Experimental Psychology: Human Perception and Performance, 17*(3), 738–748. https://doi.org/10.1037/0096-1523.17.3.738

Domeyer, J. E., Lee, J. D., & Toyoda, H. (2020). Vehicle automation-other road user communication and coordination: Theory and mechanisms. *IEEE Access, 8*, 19860–19872. https://doi.org/10.1109/ACCESS.2020.2969233

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Human Factors, 37*(1), 32–64. https://doi.org/10.1518/001872095779049543

Field, A. (2009). *Discovering statistics using spss*. Thousand Oaks, CA, USA: Sage Publications.

Grant, A. M., & Ashford, S. J. (2008). The dynamics of proactivity at work. *Research in Organizational Behavior, 28*, 3–34. https://doi.org/10.1016/j.riob.2008.04.002

Habibovic, A., Lundgren, V. M., Andersson, J., Klingegård, M., Lagström, T., Sirkka, A., … Larsson, P. (2018). Communicating intent of automated vehicles to pedestrians. *Frontiers in Psychology, 9*, 1336. https://doi.org/10.3389/fpsyg.2018.01336

Hall, E. T. (1969). *The Hidden Dimension*. Doubleday: Anchor Books.

Hamilton-Baillie, B. (2008). Towards shared space. *Urban Design International, 13*(2), 130–138. https://doi.org/10.1057/udi.2008.13

Hancock, P. A., & Caird, J. K. (1993). *The left turn*. http://hdl.handle.net/11299/156873

Hancock, P. A., Caird, J. K., & Shekhar, S. (1991). Factors influencing drivers' left turn decisions. *Proceedings of the Human Factors 35th Annual Meeting*, *35*(15), 1139–1143. https://doi.org/10.1177/154193129103501525

Heino, A., Van Der Molen, H. H., & Wilde, G. J. S. (1996). Differences in risk experience between sensation avoiders and sensation seekers. *Personality and Individual Differences, 20*(1), 71–79. https://doi.org/10.1016/0191-8869(95)00152-V

Hensch, A.-C., Beggiato, M., Schömann, M. X., & Krems, J. F. (2021). Different types, different speeds – The effect of interaction partners and encountering speeds at intersections on drivers' gap acceptance as an implicit communication signal in automated driving. In H. Krömker (Ed.), *HCI in Mobility, Transport, and Automotive Systems. HCII 2021. Lecture Notes in Computer Science* (pp. 517–528). Cham: Springer.

Hoyle, R. H., Stephenson, M. T., Palmgreen, P., Lorch, E. P., & Donohew, R. L. (2002). Reliability and validity of a brief measure of sensation seeking. *Personality and Individual Differences, 32*(3), 401–414. https://doi.org/10.1016/S0191-8869(01)00032-0

Jonah, B. A. (1997). Sensation seeking and risky driving: A review and synthesis of the literature. *Accident Analysis and Prevention, 29*(5), 651–665. https://doi.org/ 10.1016/S0001-4575(97)00017-1

Krems, J. F., & Baumann, M. R. (2009). Driving and situation awareness: A cognitive model of memory-update processes. In M. Kurosu (Ed.), *Lecture Notes in Computer Science, vol. 5619 LNCS* (pp. 986–994). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-02806-9_113

Law, D. J., Pellegrino, J. W., Mitchell, S. R., Fischer, S. C., McDonald, T. P., & Hunt, E. B. (1993). Perceptual and cognitive factors governing performance in comparative arrival-time judgments. *Journal of Experimental Psychology: Human Perception and Performance, 19*(6), 1183–1199. https://doi.org/10.1037/0096- 1523.19.6.1183

Lee, Y. M., & Sheppard, E. (2017). Differences in gap acceptance for approaching cars and motorcycles at junctions: What causes the size-arrival effect? *Transportation Research Part F: Traffic Psychology and Behaviour, 50*, 50–54. https://doi.org/10.1016/j.trf.2017.07.006

Leibowitz, H. W. (1985). Grade crossing accidents and human factors engineering. *American Scientist, 73*(6), 558–562. http://www.jstor.com/stable/27853486

National Instruments. (2015). *LabView 2015*. National Instruments.

Parkin, J., Clark, B., Clayton, W., Ricci, M., & Parkhurst, G. (2016). *Understanding interactions between autonomous vehicles and other road users: A Literature Review*. http://eprints.uwe.ac.uk/29153/

Petzoldt, T. (2016). Size speed bias or size arrival effect - How judgments of vehicles' approach speed and time to arrival are influenced by the vehicles' size. *Accident Analysis and Prevention, 95*, 132–137. https://doi.org/10.1016/j.aap.2016.07.010

Petzoldt, T., Schleinitz, K., Krems, J. F., & Gehlert, T. (2017). Drivers' gap acceptance in front of approaching bicycles – Effects of bicycle speed and bicycle type. *Safety Science, 92*, 283–289. https://doi.org/10.1016/j.ssci.2015.07.021

Raju, N., Schakel, W., Reddy, N., Dong, Y., & Farah, H. (2022). Car-Following properties of a commercial adaptive cruise control system: A pilot field test. *Transportation Research Record, 2676*(7), 128–143. https://doi.org/10.1177/03611981221077085

Robbins, C. J., Allen, H. A., & Chapman, P. (2018). Comparing drivers' gap acceptance for cars and motorcycles at junctions using an adaptive staircase methodology. *Transportation Research Part F: Traffic Psychology and Behaviour, 58*, 944–954. https://doi.org/10.1016/j.trf.2018.07.023

SAE International's new standard J3016. (2018). *Levels of driving automation*. SAE International. https://doi.org/P141661

Sagberg, F., Selpi, Bianchi Piccinini, G. F., & Engstr¨om, J. (2015). A review of research on driving styles and road safety. *Human Factors*, *57*(7), 1248–1275. https://doi.org/10.1177/0018720815591313

Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., & Merat, N. (2019). Designing the interaction of automated vehicles with other traffic participants: Design considerations based on human needs and expectations. *Cognition, Technology and Work, 21*(1), 69–85. https://doi.org/10.1007/s10111-018-0521-z

Schleinitz, K., Petzoldt, T., & Gehlert, T. (2020). Drivers' gap acceptance and time to arrival judgements when confronted with approaching bicycles, e-bikes, and scooters. *Journal of Transportation Safety and Security, 12*(1), 3–16. https://doi.org/10.1080/19439962.2019.1591551

Schleinitz, K., Petzoldt, T., Krems, J., & Gehlert, T. (2015). Geschwindigkeitswahrnehmung von einspurigen Fahrzeugen - Forschungsbericht [Speed perception of single lane vehicles - research report]. In *Gesamtverband der Deutschen Versicherungswirtschaft* (Issue 33). https://doi.org/10.26128/2021.143

Scialfa, C. T., Guzy, L. T., Leibowitz, H. W., Garvey, P. M., & Tyrrell, R. A. (1991). Age differences in estimating vehicle velocity. *Psychology and Aging, 6*(1), 60–66. https://doi.org/10.1037/0882-7974.6.1.60

Stahl, P., Donmez, B., & Jamieson, G. A. (2014). Anticipation in driving: The role of experience in the efficacy of pre-event conflict cues. *IEEE Transactions on Human- Machine Systems, 44*(5), 603–613. https://doi.org/10.1109/THMS.2014.2325558

Stange, V., Goralzik, A., Ernst, S., Steimle, M., Maurer, M., & Vollrath, M. (2022). Please stop now, automated vehicle! – Passengers aim to avoid risk experiences in interactions with a crossing vulnerable road user at an urban junction. *Transportation Research Part F: Traffic Psychology and Behaviour, 87*, 164–188. https://doi.org/10.1016/j.trf.2022.04.001

Stange, V., Kühn, M., & Vollrath, M. (2022). Manual drivers' experience and driving behavior in repeated interactions with automated Level 3 vehicles in mixed traffic on the highway. *Transportation Research Part F: Traffic Psychology and Behaviour, 87*, 426–443. https://doi.org/10.1016/j.trf.2022.04.019

Summala, H. (2007). Towards understanding motivational and emotional factors in driver behaviour: Comfort through satisficing. In P. C. Cacciabue (Ed.), *Modelling driver behaviour in automotive environments: Critical issues in driver interactions with intelligent transport systems* (pp. 189–207). London: Springer. https://doi.org/10.1007/978-1-84628-618-6

Taubman-Ben-Ari, O., Mikulincer, M., & Gillath, O. (2004). The multidimensional driving style inventory - Scale construct and validation. *Accident Analysis and Prevention, 36*(3), 323–332. https://doi.org/10.1016/S0001-4575(03)00010-1

Terken, J., & Pfleging, B. (2020). Toward shared control between automated vehicles and users. *Automotive Innovation, 3*(1), 53–61. https://doi.org/10.1007/s42154- 019-00087-9

van Loon, R. J., & Martens, M. H. (2015). Automated Driving and its effect on the safety ecosystem: How do compatibility issues affect the transition period? *Procedia Manufacturing, 3*, 3280–3285. https://doi.org/10.1016/j.promfg.2015.07.401

Wilde, G. J. S. (1976). Social interaction patterns in driver behavior: An introductory review. *Human Factors: The Journal of Human Factors and Ergonomics Society, 18* (5), 477–492. https://doi.org/10.1177/001872087601800506

Yan, X., Radwan, E., & Guo, D. (2007). Effects of major-road vehicle speed and driver age and gender on left-turn gap acceptance. *Accident Analysis and Prevention, 39* (4), 843–852. https://doi.org/10.1016/j.aap.2006.12.006

Zuckerman, M. (1994). *Behavioral expressions and biosocial bases of sensation seeking*. Cambridge University Press.

PAPER II

EFFECTS OF A LIGHT-BASED COMMUNICATION APPROACH AS AN EXTERNAL HMI FOR AUTOMATED VEHICLES - A WIZARD-OF-OZ STUDY

Citation:

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems J. F. (2019). Effects of a light-based communication approach as an external HMI for Automated Vehicles - a Wizard-of-Oz Study. *Transaction and Transport Sciences, 10*(2), 18-32. https://doi.org/10.5507/tots.2019.012

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EFFECTS OF A LIGHT-BASED COMMUNICATION APPROACH AS AN EXTERNAL HMI FOR AUTOMATED VEHICLES - A WIZARD-OF-OZ STUDY

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Abstract

Communication between automated vehicles (AVs) and vulnerable road users (VRUs) is highly relevant in coordinating traffic maneuvers and therefore ensuring road safety. Especially in shared spaces such as parking areas, communication is highly important. As automated driving changes the driver's role, communication between different traffic participants will also change. External human-machine interfaces (eHMIs) may enhance safety and effective communication between VRUs and AVs by providing relevant information to other traffic participants if informal communication is insufficient. Hence, a variety of information (e.g., about AVs' driving mode or future maneuvers) is recommended to be communicated to VRUs. Therefore, we investigated the effects of three different light signals, presented by a light bar placed on the test vehicle's roof, as a form of an eHMI: automation mode, starting mode and crossing mode. Moreover, two different driving conditions (i.e., a manual and a simulated automated driving condition) were implemented to investigate the effects between these conditions. Either the driver was visible in the manual condition or the vehicle appeared driverless as a seat suit covered the driver in the simulated automated condition (Wizard-of-Oz design). A total of $N = 173$ random pedestrians passing by were interviewed and behavioral data were collected from over 1500 pedestrians. Results indicate that participants felt significantly safer during the interaction with the vehicle when a driver was visible. Although VRUs evaluated the general approach of applying light signals as eHMIs for AVs as useful, they assessed the presented light signals as only partially trustworthy and rather unintuitive. Moreover, many participants were unsure of whether the light signals were directed towards them, thus the directedness of light signals should be considered when implementing a light-based eHMI in AVs. Further, moving light signals attracted more attention (i.e., increased pedestrians' head movements towards the vehicle) than a steady or no light signal did. Interestingly, no difference existed between the investigated steady light signal and

the baseline condition (i.e., no light signal) regarding head movements towards the vehicle. The results underline the importance of implementing an appropriate eHMI design in AVs.

Keywords: Wizard-of-Oz, automated vehicles, external HMI, light-based communication, vulnerable road users

1 Introduction

Vehicle features have become increasingly automated in recent years, resulting in various classifications of different levels of automation (SAE, 2018). Therefore, a long transition period including mixed traffic of different levels of automation (i.e., manual, partially and fully automated vehicles) is expected (Litman, 2019). One crucial aspect in terms of road safety is the assurance of clear and intuitive communication between vulnerable road users (VRUs) and vehicles (Rasouli, Kotseruba, & Tsotsos, 2018) with a variety of levels of automation, even if the driver is absent to ensure road safety (Ackermann, Beggiato, Schubert, & Krems, 2019).

1.1 The role of communication in manual driving

In manual driving scenarios, the interaction between VRUs and drivers occurs as a dynamic bidirectional process where traffic participants have to act and react to each other's maneuvers (Hölzel, 2008) to negotiate priority and coordinate prospective movements (Schieben et al., 2019; Witzlack, Beggiato, & Krems, 2016). In SAE Levels 4 and 5 the driving task is executed by the system (SAE, 2018) while the driver might be engaged in other tasks than driving (Jamson, Merat, Carsten, & Lai, 2013). Consequently, the interaction between vehicles and other traffic participants (e.g., VRUs) will change across these varying levels of automation (Schieben et al., 2019). To design a safe and comfortable interaction, and therefore support VRUs' trust and acceptance of automated vehicles (AVs), communication needs to be designed appropriately (Merat, Louw, Madigan, Wilbrink, & Schieben, 2018). In manual driving settings, formal (for Germany road traffic regulations (StVO; Straßenverkehrsordnung, 2018)) and informal communication allows the interaction between the different traffic participants (Hölzel, 2008). Formal communication is described by laws (e.g., StVO; Straßenverkehrsordnung, 2018), whereas informal communication includes trajectory, eye contact or gestures (Hölzel, 2008). Informal communication is particularly relevant in shared spaces (e.g., parking areas), where different traffic participants (i.e., vehicles and VRUs) need to interact and communicate to ensure traffic flow and road safety (Hamilton-Baillie, 2008). Since the traffic regulation by law is ambiguous in parking areas, there is a high variety of possible maneuvers, thus resulting traffic situations might be ambiguous (Witzlack et al., 2016). Informal communication (e.g., eye contact; Šucha, Dostal, & Risser, 2017) could help to coordinate interpersonal movements and right of way in ambiguous traffic situations (Hamilton-Baillie, 2008). Eye contact presents an important form of communication by creating a social relationship between different interaction partners (Rasouli & Tsotsos, 2018). Currently in manual driving scenarios, eye contact signals awareness of the mutual presence between drivers and surrounding traffic participants and thereby coordinates their actions (Rasouli et al., 2018). Previous research has highlighted the importance of eye contact

between VRUs and drivers during the interaction in manual driving: For example, Šucha et al. (2017) found that 84% of pedestrians made eye contact with the driver while crossing a road. Moreover, this eye contact increased cooperation between the different traffic participants, resulting in increased traffic safety (Guéguen, Meineri, & Eyssartier, 2015). In AV scenarios, where the driver is potentially distracted or absent, this source of information will not be available to establish communication between the different traffic participants. Hence, the mutual coordination of movements between the different traffic participants is inhibited (Rasouli & Tsotsos, 2018).

1.2 The prospective transformation of communication in automated driving

One important issue in automated driving is the effect of a distracted or absent driver, which might be the case for AV scenarios, on different aspects of vehicle to pedestrian communication (e.g., Lundgren et al., 2017; Rodríguez Palmeiro et al., 2018; Rothenbücher, Li, Sirkin, Mok, & Ju, 2016). Previous studies underlined the importance of informal communication between VRUs and drivers (e.g., eye contact in manual driving scenarios; see Šucha et al., 2017). Drivers' distraction or absence could be shown to influence participants' evaluation of the interaction with the vehicle. Participants felt safer when they made eye contact with the driver, whereas feeling of safety decreased when the driver was inattentive (Lundgren et al., 2017). Moreover, VRUs' uncertainty about the vehicle's behavior increased when the driver was absent (Deb, Hudson, Carruth, & Frey, 2018). In contrast, Fuest, Michalowski, Traris, Bellem, and Bengler (2018) reported that ratings of perceived criticality did not differ depending on whether the driver was visible. However, Nuñez Velasco, Rodriguez, Farah, and Hagenzieker (2016) found that VRUs perceived higher levels of safety during AV interactions in shared spaces compared to manual vehicle interactions. In sum, inconsistent results exist across previous studies regarding VRUs' feeling of safety in terms of making eye contact with the driver in AVs (Fuest et al., 2018; Lundgren et al., 2017). Furthermore, the drivers' distraction or absence has shown to influence VRUs' behavioral aspects. Previous studies have revealed that VRUs' road crossing decisions are not only influenced by vehicles' speed and distance, but also by the perceived level of driver distraction (Rodríguez Palmeiro et al., 2018). Participants' willingness to cross the street decreased when the driver was noticeably engaged in secondary tasks compared to when eye contact to the driver could be established (Lundgren et al., 2017). Due to drivers' distraction or absence, the communication between vehicles and VRUs requires transformation in AVs, where eye contact needs to be replaced (Schieben et al., 2019). Informal communication could provide a variety of information about the vehicles' current state (e.g., by trajectory; Beggiato, Witzlack, Springer, & Krems, 2018). In addition, explicit communication could supplement implicit

messages (Ackermann et al., 2019) and therefore ensure an accurate interpretation of the AVs' maneuvers (Schieben et al., 2019).

External human-machine interfaces (eHMIs) offer one opportunity for AVs to communicate with other traffic participants and thereby enhance traffic flow, road safety (Schieben et al., 2019) and feeling of safety of surrounding traffic participants (Böckle, Brenden, Klingegård, Habibovic, & Bout, 2017; de Clercq, Dietrich, Núñez Velasco, de Winter, & Happee, 2019). For instance, eHMIs might communicate with other traffic participants by providing a variety of information about the vehicles' states and future maneuvers (Schieben et al., 2019) as well as compensate for the lack of eye contact between the driver and other traffic participants (Lundgren et al., 2017). To encourage acceptance and trust of eHMIs, a report by the International Organization for Standardization (ISO) on external communication in AVs recommends having consistent signals among different manufacturers (International Organization for Standardization, 2018). Previous studies emphasize the demand for communication between VRUs and AVs (where the driver is potentially absent; SAE, 2018) to enhance VRUs' feeling of safety (Schieben et al., 2019). VRUs' need for communication is reflected in their feeling of safety ratings (de Clercq et al., 2019) as well as in their observable behavior (Rothenbücher et al., 2016). In general, participants preferred eHMIs as a form of communication compared to having no eHMI present in AVs (de Clercq et al., 2019). Previous studies have found a positive effect of eHMI application on emotional ratings (Lagström & Lundgren, 2015). Particularly, VRUs' feeling of safety significantly increased when interacting with a vehicle containing an eHMI, in contrast to when no eHMI was presented (Böckle et al., 2017; de Clercq et al., 2019). The application of eHMIs could help to increase the amount of safe street crossing by participants in front of a vehicle (Lagström & Lundgren, 2015). In addition, VRUs perceived comfort increased significantly during the interaction, when an eHMI was applied, in contrast to when no eHMI was used (Böckle et al., 2017). Other studies have investigated the effects of eHMIs on VRUs behavior (e.g., Chang, Toda, Sakamoto, & Igarashi, 2017; Rothenbücher et al., 2016). For example, Chang et al. (2017) found significantly decreased reaction times for crossing decisions in the eHMI condition compared to a baseline condition without any communication between the vehicle and VRUs. Further, VRUs reduced their walking speed and searched for vehicles' implicit movement cues due to the uncertainty during the interaction when no driver was visible inside the vehicle (Rothenbücher et al., 2016). Therefore, eHMIs have the potential to communicate AVs' intentions and future maneuvers to VRUs (Lagström & Lundgren, 2015).

1.3 Designing interactions in automated driving

Various studies have investigated eHMI signals' specific content. Specifically, various presented information were evaluated to be differently relevant (Ackermann et al., 2019; Merat et al., 2018; Zhang, Vinkhuyzen, & Cefkin, 2018). Information regarding AVs' intention was considered more important than information about whether the vehicle detected the VRU (Mahadevan, Somanath, & Sharlin, 2018). An exploratory study by Merat et al. (2018) showed that VRUs rated messages about AVs' starting, stopping and turning maneuvers as significantly more important than information regarding the vehicles' speed. Therefore, it was recommended to present messages about the vehicles' current state and future maneuvers to VRUs. In particular, AVs should provide information about a) the activation of the automated driving system, b) approaching maneuvers and c) yielding maneuvers (SAE as cited in Wilbrink et al., 2018). In a study by Zhang et al. (2018) VRUs interpreted the presented light signals as information about the vehicles' future states and maneuvers. Therefore, the authors suggested designing light signals in form of vehicles' state information rather than VRUs' advice-based information. In contrast, Ackermann et al. (2019) found that advice-based eHMI messages were rated as more comfortable than information about the vehicles' current state did. However, AVs' explicit general advice to VRUs could potentially be problematic regarding liability and traffic safety (Schieben et al., 2019). Schieben et al. (2019) collected VRU demands regarding an appropriate interaction configuration between AVs and other traffic participants. Based on the previous literature, four information categories were identified, including information about a) the vehicles' driving mode, b) the vehicles' next maneuvers, c) the perception of the environment, and d) the capabilities for AV and VRU cooperation. Information about AVs' behavior could enhance understanding and anticipation of their maneuvers (Schieben et al., 2019). Participants rated communication with the AVs as significantly more important in shared spaces with no road markings as opposed to when road markings existed. Furthermore, information about the AVs' stopping behavior were rated as the most important in shared spaces, suggesting that providing information in these particular situations is more likely to enhance traffic safety (Merat et al., 2018).

To sum it up, informal communication, particularly eye contact should be highlighted to coordinate actions in ambiguous traffic situations (Šucha et al., 2017) and therefore ensure road safety (Rasouli et al., 2018). In automated driving, communication using eye contact will be limited, since the driver is potentially distracted (SAE, 2018). Hence, an appropriate alternative regarding this source of information needs to be investigated to support road safety (Merat et al., 2018) especially if implicit communication is insufficient (Ackermann et al., 2019). Moreover, ISO's recommendations should be also considered in research. Therefore, the current study considers both: a) the findings of previous studies (e.g., Lagström & Lundgren,

2015; Rothenbücher et al., 2016) and b) ISO recommended guidelines (International Organization for Standardization, 2018). Upon previous results the current study examined three different light signals including different information categories and a baseline condition without any light signal in a shared space setting as an important interaction scenario (Hensch, Neumann, Beggiato, Halama, & Krems, 2020). Aspects of feeling of safety, trust, acceptance, comprehensibility and usefulness, as well as the behavioral indicator of head movements towards the vehicle, were compared across two driving conditions.

1.4 Research questions and aim of the study

The aim of the current study was to assess the effects of three different light signals and a baseline condition (without any light signal) as a form of AV's explicit communication. The different light signals intended to communicate different messages to the surrounding traffic participants (a) information about vehicles' state; b) information about vehicles' future maneuvers; and c) advice-based information to surrounding traffic participants; according to Ackermann et al., 2019; Schieben et al., 2019). Therefore, a light bar, which represented an eHMI, was implemented on the test vehicle's roof (see also Rodríguez Palmeiro et al., 2018). During the study, uninformed pedestrians passing by were interviewed randomly in a parking area. Additionally, two different driving conditions were compared: a manual driving condition (i.e., driver present) and a simulated automated driving condition (i.e., driver hidden by a seat suit) using a Wizard-of-Oz approach. Since uninformed pedestrians were interviewed, each participant evaluated one condition, resulting in a 4 (three different light signals, baseline condition) x 2 (driving conditions) between-subjects design.

Beside questionnaire and interview data, behavioral data from video recordings were examined. The collected questionnaire and interview data examined comprehensibility, trust and perceived usefulness of the light signals that represented an eHMI for AVs. Moreover, the perceived safety during the interaction with the vehicle was assessed. These data were supplemented by behavioral data from video recordings, which documented the duration of head movements towards the test vehicle.

Therefore, the subsequent constructs and respective research questions were analyzed:

(Q1) *Comprehensibility:* How do participants interpret the meanings of the different light signals? Do any differences exist for assessed comprehensibility between the different light signals and driving conditions?

(Q2) *Trust:* Do any differences exist for participants' trust ratings amongst the presented light signals and driving conditions?

(Q3) *Feeling of Safety*: Do any differences exist for participants' feeling of safety between the presented light signals and driving conditions? What reasons do participants state for their ratings?

(Q4) *Usefulness of the presented light signals:* Do any differences exist for participants' perceived usefulness ratings between the presented light signals and driving conditions?

(Q5) *General usefulness of light signals:* Do any differences exist for participants' perceived *general* usefulness ratings between the presented light signals and driving conditions? What reasons do participants mention for their assessment?

(Q6) *Alternative design suggestions:* What are participants' suggestions regarding alternative eHMI designs?

(Q7) *Head movements towards the vehicle:* Do any differences exist for pedestrians' head movements towards the vehicle between the investigated light signals or driving conditions?

2 Method

2.1 Setting

The current study was conducted within three days in June 2018, from 10 am to 3 pm each day. The parking area on the Chemnitz University of Technology campus (Germany) represented a shared space as it connects the cafeteria with the rest of the campus. Hence, there was a high appearance of VRUs present in between lectures, necessitating a high amount of communication between the different traffic participants.

2.2 Procedure

Various drives across the different conditions (i.e., assessed light signals and driving conditions) were conducted in a randomized order on the university's parking area. To prevent biases during the data collection (e.g., due to weather conditions), all conditions were constantly conducted across the investigation period. Moreover, the investigated light signals and driving conditions occurred in a random order. There were two researchers inside the vehicle; one as the driver and the other to communicate with additional researchers in the parking area via mobile phone. In addition, four to six interviewers were present throughout the study to interview pedestrians passing by randomly. Pedestrians were interviewed immediately after the vehicle was visible to them.

2.3 Participants

A total of $N = 173$ uninformed pedestrians passing by were randomly interviewed by investigators. Since the study's participants were selected randomly they were not invited or informed about the study's purpose. In sum, the sample consisted of 66% men and 34% women with a mean age of $M = 29$ years ($SD = 10.6$). Before the interview, participants' informed consent was obtained and anonymity was guaranteed. No financial compensation was given for study participation, which took about 5 minutes.

Behavioral data was collected from $N = 1526$ pedestrians during the study. After exclusion due to a lack of visibility of the participants' head movement towards the vehicle $n = 1018$ pedestrians (68.9% men, 31.1% women) with an estimated mean age of $M \approx 29$ years ($SD \approx 9.1$) were available. Since differences in head movements towards the vehicle should be analyzed, participants never or always looking towards the vehicle were excluded. This resulted in a final sample of $n = 389$ pedestrians (68.4% men, 31.6% women) with an estimated mean age of $M \approx 29$ years ($SD \approx 9.9$).

2.4 Design

To investigate the effects of an eHMI in AVs, a Wizard-of-Oz approach was employed in a field study (Hensch et al., 2020). This approach was adopted since previous studies have demonstrated to successfully simulate an AV by making participants believe the vehicle was automated and the driver was missing (Rothenbücher et al., 2016).

The present study examined: 1) three different light signals representing an eHMI (automation mode, starting mode, crossing mode), as well as a baseline condition without any light signal; and 2) two different driving conditions (simulated automated driving condition vs. manual driving condition) on uninformed pedestrians randomly passing by.

2.5 Apparatus and material

The study's test vehicle was a Ford Tourneo Connect. Since eHMIs in AVs were assessed, a manual driving condition (including a visible driver) was compared to a simulated automated driving condition that included a seat suit to let the vehicle appear driverless (similar to Röthenbücher et al., 2016). Moreover, a similar suit was placed over the front passenger seat to keep the appearance of both seats consistent (Figure 1a). Three different light-based communication messages were investigated as an eHMI (Figure 1b):

a) Automation mode: steady light, intended to indicate that the vehicle was operating autonomously (information about vehicles' driving mode according to Schieben et al. (2019));

b) Starting mode: flashing light, intended to indicate that the vehicle was approaching (information about vehicles' state and future maneuvers according to Schieben et al. (2019)); and
c) Crossing mode: sweeping light, intended to indicate that a pedestrian could cross in front of the vehicle (advice-based information about vehicles' future maneuvers according to Ackermann et al. (2019)).

A light bar presented the light signals to pedestrians passing by. It was placed on the test vehicles' roof to ensure sufficient visibility of the light signals. The eHMI presented the messages at the vehicle's front side. The light bar included 12 horizontally spaced LEDs with a luminous flux of two lumen respectively. As recommended by Wilbrink et al. (2018), the light signals were presented in a cyan color (Figure 1c). Spectrum analysis revealed a dominate wavelength of 488.86nm. The driver of the vehicle selected the respective light signal via a touch pad in the center console.

Furthermore, a baseline condition (without any light signal) was investigated. To examine pedestrians' behavior (i.e., head movements towards the vehicle), four dashcams were installed in a 360° angle inside the test vehicle. Therefore, one Black Vue DR650S-2CH (Blackvue, 2018) front camera (1920x1080 pixels, 30 fps) was installed in the windscreen and the rear window respectively. Moreover, one Black Vue DR650S-2CH rear camera (1280x720 pixels, 30 fps) was placed in the right and left side window of the test vehicle respectively.

Figure 1

The seat suit covering the driver to simulate the automated driving condition (a), schematic visualization of the presented light signals (top: automation mode; middle: starting mode; bottom: crossing mode (b), light bar on the vehicle's roof presenting the investigated automation mode (c)

a) b) c)

2.6 Questionnaires and behavioral data

The interview included 7-point Likert scale ratings (from [1] "*I completely disagree*" to [7] "*I completely agree*"), judgments and open-ended questions. During the first part of the interview, the assumed meaning and the intuitiveness of the respective *presented* light signal was investigated. For this reason, participants were uniformed about the study's context and the intended meaning of the *presented* light signals. This part of the interview was supplemented by data regarding participants' perception of the respective light signal, directedness of the light signals, feeling of safety during the interaction with the vehicle as well as participants' assumption of the test vehicle's automation and drivers' visibility. For the second part of the interview, participants were informed about the study's context and meaning of the *presented* light signals. Participants' feedback was collected regarding the comprehensibility of the respective light signal, trust in the light signal, and its perceived usefulness of the presented light signals and light signals in AVs in general. Trust towards the respective light signal was assessed across three items from the trust in automation scale (Jian, Bisantz, & Drury, 2000; items adapted). The item values were aggregated into an overall satisfactory score that was used for further analysis (Cronbach's α = .68; Hair, Black, Babin, & Anderson, 2014). Further details are given in Table 1.

The recorded interview data of the judgements and open-ended questions were transcribed verbatim and then screened. A coding system relating to the thematic analysis (Braun & Clarke, 2006) was developed and reviewed. Finally, the transcribed data were coded according to the developed coding system. Two independent raters coded 25% of participants' answers, showing a substantial interrater reliability (Cohen's Kappa κ = .75; Landis & Koch, 1977). Behavioral data considering the duration of pedestrians' head movements towards the vehicle were investigated by video data. Therefore, video data were screened and an annotation scheme was developed that contained four categories. The first category included pedestrians' head movements towards the vehicle, assuming the attention was directed to the vehicle or light bar. The second category focused on head movements other than towards the vehicle, assuming the attention not on the vehicle or light bar (Anderson, 2014). Annotation category three and four included obscured (e.g., by other pedestrians) or barely visible head movements (e.g., due to the distance between cameras and pedestrians). The video data were annotated frame by frame. The respective category's onset was specified by either the first frame pedestrians' head was allocated towards the vehicle or the first frame of head movements towards other than the vehicle. Behavioral data were annotated by the software ELAN (2004). Afterwards, the duration of pedestrians' head movements towards the vehicle was qualified by the total duration the pedestrians were visible in the video data.

Table 1

Overview of the Wizard-of-Oz Study

Construct	Statement/ Question	Information to participants	ANOVA		
			Main effects		Interactions (Light signals x Drivers' visibility)
			Light signals *p*	Drivers' visibility *p*	*p*
Perception of light signals	Did you notice the light signal on the vehicle's roof?	uninformed	-	-	-
Directedness of light signals	Did you believe that the light signal was addressed to you?	uninformed	-	-	-
Vehicles' automation	Did you see any driver inside the vehicle?	uninformed	-	-	-
	Did you think that the vehicle operated autonomously?	uninformed	-	-	-
Feeling of safety	I felt safe when interacting with the vehicle.*	uninformed	.193	.046	.335
	Could you please explain the extent of agreement?	uninformed	-	-	-
Comprehensibility	What do you think was indicated by the light signal?	uninformed	-	-	-
	The light signal is comprehensible.*	informed	.991	.991	.099
Trust (Jian et al., 2000)	The system is deceptive.*	informed	-	-	-
	The system provides security.*	informed	-	-	-
	I can trust the system.*	informed	-	-	-
	Aggregated overall trust score		.964	.724	.428
Usefulness (*presented* light signals)	The presented light signal is useful.*	informed	.101	.875	.232
Usefulness (*general* use of light signals)	A light signal that indicates [meaning of the respective light signal] is generally useful.*	informed	.471	.157	.774
	Could you please explain the extent of agreement?	informed	-	-	-
Alternative design suggestions	Do you have alternative design suggestions for an eHMI indicating [meaning of the respective light signal]?	informed	-	-	-

*A 7-point Likert scale from [1] "I completely disagree" to [7] "I completely agree" was used.

3 Results

3.1 Manipulation check

In general, most participants (89%) noticed the light signals presented by the light bar on the top of the test vehicle. However, most VRUs (86%) did not believe that the light signal was addressed to themselves. The majority of participants (79%) did not see any driver inside the

vehicle during the simulated automated driving condition. However, in the manual driving condition, when the driver should have been visible, only a slight majority (52%) reported seeing a driver. This could have been due to windshield glare. Most VRUs (59%) in the simulated automated driving condition believed the vehicle drove autonomously, whereas over two thirds of participants (69%) did not assume the vehicle drove autonomously in the manual driving condition.

3.2 Comprehensibility (Q1)

When asked about the intended meaning of the presented light signals, participants assumed diverse interpretations. Table 2 presents the extracted response categories referred by at least 5% of participants in the interviews as well as example quotes regarding the suspected meaning of the presented light signals (translated from German into English). Participants most often indicated uncertainty about the presented light signals' meanings (38%). About one-fourth of interviewed VRUs (22%) hypothesized that the light signals represented a warning/caution message to other road users. Some participants associated the presented light signals with a police (16%) or emergency vehicle in general (8%). Findings from qualitative data regarding comprehensibility of the light signals are supported by questionnaire ratings, suggesting that the investigated light signals were perceived as rather unintuitive (M = 3.16, SD = 1.67). A two-way ANOVA (including the factors light signal and driving condition) revealed no statistical difference between the investigated *light signals* ($F(2,116) = 0.01$, $p = .991$, $\eta_p^2 = .00$) or *driving conditions* ($F(1,116) = 0.00$, $p = .991$, $\eta_p^2 = .00$) across comprehensibility ratings. Further, no interaction effect was found ($F(1,116) = 2.36$, $p = .099$, $\eta_p^2 = .04$).

3.3 Trust (Q2)

Overall, participants felt that the investigated light signals were only partially trustworthy (M = 4.01, SD = 1.35). A two-way ANOVA revealed no statistical difference for *light signals* ($F(2,117) = 0.04$, $p = .964$, $\eta_p^2 = .00$) or for *driving condition* ($F(1,117) = 0.13$, $p = .724$, $\eta_p^2 = .00$) across trust ratings. Further, there was no interaction effect ($F(1,117) = 0.85$, $p = .428$, $\eta_p^2 = .01$).

Table 2

Extracted response categories and example quotes regarding the assumed meaning of the light signals

Category	Frequency (quantity)	Example quotes (participant number)
No idea	52	"I have no idea." (P24)
Warning/ caution	30	"Usually it [the light signal] is some kind of warning signal." (P228)
Attention	12	"[The light signal] attracts attention." (P280)
Police	22	"I thought: police." (P05)
Emergency vehicle (not specified)	11	"[…] this blue caution light is associated with the fire department, police [vehicles], and ambulance vehicles." (P87)
Automated/ driverless vehicle	10	"[The light signal means] it's autonomous driving […] there is no driver inside [the vehicle]." (P17)
Object/ obstacle detection	8	"[…] looking for obstacles, maybe." (P327)

Note. N = 137; extracted response categories referred to by at least 5% of participants; analysis of answers across all conditions. Information in square brackets were added by the authors to enhance comprehensibility.

3.4 Feeling of safety (Q3)

Generally, ratings regarding feeling of safety indicated that participants felt rather safe during the interaction with the vehicle (M = 5.17, SD = 1.64). Although a two-way ANOVA revealed no main effect for *light signals* ($F(3,161) = 1.59$, $p = .193$, $\eta_p^2 = .03$), it did show a main effect for *driving condition* across participants' feeling of safety rating ($F(1,161) = 4.03$, $p = .046$, $\eta_p^2 = .02$). A pairwise post-hoc comparison (Bonferroni-corrected) revealed a significant effect for starting mode ($t_{starting}(44.69) = 2.47$, $p = .017$, $d = -0.68$). Specifically, VRUs felt significantly safer during the manual driving condition compared to the simulated automated driving condition. There was no significant interaction between light signal and driving condition ($F(2,161) = 1.10$, $p = .335$, $\eta_p^2 = .01$).

In addition, participants provided further explanations for their feeling of safety ratings during the interview. Over half of interviewed VRUs (56%) reported feeling safe during the interaction. In detail, participants described not perceiving hazards (25%) as the most common reason for feeling safe. However, several participants mentioned the slow speed of the vehicle (19%) and the distance of the vehicle (10%) as affecting their safety rating during the interaction. Interestingly, some participants reported not perceiving any interaction with the vehicle at all (17%), resulting in higher perceived safety ratings. Some VRUs felt that the light signals were an announcement of the vehicle's presence (9%), which increased feeling of safety during the interaction. Furthermore, other aspects of driving behavior (e.g., trajectory, flexible adaptation of maneuvers) were mentioned to improve safety during the interaction (9%). In contrast, some participants (21%) felt rather unsafe during the interaction. These

participants referred to their inexperience with this scenario (15%) and confusion regarding the light signal (7%) as reasons for lowering their safety ratings. Besides, the absence of a driver noticeable negatively influenced feeling of safety (9%). Another 10% of interviewed VRUs were undecided about the scenario's safety.

3.5 Usefulness of the presented light signals (Q4)

Overall, participants were rather undecided regarding the usefulness of the *presented* light signals (M = 4.01, SD = 1.92). A two-way ANOVA did not reveal a statistical effect for *light signal* ($F(2,116) = 2.33$, $p = .101$, $\eta_p^2 = .04$) or *driving condition* ($F(1,116) = 0.03$, $p = .875$, $\eta_p^2 = .00$) across the perceived usefulness of the *presented* light signals. Moreover, no interaction effect was found ($F(2,116) = 1.48$, $p = .232$, $\eta_p^2 = .03$).

3.6 General usefulness of light signals (Q5)

Light signals as a form of an eHMI in AVs were *generally* assessed as beneficial by the participants (M = 5.80, SD = 1.74). No statistical effect could be found for *light signals* ($F(2,130) = 0.76$, $p = .471$, $\eta_p^2 = .01$). Interestingly, there was also no statistical differences for *driving conditions* ($F(1,130) = 2.03$, $p = .157$, $\eta_p^2 = .02$) regarding the perceived general usefulness of the light signals, indicating that light signal use in AVs is independent of whether the driver is visible. Moreover, no interaction existed ($F(2,130) = 0.26$, $p = .774$, $\eta_p^2 = .00$). Additionally, interviewed VRUs provided further explanations for their *general* usefulness ratings of the specific light signal. Table 3 provides the extracted response categories (referred to by at least 5% of participants) and translated example quotes from the interview. Over half of participants (57%) indicated that light signals could be generally useful as a form of communication in AVs. In more detail, several VRUs highlighted that light signals could provide information about AVs' current states and future maneuvers (39%). Moreover, light signals were assessed as beneficial in communicating with other traffic participants (31%). In contrast, several participants felt that the general application of light signals was not useful (17%), particularly due to light signals' incomprehensibility (18%). Some participants were undecided about whether light signals in AVs were useful (14%). In addition, several participants believed that light signals as an eHMI were only useful in the context of mixed traffic that included manual and automated vehicles (7%).

Table 3

Extracted response categories and example quotes regarding the general usefulness of light signals in AVs

Category	Sub-category	Frequency (quantity)	Example quotes (participant number)
General usefulness (agree)	Information about AVs' states and maneuvers	54	"For this reason, I think it is better one knows that it [the vehicle] is automated." (P218)
	Communication with other traffic participants	43	"It would be useful [to know] that the vehicle is automated, for drivers, for other drivers [in surrounding vehicles] and for pedestrians." (P124)
	AV interaction/ feeling of safety	25	"It [the light signal] can create trust." (P133)
	Traffic safety	25	"Well, I like it for [the reason of] safety." (P285)
	Behavioral adaptation	24	"[…] maybe that one looks again, looks additionally […]." (P23)
	Replacing driver as communication partner	18	"A driver makes eye contact with me as a pedestrian. This [the eye contact] is difficult for an automated system." (P184)
	Communication of signals' meanings/ consensus	12	"Publicity, if everybody knows that it [the light signal] indicates an automated vehicle then everybody knows it. Just as I know [for example] the fire truck with horn and signal."(P69)
General usefulness (disagree)	Lack of knowledge about light signals' meanings	25	"It [the light signal] didn't help me, because I didn't know what it meant." (P33)
	Mistrust/ reliability	8	"[…] technology could fail." (P15)
	Information presented by implicit communication	8	"Generally, a normal [manual] vehicle has no approaching signal besides the […] sound of the engine." (P183)

Note. N = 138; extracted response categories referred to by at least 5% of participants; analysis of answers across all conditions. Information in squares bracket were added by the authors to enhance comprehensibility.

3.7 Alternative design suggestions (Q6)

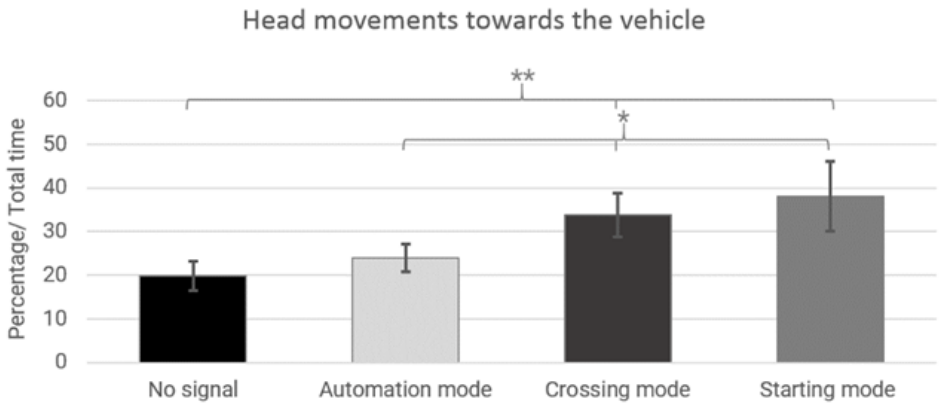
Concerning alternative designs, participants most often suggested that light signals should be used as a modality for eHMIs (25%). However, several VRUs recommended a different color than the investigated cyan in general (17%). Depending on the signals' meaning, participants suggested using green (7%), yellow/ orange (6%) or red (6%) as an appropriate color for a light signal in AVs. Furthermore, some interviewed VRUs proposed using text messages (10%) or icons (7%) in the design of the eHMI. Participants indicated that the eHMI should also be visible by following traffic (5%). However, several VRUs stated that the current light signal set-up was sufficient and did not need improvement (12%). In contrast, some participants felt that eHMIs were rather unnecessary in context of AVs (9%).

3.8 Head movements towards the vehicle (Q7)

The analyzed video data were log-transformed to correct for the violated homogeneity of variance. A two-way ANOVA showed significant differences between the investigated *light signals* regarding VRUs' head movement towards the vehicle ($F(3,381) = 9.17$, $p < .001$, $\eta_p^2 = .07$). Pairwise comparisons (Bonferroni-corrected) revealed that head movements towards the vehicle lasted significantly longer during the starting and crossing mode compared to the baseline condition without any light signal ($p = .001$ respectively). Moreover, these head movements towards the vehicle lasted significantly longer during the starting ($p = .002$) and crossing mode ($p = .004$) compared to the automation mode. No significant difference existed between the automation mode and the baseline condition or between the crossing and starting mode ($p > .999$ respectively, Figure 2). Further, no statistical differences could be found for the *driving conditions* ($F(1,381) = 2.71$, $p = .101$, $\eta_p^2 = .01$). There was also no significant interaction effect ($F(3,381) = 0.592$, $p = .621$, $\eta_p^2 = .01$).

Figure 2

The qualified percentage of pedestrians' head movements towards the vehicle by total time



Note. Error bars indicate 95% confidence intervals.

* indicates a significant difference of $p < .01$.

** indicates a significant difference of $p < .001$.

4 Discussion

4.1 Findings

The current study investigated three different light signals (i.e., automation mode, starting mode, and crossing mode) serving as an eHMI compared across a manual and a simulated automated driving condition. Results demonstrated a successful manipulation of the drivers'

visibility by employing the seat suit during the simulated automated driving condition, confirming findings by Rothenbücher et al. (2016) (for Wizard-of-Oz studies in general see Dahlbäck, Jönsson, & Ahrenberg, 1993). However, during the manual driving condition, only half of participants noticed a driver inside the vehicle. This may have been due to windshield glare, a phenomenon also observed in other studies that reported only a small amount of eye contact between pedestrians and the driver of a vehicle due to windshield glare (Schneemann & Gohl, 2016). The current study assessed participants' general perception of a driver inside the vehicle, which is less specific than eye contact. Nevertheless, the number of participants indicated perceiving a driver in the manual driving condition remained relatively small. Moreover, the findings revealed that the applied AV manipulation was partially successful. Only half of participants were convinced that the vehicle was operated autonomously during the simulated automated driving condition in the current study. This is quite lower compared to Rothenbücher et al. (2016), where 87% of participants assumed the vehicle driving autonomously. However, this discrepancy might be explained by the different study locations and the resulting statutory regulations: AVs would more likely be expected on the streets in Silicon Valley, CA (Rothenbücher et al., 2016) than in Chemnitz, Germany (current study). Since this study incorporated a field setting, specific parameters (e.g., distance between the VRU and vehicle) might have varied between different participants. In addition, influencing issues such as prior knowledge and experience with AVs likely differed between participants. However, these parameters might also vary under real-world conditions. The study's aim was to investigate VRUs' unbiased evaluation and reaction to light signals as eHMIs in AVs in a field setting and therefore enhance external validity of the results.

Furthermore, the study examined the (Q1) comprehensibility of the applied light signals, (Q2) trust in the respective light signal and (Q3) participants' feeling of safety. In terms of comprehensibility of the light signals' meanings the quantitative and interview data matched considerably. Questionnaire data consistently revealed a rather low level of comprehensibility of the presented light signals. Interview data displayed a wide range of assumed meanings given by participants, though those interpretations predominantly did not match the intended meaning. Overall, the evaluated eHMI light signals were not considered intuitive (as also mentioned in Schieben et al., 2019). The results are also supported by previous findings from Ackermann et al. (2019) showing that participants misinterpreted the investigated light signals since the light bar represents an ambiguous eHMI. In the current study, some participants suggested using text messages as an alternative design approach for eHMIs, which is also similar to Ackermann et al. (2019). However, incorporating text messages as an eHMI in AVs may potentially require a large display for presentation and VRUs' reading and language skills

should be considered when implementing text messages as eHMIs in AVs (Schieben et al., 2019).

Moreover, the interviewed VRUs perceived the light signals as only partially trustworthy. Participants' feeling of safety enhanced during the manual driving condition where a driver was present compared to the simulated automated driving condition where the driver was apparently missing, which was also found in previous studies (Lagström & Lundgren, 2015; Rothenbücher et al., 2016). Only half of participants noticed a driver in the manual driving condition whereas in the simulated automated driving condition the majority believed there was no driver present. This expectation might influence VRUs' attention. No difference in safety ratings across the investigated light signals could be found, which might be confounded by the low comprehensibility and trust ratings of the investigated light signals. Moreover, the primary reasons reported for rating safety as low during the interaction with the vehicle were a) the missing experience during the interaction with AVs and eHMIs as well as b) the perceived distrust towards the light signals. Since previous research indicated a positive effect of comprehensibility (e.g., for icon usage; Isherwood, McDougall, and Curry (2007)) and experience on trust, that could be increased by further experience during the interaction with eHMIs and AVs (as shown with AVs in general e.g., by Penmetsa, Adanu, Wood, Wang, and Jones (2019)). Although most participants generally noticed the respective light signal, they did not assume that it was directed to themselves. The results underline the influence of light signals' directedness with regard to feeling of safety and an intuitive design. Hence, eHMIs' directedness should be considered as an important factor when implemented in AVs (Willrodt, Strothmann, & Wallaschek, 2017). Thus, the results underline the importance of a) comprehensibility (Isherwood et al., 2007) and b) experience with light signals as eHMIs, both of which could increase perceived trust and safety during the interaction with AVs (Penmetsa et al., 2019). Therefore, it is suggested that information about light signals' meanings should be provided beforehand to other traffic participants. Moreover, a consensus regarding applied eHMIs might be necessary across different manufacturers (International Organization for Standardization, 2018). Qualitative data could also show that over half of VRUs felt safe during the interaction with the vehicle given the vehicle's slow speed and the large distance to the vehicle. The reported parameters describe implicit communication characteristics that should also be considered in AVs (Beggiato et al., 2018).

Furthermore, participants evaluated (Q4) the usefulness of the *presented* light signals and (Q5) the *general* usefulness of light signals as eHMIs in AVs. Participants' evaluation regarding both types of usefulness did not differ significantly between the investigated light signals. Interestingly, ratings also did not differ between the investigated driving conditions. However, it should be considered that only half of participants noticed a driver present in the

manual driving condition, whereas merely a slight majority believed the vehicle operated autonomously during the simulated automated driving condition. Participants indecision about the usefulness of the presented light signals might be also confounded by the light signals' comprehensibility. Based on the quantitative and qualitative data, participants believed that light signals in general were useful as an eHMI for AVs, which corresponds with Clamann, Aubert, and Cummings (2016). However, in the study by Clamann et al. (2016) the investigated eHMIs were marginally used by participants, nevertheless most participants perceived the applied eHMIs as useful.

For the behavioral data (Q7), significant differences in head movement durations towards the vehicle were observed amongst the investigated light signals. The two animated signals (i.e., starting mode and crossing mode) particularly led to longer durations of head movements towards the vehicle compared to the non-animated light signal (i.e., automated mode). This effect could be explained by an increased salience due to the signals' movement, which could have led to longer durations of head movements towards the vehicle. Surprisingly, no statistical difference was found between the automation mode and the baseline condition despite using a light signal in general. Furthermore, there was also no statistical difference between the two driving conditions regarding head movements towards the vehicle. The latter matches participants' ratings regarding whether the driver was visible that might be affected by windshield glare (which is similar to the results for eye contact from Schneemann and Gohl, 2016). The current study did not examine eHMI's effect on participants' road crossing behavior. Moreover, precise implicit communication parameters (e.g., vehicles' trajectory) regarding a potentially necessary transition from informal to formal communication need to be further investigated when applying eHMIs in AVs (Beggiato et al., 2018). It should also be considered that eHMIs potentially increase complexity of traffic situations (Ackermann et al., 2019), particularly if they are used by several traffic participants (Schieben et al., 2019). Therefore, Ackermann et al. (2019) suggested the application of eHMIs as an addition in AVs if informal communication is insufficient to ensure road safety. However, participants believed that the general use of light signals as eHMIs was beneficial, despite that the investigated light signals rather decreased feeling of safety due to incomprehensibility. Regarding alternative design applications (Q6), light signals were the most favored communication approach in eHMI application (as also shown by Mahadevan et al., 2018) and thereby were preferred over acoustic signals as the modality for eHMIs (also shown by Merat et al., 2018). When referring to a specific communication content, VRUs particularly focused on information about AVs' current and future states and maneuvers. The results are in line with previous findings regarding the design of AVs' capability to communicate with VRUs (Schieben et al., 2019).

4.2 Implications

Results of the present study showed that participants evaluated the *general* use of light signals in AVs as beneficial for providing information about the AVs' states and maneuvers and therefore maintain road safety. However, the *presented* light signals were assessed as unintuitive if there was no prior knowledge about their specific meaning. Hence, it seems recommendable to introduce AVs' means of communication to the public before it is implemented in transport. Information about AVs in general and experience in the interaction with AVs should be provided to improve trust in AVs (Penmetsa et al., 2019) and the perceived comfort during the interaction with AVs (Böckle et al., 2017). Prior information could enhance the development of an eligible mental model concerning AVs means of communication. Therefore, the resulting expectations regarding AVs' interaction behavior might be more appropriate. Moreover, the respective light signals should be attributed to a specific meaning in analogy to the direction indicator. The three investigated light signals presenting an eHMI for AVs would refer to:

a) Automation mode: indicates that the vehicles is operating autonomously (steady light signal);
b) Starting mode: indicates that the vehicle is approaching (flashing light signal);
c) Crossing mode: indicates that a pedestrian could cross in front of the vehicle (sweeping light signal).

Moreover, the applied signals should be considered as cultural independent (Schieben et al., 2019) and could be standardized among manufacturers (International Organization for Standardization, 2018). Further studies should also consider different eHMI design aspects regarding, for example, the directedness of communication signals (Willrodt et al., 2017) or its visibility from behind the vehicle. Moreover, it should be considered that vehicles' speed and trajectory could be used as specific parameters of informal communication in AVs (Beggiato et al., 2018) to avoid an informational overload in complex situations (Schieben et al., 2019). In general, eHMIs could potentially support the communication between AVs and surrounding traffic participants in ambiguous traffic situations when informal communications' resources are exhausted (e.g., in deadlock situations; Ackermann et al., 2019).

Acknowledgements

The current study was conducted in the project “InMotion – Light-based communication between automated vehicles and other road users” and is supported by the German Federal Ministry of Transport and Digital Infrastructure (BMVI), grant no 16AVF2016A.

The test vehicle for conducting the study was provided by the Ford Motor Company.

5 References

Ackermann, C., Beggiato, M., Schubert, S., & Krems, J. F. (2019). An experimental study to investigate design and assessment criteria: What is important for communication between pedestrians and automated vehicles? *Applied Ergonomics*, *75*, 272–282. https://doi.org/10.1016/j.apergo.2018.11.002

Anderson, J. R. (2014). *Cognitive psychology and its implications*. London, England: Macmillan Publishers.

Beggiato, M., Witzlack, C., Springer, S., & Krems, J. F. (2018). The right moment for braking as informal communication signal between automated vehicles and pedestrians in crossing situations. In N. Stanton (Ed.), *Advances in Human Aspects of Transportation. AHFE 2017. Advances in Intelligent Systems and Computing, vol 597*. Cham, Switzerland: Springer. https://doi.org/10.1007/978-3-319-93885-1

Blackvue [Apparatus and software]. (2018). Seoul, Korea: Blackvue.

Böckle, M.-P., Brenden, A. P., Klingegård, M., Habibovic, A., & Bout, M. (2017). SAV2P: Exploring the impact of an interface for shared automated vehicles on pedestrians' experience. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*, 136–140. https://doi.org/10.1145/3131726.3131765

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Chang, C.-M., Toda, K., Sakamoto, D., & Igarashi, T. (2017). Eyes on a car: an Interface design for communication between an autonomous car and a pedestrian. *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 65–73. https://doi.org/10.1145/3122986.3122989

Clamann, M., Aubert, M., & Cummings, M. L. (2017). Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles. *Transportation Research Board 96th Annual Meeting (No. 17-02119)*.

Dahlbäck, N., Jönsson, A., & Ahrenberg, L. (1993). Wizard of Oz studies — why and how. *Knowledge-Based Systems*, *6*(4), 258–266. https://doi.org/10.1145/169891.169968

de Clercq, K., Dietrich, A., Núñez Velasco, J. P., de Winter, J., & Happee, R. (2019). External human-machine interfaces on automated vehicles: Effects on pedestrian crossing decisions. *Human Factors*, 1–18. https://doi. org/10.1177/0018720819836343

Deb, S., Hudson, C. R., Carruth, D. W., & Frey, D. (2018). Pedestrians receptivity in autonomous vehicles: Exploring a video-based assessment. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *62*(1), 2061–2065. https://doi.org/10.1177/1541931218621465

ELAN (Version 5.2) [Software] (2004). Nijmegen, The Netherlands: Max Planck Institute for Psycholinguistics. Retrieved from https://tla.mpi.nl/tools/tla-tools/elan/

Fuest, T., Michalowski, L., Traris, L., Bellem, H., & Bengler, K. (2018). Using the driving behavior of an automated vehicle to communicate intentions - A Wizard of Oz Study. *21st International Conference on Intelligent Transportation Systems (ITSC)*, 3596–3601. https://doi.org/10.1109/ITSC.2018.8569486

Guéguen, N., Meineri, S., & Eyssartier, C. (2015). A pedestrian's stare and drivers' stopping behavior: A field experiment at the pedestrian crossing. *Safety Science*, *75*, 87–89. https://doi.org/10.1016/j.ssci.2015.01.018

Hair, J. F., Black, W. C., Babin, B. J., & Anderson, R. E. (2014). *Multivariate data analysis* (7th ed.). New Jersey, NJ: Pearson Education.

Hamilton-Baillie, B. (2008). Shared space: Reconciling people, places and traffic. *Built Environment*, *34*(2), 161–181. https://doi.org/https://doi.org/10.2148/benv.34.2.161

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems, J. F. (2020). How should Automated Vehicles communicate? – Effects of a light-based communication approach in a Wizard-of-Oz study. In Neville Stanton (Ed.), *Advances in Human Factors of Transportation. AHFE 2019. Advances in Intelligent Systems and Computing, vol 964*. https://doi.org/https://doi.org/10.1007/978-3-030-20503-4_8

Hölzel, A. (2008). *Unterscheidung von formeller und informeller Kommunikation im Straßenverkehr [Distinction of formal and informal communication in traffic.]* (Diploma thesis). Universität Wien, Vienna, Austria.

International Organization for Standardization (2018). Road vehicles - Ergonomic aspects of external visual communication from automated vehicles to other road users (ISO/DIS Standard No. 23049). Retrieved from https://www.iso.org/standard/74397.html

Isherwood, S. J., McDougall, S. J., & Curry, M. B. (2007). Icon Identification in context: The changing role of icon characteristics with user experience. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *49*(3), 465–476. https://doi.org/10.1518/001872007x200102

Jamson, A. H., Merat, N., Carsten, O. M., & Lai, F. C. (2013). Behavioural changes in drivers experiencing highly-automated vehicle control in varying traffic conditions. *Transportation Research Part C: Emerging Technologies*, *30*, 116–125. https://doi.org/10.1016/j.trc.2013.02.008

Jian, J.-Y., Bisantz, A. M., & Drury, C. G. (2000). Foundations for an empirically determined scale of trust in automated systems. *International Journal of Cognitive Ergonomics*, *4*(1), 53–71. https://doi.org/10.1207/S15327566IJCE0401_04

Lagström, T., & Lundgren, V. M. (2015). *AVIP - Autonomous vehicles interaction with pedestrians - An investigation of pedestrian- driver communication and development of a vehicle external interface* (Master thesis). Chalmers University of Technology, Gothenburg, Sweden.

Landis, J. R., & Koch, G. G. (1977). The Measurement of observer agreement for categorical data. *Biometrics*, *33*(1), 159–174. https://doi.org/10.2307/2529310

Litman, T. (2019). *Autonomous vehicle implementation predictions*. Victoria Transport Policy Institute. Retrieved from https://www.vtpi.org/avip.pdf

Lundgren, V. M., Habibovic, A., Andersson, J., Lagström, T., Nilsson, M., Sirkka, A., … Saluäär, D. (2017). Will there be new communication needs when introducing automated vehicles to the urban context? In N. Stanton, S. Landry, G. Di Bucchianico, & A. Vallicelli. (Eds.), *Advances in Human Aspects of Transportation. Advances in Intelligent Systems and Computing, vol 484.* (pp. 485–497). Cham, Switzerland: Springer.

Mahadevan, K., Somanath, S., & Sharlin, E. (2018). Communicating awareness and intent in autonomous vehicle-pedestrian interaction. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. https://doi.org/10.1145/3173574.3174003

Merat, N., Louw, T., Madigan, R., Wilbrink, M., & Schieben, A. (2018). What externally presented information do VRUs require when interacting with fully Automated Road Transport Systems in shared space? *Accident Analysis and Prevention*, *118*, 244–252. https://doi.org/10.1016/j.aap.2018.03.018

Nuñez Velasco, J. P., Rodriguez, P., Farah, H., & Hagenzieker, M. P. (2016). Safety of pedestrians and cyclists when interacting with self-driving vehicles: A case study of the WEpods (PPT). *ITRL Conference on Integrated Transport*, 782–792. https://doi.org/10.1016/j.aap.2008.12.001

Penmetsa, P., Adanu, E. K., Wood, D., Wang, T., & Jones, S. L. (2019). Perceptions and expectations of autonomous vehicles – A snapshot of vulnerable road user opinion.

Technological Forecasting and Social Change, *143*, 9–13. https://doi.org/10.1016/j.techfore.2019.02.010

Rasouli, A., Kotseruba, I., & Tsotsos, J. K. (2018). Understanding pedestrian behavior in complex traffic scenes. *IEEE Transactions on Intelligent Vehicles*, *3*(1), 61–70. https://doi.org/10.1109/tiv.2017.2788193

Rasouli, A., & Tsotsos, J. K. (2018). *Joint attention in driver-pedestrian interaction: from theory to practice*. Manuscript submitted for publication. Retrieved from https://arxiv.org/pdf/1802.02522.pdf

Rodríguez Palmeiro, A., van der Kint, S., Vissers, L., Farah, H., de Winter, J. C., & Hagenzieker, M. (2018). Interaction between pedestrians and automated vehicles: A Wizard of Oz experiment. *Transportation Research Part F: Traffic Psychology and Behaviour*, *58*, 1005–1020. https://doi.org/10.1016/j.trf.2018.07.020

Rothenbücher, D., Li, J., Sirkin, D., Mok, B., & Ju, W. (2016). Ghost driver: A field study investigating the interaction between pedestrians and driverless vehicles. *25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 795–802. https://doi.org/10.1109/ROMAN.2016.7745210

SAE International's new standard J3016. (2018). Levels of driving automation. Retrieved from: https://doi.org/P141661

Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., & Merat, N. (2019). Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology and Work*, *21*(1), 69–85. https://doi.org/10.1007/s10111-018-0521-z

Schneemann, F., & Gohl, I. (2016). Analyzing driver-pedestrian interaction at crosswalks: A contribution to autonomous driving in urban environments. *IEEE Intelligent Vehicles Symposium*, (IV), 38–43. https://doi.org/10.1109/IVS.2016.7535361

Straßenverkehrsordnung (StVO). (2013). Retrieved from https://www.stvo.de/strassenverkehrsordnung

Šucha, M., Dostal, D., & Risser, R. (2017). Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis and Prevention*, *102*, 41–50. https://doi. org/10.1016/j.aap.2017.02.018

Wilbrink, M., Schieben, A., Kaup, M., Willrodt, J.-H., Weber, F., & Lee, Y. M. (2018). *Preliminary interaction strategies for the interACT automated vehicles*. Retrieved from https://www.interact-roadautomation.eu/wp-

content/uploads/interACT_WP4_D4.1_Preliminary_Human_Vehicle_Interaction_Strategies_v1.0_draftWebsite.pdf

Willrodt, J.-H., Strothmann, H., & Wallaschek, J. (2017). Optical car-to-human communication for Automated Vehicles. In T. Q. Khanh (Ed.), *12th International Symposium on Automotive Lighting* (pp. 579–588). Munich, Germany: UTZ Verlag GmbH.

Witzlack, C., Beggiato, M., & Krems, J. F. (2016). Interaktionssequenzen zwischen Fahrzeugen und Fußgängern im Parkplatzszenario als Grundlage für kooperativ interagierende Automatisierung. [Interaction between vehicles and pedestrians as a basis for cooperative automation.]. In VDI (Ed.), *32. VDI/ VW-Gemeinschaftstagung, Fahrerassistenz und automatisiertes Fahren, VDI-Berichte 2288* (pp. 323–336). Düsseldorf, Germany: VDI-Verlag GmbH.

Zhang, J., Vinkhuyzen, E., & Cefkin, M. (2018). Evaluation of an autonomous vehicle external communication system concept: A survey study. In N. Stanton (Ed.), *Advances in Human Aspects of Transportation. AHFE 2017. Advances in Intelligent Systems and Computing, vol 597* (pp. 650–661). https://doi.org/10.1007/978-3-319-60441-1_63

PAPER III

THE EFFECT OF EHMI MALFUNCTIONS ON YOUNGER AND ELDERLY PEDESTRIANS' TRUST AND ACCEPTANCE OF AUTOMATED VEHICLE COMMUNICATION SIGNALS

Citation:

Hensch, A.-C., Kreißig, I., Beggiato, M., & Krems, J. (2022). The Effect of eHMI Malfunctions on Younger and Elderly Pedestrians' Trust and Acceptance of Automated Vehicle Communication Signals. *Frontiers in Psychology,* 13:866475. https://doi.org/10.3389/fpsyg.2022.866475

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Hensch A-C, Kreißig I, Beggiato M and Krems JF (2022) The Effect of eHMI Malfunctions on Younger and Elderly Pedestrians' Trust and Acceptance of Automated Vehicle Communication Signals. *Front. Psychol*. 13:866475. doi: 10.3389/fpsyg.2022.866475

THE EFFECT OF EHMI MALFUNCTIONS ON YOUNGER AND ELDERLY PEDESTRIANS' TRUST AND ACCEPTANCE OF AUTOMATED VEHICLE COMMUNICATION SIGNALS

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Abstract

To ensure traffic flow and road safety in automated driving, external human–machine interfaces (eHMIs) could prospectively support the interaction between automated vehicles (AVs; SAE Level 3 or higher) and pedestrians if implicit communication is insufficient. Particularly elderly pedestrians (≥ 65 years) who are notably vulnerable in terms of traffic safety might benefit of the advantages of additional signals provided by eHMIs. Previous research showed that eHMIs were assessed as useful means of communication in AVs and were preferred over exclusively implicit communication signals. However, the attitudes of elderly users regarding technology usage and acceptance are ambiguous (i.e., less intention to use technology vs. a tendency toward overreliance on technology compared to younger users). Considering potential eHMI malfunctions, an appropriate level of trust in eHMIs is required to ensure traffic safety. So far, little research respected the impact of multiple eHMI malfunctions on participants' assessment of the system. Moreover, age effects were rarely investigated in eHMIs. In the current monitor-based study, *N* = 36 participants (19 younger, 17 elderly) repeatedly assessed an eHMI: During an initial measurement, when encountering a valid system and after experiencing eHMI malfunctions. Participants indicated their trust and acceptance in the eHMI, feeling of safety during the interaction and vigilance toward the eHMI. The results showed a positive effect of interacting with a valid system that acted consistently to the vehicle's movements compared to an initial assessment of the system. After experiencing eHMI malfunctions, participants' assessment of the system declined significantly. Moreover, elderly participants assessed the eHMI more positive across all conditions than younger participants did. The findings imply that participants considered the vehicle's movements as implicit communication cues in addition to the provided eHMI signals during the encounters. To support traffic safety and smooth interactions, eHMI signals are required to be in line with vehicle's movements as implicit communication cues. Moreover, the results underline the importance of calibrating an appropriate level of trust in eHMI signals. An

adequate understanding of eHMI signals needs to be developed. Thereby, the requirements of different user groups should be specifically considered.

Keywords: automated vehicles, communication cues, external human–machine interface, system malfunctions, trust, acceptance, vulnerable road users, elderly pedestrians

1 Introduction

Pedestrians are the most vulnerable road user group when it comes to traffic accidents due to the high number of 20% of all road fatalities (European Commission, 2020). Since they are over-represented regarding severe injuries in case of accidents, elderly pedestrians (≥ 65 years) are particularly vulnerable in terms of traffic safety (European Commission, 2021). Therefore, this user group should be specifically considered when it comes to road safety. Automated vehicles (AVs, SAE Level 3 or higher) provide the potentials of increased road safety, traffic efficiency, and enhanced driving comfort (SAE, 2018). However, to benefit from increased automated driving functions, AVs need to provide safe and smooth interactions with manual traffic participants in- and outside the vehicle and need to be accepted (Habibovic et al., 2018). Thus, AVs' interaction capabilities need to be transparent and predictable to prevent from breakdowns, provide a common ground of interactions, and thus intuitive and safe encounters with other road users (Clark and Brennan, 1991; Endsley, 1995). Therefore, established interaction capabilities of manual traffic participants should be considered to be prospectively implemented in AVs (Portouli et al., 2014).

Since traffic is a social system, the different participants use various information of the driving scene to anticipate and coordinate prospective movements (Wilde, 1976). A coordination of actions is particularly required in shared spaces, such as parking areas, that are characterized by a high number of potentially ambiguous encounters due to limited statutory regulations and a diversity of traffic participants, such as pedestrians and vehicles, that need to interact (Hamilton-Baillie, 2008). To resolve ambiguities and support traffic safety, the communication between different traffic participants is required. Thereby, road users apply implicit (e.g., trajectory) and explicit (e.g., turn indicator) signals to communicate (Dey and Terken, 2017; for an overview of pedestrian-driver interaction see Rasouli and Tsotsos, 2019). In AVs, interactions between drivers and surrounding traffic participants will prospectively change since the driver might potentially be engaged in other tasks than driving and will no longer be available as an interaction partner. Thus, established communication cues between drivers and pedestrians, such as eye contact, need to be substituted in AVs (Lundgren et al., 2017). External human–machine interfaces (eHMIs) might compensate for a potentially missing interaction between drivers and surrounding traffic participants (Schieben et al., 2019) and offer the potential to support interactions in AVs if implicit communication is insufficient (Ackermann et al., 2019).

The current study aimed at investigating the development of participants' assessment of an eHMI as potential means of communication in AVs during repeated measures. Thereby, the influence of system experience, valid and invalid eHMI functions, and the effect of participants' age on the system assessment was investigated.

1.1 External human–machine interfaces in automated vehicles

As potential communication signals in automated driving, eHMIs could provide additional information about the AVs' state and thus supply feedback to other traffic participants and could prevent confusion of surrounding road users. Moreover, eHMIs have the potential to announce prospective driving maneuvers of AVs and support the anticipation of the prospective development of the traffic scenario. Therefore, eHMIs are assumed to support pedestrians' situational awareness of the traffic scenario and could, in turn, enhance traffic safety (Endsley, 1995; Krems and Baumann, 2009; Habibovic et al., 2018). However, pedestrians need to consider the eHMI signals as a source of information to benefit of the additional information. Previous research could show that eHMIs as means of communication in AVs generally supported the interaction with surrounding traffic participants (for an overview see Rouchitsas and Alm, 2019), especially in shared space settings comprising a high number of ambiguous encounters between diverse traffic participants (Merat et al., 2018). In detail, participants indicated higher trust ratings (Faas et al., 2020), higher acceptance ratings (Schindler et al., 2020), and higher feeling of safety (Böckle et al., 2017; de Clercq et al., 2019) during encounters including eHMI signals compared to baseline conditions that exclusively comprised implicit communication signals, such as the vehicles' movement (i.e., dynamic HMI; Bengler et al., 2020). Since trust and acceptance display essential factors for a system's usage and the users' reliance (Lee and See, 2004; Ghazizadeh et al., 2012), these concepts need to be further considered for eHMIs as means of communication in AVs.

1.2 Trust in automation and influencing factors

Trust in automation is an essential determinant for system usage and can be described as "the attitude that an agent will help achieve an individual's goals in a situation characterized by uncertainty and vulnerability" (Lee and See, 2004, p. 51). To maintain safe interactions but also apply the benefits of automated systems, an *appropriate* level of trust in the automation, that matches the capabilities of the system, is required. An *inappropriate* level of trust, on the other hand, could either lead to distrust or overtrust in the system. Distrust describes an insufficient level of trust in a system, leading to non-usage and, in turn, a loss of the advantages of the technical system (Lee and See, 2004). In the context of eHMIs, distrust in the system would lead to pedestrians' reduced willingness to use the provided information by eHMI signals (Faas et al., 2021). Whereas, overtrust would result if the users' trust exceeds the system's capabilities. The users' overtrust in a system, as an attitude, leads to overreliance in the system's capabilities as a behavioral aspect (Lee and See, 2004). With regard to eHMIs in AVs, overtrust implies an overreliance in the eHMI signals that could lead to insufficient considerations of implicit communication signals that are provided by the vehicle's driving

behavior (Faas et al., 2021). Hence, overtrust should be respected as an essential safety issue in eHMIs (Tabone et al., 2021). Considering trust calibration and influencing factors, Hoff and Bashir (2015) proposed a theoretical framework that considers three layers of trust.

According to the framework, a person's *dispositional trust* is a relatively stable trait over time and reflects the general tendency for trust in automation, which, for instance, is influenced by the users' age. In addition, dynamic factors reflected in *situational trust* and *learned trust* are also reported to influence users' trust in a system. In particular, experience with the system and its performance influence the users' learned trust in a system. To facilitate an appropriate usage of eHMI signals if applied in AVs, an adequate trust calibration in eHMI signals and potentially influencing factors need to be further considered. As an influencing factor on the users' learned trust (Hoff and Bashir, 2015), experience with a system was shown to support the development of the users' trust in the automated system (Muir and Moray, 1996). The positive influence of system experience on users' trust has been also shown for the technology of eHMIs. Faas et al. (2020) investigated the development of users' trust in eHMIs in three sessions of encounters with the system over a period of three weeks. The authors reported a constant increase of users' trust when gaining experience with the investigated eHMI (Faas et al., 2020).

Besides experience with the system, its performance and reliability were also shown to influence the users' trust in a system. More specifically, system failures were shown to decrease the users' trust in the automation (Lee and Moray, 1992). Considering eHMIs, potential malfunctions cannot be excluded if the systems are applied as means of communication in AVs (Holländer et al., 2019). In the context of this study, eHMI malfunctions imply a mismatch between vehicles' movements as implicit communication cues and eHMI signals. With regard to traffic safety, pedestrians need to be aware of potential malfunctions of eHMIs and are required to react appropriately in such potentially hazardous situations. For instance, pedestrians need to consider vehicles' implicit communication cues (e.g., trajectory) over the eHMI signals in such cases (Kaleefathullah et al., 2020). Thus, to maintain traffic safety but also apply the benefits of AVs and potential eHMI signals, an *appropriate* level of trust in eHMI signals, that matches the capabilities of the system, is required if eHMIs are applied in AVs (Lee and See, 2004). Previous studies that investigated eHMI malfunctions, realized the malfunctions by contradicting information of the provided eHMI signals and the vehicles' driving behavior as implicit communication signals. First research results indicated a decline of participants' trust after encountering invalid eHMI functions in street crossing scenarios (Kaleefathullah et al., 2020; Faas et al., 2021). Faas et al. (2021) reported that participants' trust declined temporarily after experiencing a single eHMI malfunction. Therefore, the authors concluded that participants' trust formation in eHMIs can be seen as a

dynamic process that is based on previous experience during encounters with the system (Faas et al., 2021). In order to prevent potentially safety critical situations and the users' overtrust, the effect of multiple eHMI malfunctions was investigated in the current study in a shared space setting, comprising ambiguous encounters between the involved traffic participants.

1.3 Effects of invalid system functions on acceptance, feeling of safety, and vigilance toward the automated system

A further essential predictor for system usage, which is strongly related to trust in automation, is the acceptance of an automated system (Ghazizadeh et al., 2012; Nordhoff et al., 2019). In the current study, the acceptance of a system will be defined as the users' "direct attitude towards a system" according to Van Der Laan et al. (1997, p. 2). In the context of eHMIs as means of communication in AVs, the signals need to be accepted by pedestrians to benefit from the provided information of the system. Generally, previous research reported a benefit of eHMI signals for pedestrians when encountering AVs (Rouchitsas and Alm, 2019). With regard to traffic safety and the intention to use the information provided by an eHMI, pedestrians' acceptance of the system also needs to be investigated in case of eHMI malfunctions, which might be unexpected for the pedestrians (Venkatesh et al. 2003). Beggiato and Krems (2013) investigated the effect of omitted system failures of an adaptive cruise control, as a form of driving assistance systems, on the users' acceptance during multiple driving simulator sessions. The authors reported a sharp decline of the users' acceptance when experiencing omitted system failures of the investigated driving assistance system (Beggiato and Krems, 2013). Since previous research reported a decline of participants' acceptance due to invalid system's functions, the influence of eHMI malfunctions on participants' acceptance should be also investigated.

Besides potentially impairing the users' acceptance, invalid system functions might also influence additional aspects of the interaction with eHMIs. For instance, Holländer et al. (2019) reported that even a single eHMI malfunction reduced the participants' perceived safety during encounters with a vehicle in a simulated street crossing scenario. Moreover, due to the contradicting information between the eHMI signal and the interaction vehicle's driving behavior, participants' confidence regarding the vehicle's prospective driving behavior declined significantly (Holländer et al., 2019). In addition, the supervisors' vigilance toward a system represents an essential component to detect system failures and thus support safe interactions with automated systems, such as AVs. However, vigilance toward a system demands additional mental workload for monitoring the automated system (Warm et al., 2008). In the context of automated driving, vigilance was described as "state or degree of readiness

to detect and to react to small changes in the environment that appear in random intervals" (Körber et al., 2015, p. 71). To gain more insight on the effects of eHMI malfunctions, the current study investigated multiple malfunctions and repeatedly examined participants' assessment of the system regarding, trust, acceptance, perceived safety during the interaction and vigilance toward the system.

1.4 Age effects in eHMI assessment and traffic safety

Signals provided by eHMIs and potential system malfunctions might be assessed differently among various user groups. Since elderly pedestrians (≥ 65 years) are over-represented regarding severe injuries in case of accidents, this user group is particularly vulnerable in terms of traffic safety (European Commission, 2021). Therefore, elderly pedestrians might particularly benefit of increased road safety as an advantage of AVs. Since eHMI signals are assumed to support pedestrians' situational awareness by providing additional information of the traffic scene (Endsley, 1995; Habibovic et al., 2018), the signals might compensate for age-related declines, such as cognitive and sensory abilities as well as psycho-motoric functions of elderly (for an overview see Dunbar et al., 2004; Polders et al., 2015). According to the trust framework by Hoff and Bashir (2015), an influencing aspect of dispositional trust is reflected in the users' age. However, there are ambiguous findings regarding elderly users' attitudes toward technology. On the one hand, elderly users' reported lower actual usage rates, less interest to use technology (Czaja et al., 2006), and reduced comfort when interacting with technology compared to younger users (Czaja and Sharit, 1998). In contrast, it was also reported that elderly users were more likely to trust automated systems (for an overview see Schaefer et al., 2016) and indicated a more positive attitude toward automated systems (e.g., Rödel et al., 2014; Hartwich et al., 2019). When investigating light-based eHMI signals in a field study, elderly participants indicated higher usefulness ratings (i.e., acceptance ratings) of the investigated signals than younger participants. The results might be constituted in elderly participants' awareness that eHMI signals could provide additional information of driving scenes and might therefore compensate for age-related impairments, which could enhance traffic safety (Hensch et al., 2019b).

With regard to invalid functions of automated systems, Ho et al. (2005) compared younger and elderly participants' trust and reliance on an automated decision aid. It was shown that elderly users were less sensitive in case of system failures and showed a tendency of overreliance on the system. Moreover, elderly users adjusted their trust in case of invalid functions of the automation aids less than younger users (Ho et al., 2005). Due to several age-related impairments (Dunbar et al., 2004; Polders et al., 2015) and the ambiguous relation between elderly and their attitude toward technology (Czaja et al., 2006; Schaefer et al., 2016),

this specific user group needs to be particularly considered when it comes to eHMIs and potential malfunctions including possible safety issues. Currently, age-related differences in eHMI assessment are rarely investigated (as exceptions see Othersen et al., 2018; Hensch et al., 2019b). For this reason, the current study specifically investigated the effect of eHMI malfunctions on elderly participants (≥65 years) assessment of the system.

1.5 Research questions and hypothesis

Since previous research reported a benefit of eHMIs for the communication in AVs, these signals seem a promising approach to support prospective interactions between AVs and surrounding traffic participants (Rouchitsas and Alm, 2019). Particularly in shared spaces with ambiguous encounters and diverse traffic participants interacting (Hamilton-Baillie, 2008), eHMIs might potentially support the communication and enhance traffic safety (Habibovic et al. 2018). However, with regard to safety aspects, pedestrians need to be aware of potential eHMI malfunctions (Holländer et al., 2019). Therefore, the current study investigated the effect of eHMI experience and repeated eHMI malfunctions in a shared space scenario. The influence on participants' trust, acceptance, feeling of safety, and vigilance toward the eHMI was examined considering an elderly and a younger age group. Thereby, valid eHMI functions (i.e., match between vehicle's movements and the eHMI signals) and invalid eHMI functions (i.e., mismatch between vehicle's movements and the eHMI signals resulting in system malfunctions) were manipulated across three points of measurement:

- (t0) initial measurement (encountering the eHMI signals without being introduced in the study's scenario of the parking lot as a shared space),
- (t1) measurement with system experience comprising exclusively valid system functions,
- (t2) measurement with system experience comprising valid and invalid system functions.

Thus, the first research question (RQ) addressed within the study is: How does participants' trust in eHMIs develop across the points of measurement (RQ1)? Based on previous findings that reported an increase of users' trust when gaining experience with an eHMI (Faas et al., 2020) and a decline of trust after experiencing system malfunctions (Kaleefathullah et al., 2020), it is assumed that: (H1a) Participants' trust increases after experiencing exclusively valid system functions compared to the initial measurement ($t0 < t1$); (H1b) Participants' trust in eHMIs decreases after experiencing multiple system malfunctions compared to exclusively valid system functions ($t1 > t2$).

The second RQ considers participants' acceptance of the system: How does participants' acceptance of eHMIs develop across the points of measurement (RQ2)? Based on findings by Beggiato and Krems (2013) who reported a decrease of the users' acceptance after experiencing system failures that were not introduced beforehand, it is assumed that (H2): Participants' acceptance in eHMIs decreases after experiencing system malfunctions compared to exclusively valid system functions (t1 > t2).

Furthermore, the current study examined the development of participants' reported feeling of safety and vigilance toward the system as an indicator for participants' awareness of potential eHMI malfunctions after interacting with a valid (t1) and an invalid system (t2). Therefore, the following RQs are investigated: How is participants' feeling of safety affected by eHMI malfunctions (RQ3)? How is participants' vigilance toward the eHMI affected by system malfunctions (RQ4)?

Based on the specific relevance due to the high vulnerability of elderly pedestrians in case of accidents (European Commission, 2021) but also ambiguous findings regarding attitudes of technology acceptance and usage by elderly (Czaja et al. 2006; Schaefer et al. 2016), it is of specific importance to investigate this user group regarding the means of communication between AVs and pedestrians. Thus, younger (18 - 40 years) and elderly participants' (≥65 years) assessment of an eHMI is examined and compared for the different stages of system experience. This leads to the following research question addressed within the study: How do the investigated age groups differ regarding the assessment of the eHMI as potential means of communication in AVs across the different points of measurement (RQ5)?

2 Material and methods

2.1 Research design

The current study investigated the effects of eHMI malfunctions (i.e., a mismatch between implicit communication cues of the vehicle's movements and eHMI signals) on participants' assessment of the system. A 3 (points of measurements, within-subject factor) x 2 (age groups, between-subjects factor) mixed design, with repeated measures on the points of measurements, was applied. The participants repeatedly assessed the system during three points of measurements [initial measurement (t0); after experiencing valid eHMI functions (t1); and after experiencing valid and invalid eHMI functions (t2)]. To investigate age-related differences of the eHMI assessment, participants' age groups (18 - 40 years vs. ≥ 65 years) were applied as a between-subjects variable. The participants indicated their trust in and acceptance of the eHMI (t0 - t2) as well as their feeling of safety during the interaction and the vigilance toward the eHMI (t1 and t2) as dependent variables.

2.2 Material

2.2.1 Video material

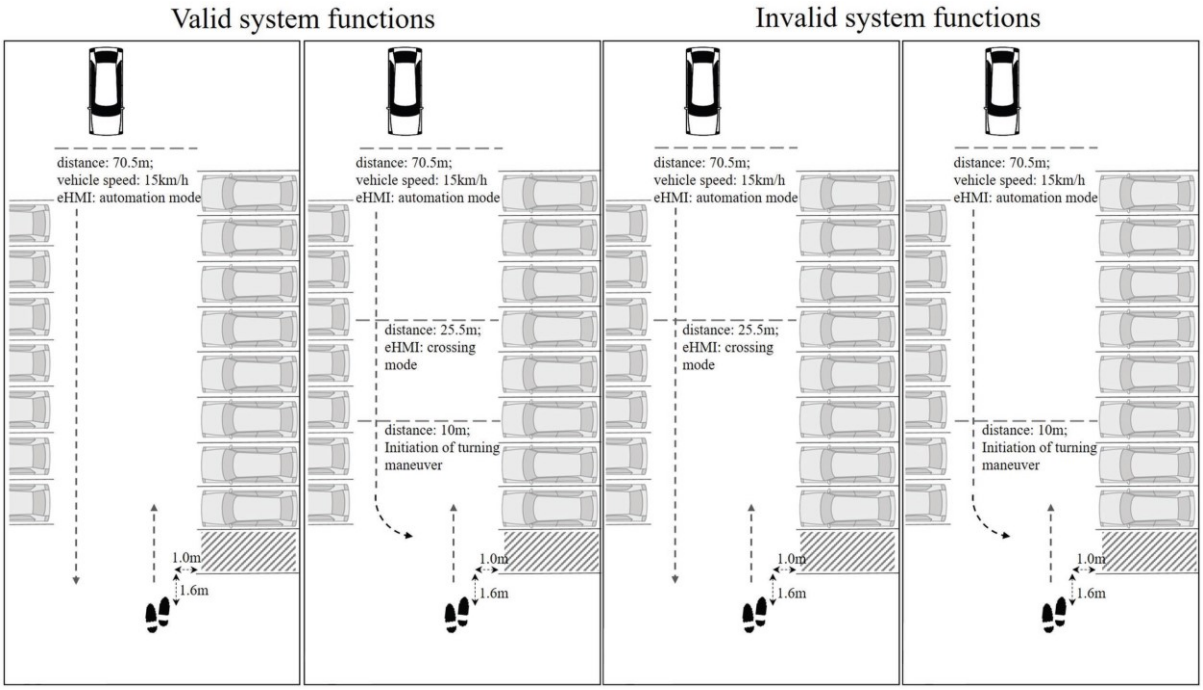
The study applied real-world videos as study material displaying a straight encountering vehicle in a shared space setting. The videos were presented in a simulation environment that allowed for experimental control and standardized instructions. The environment was presented on a 28″ screen to the participants and was programmed in LabView (National Instruments, 2015). The videos were recorded on a parking area of Chemnitz University of Technology (Germany) by a GARMIN VIRB Ultra 30 (1920 × 1080 pixels, 100 fps). The position of the camera was set up to indicate a pedestrian's perspective standing in front of an empty parking space that the participants were instructed intending to cross. To provide a realistic impression of the scenario, the camera was placed on a tripod at a height of 1.70 m in front of an empty parking space (Figure 1). The encountering interaction vehicle (BMW i3) approached with a speed of 15 km/h. A light-based eHMI in cyan color (R = 31/G = 237/B = 255) was augmented in the windscreen of the encountering vehicle with Adobe After Effects (Adobe Inc., 2020). To create valid and invalid eHMI functions, two augmented light-based eHMI signals and two different videos that displayed different trajectories of the approaching vehicle were applied (for an overview of the resulting conditions see Table 1; Figure 1).

With regard to the augmented light-based eHMI, a light bar in the windscreen of the vehicle displayed two abstract signals to the participants (Hensch et al., 2019a):

- Automation mode (screenshot of the signal see Figure 2): the automation mode displayed a steady light signal that intended to indicate that the vehicle was driving automated. In the respective conditions (Table 1), the automation mode was presented during the entire video [Figure 1 (I)].
- Crossing mode (screenshots of the signal see Figure 3): the crossing mode displayed a sweeping light signal that intended to indicate that the vehicle in automation mode would yield and the pedestrian could cross the empty parking space in front of the vehicle. In the respective conditions (Table 1), the automation mode was activated at the beginning of the trials and then switched to the crossing mode signal [Figure 1 (II)].

Figure 1

Schematic overview of the investigated scenario in the parking lot (top view)



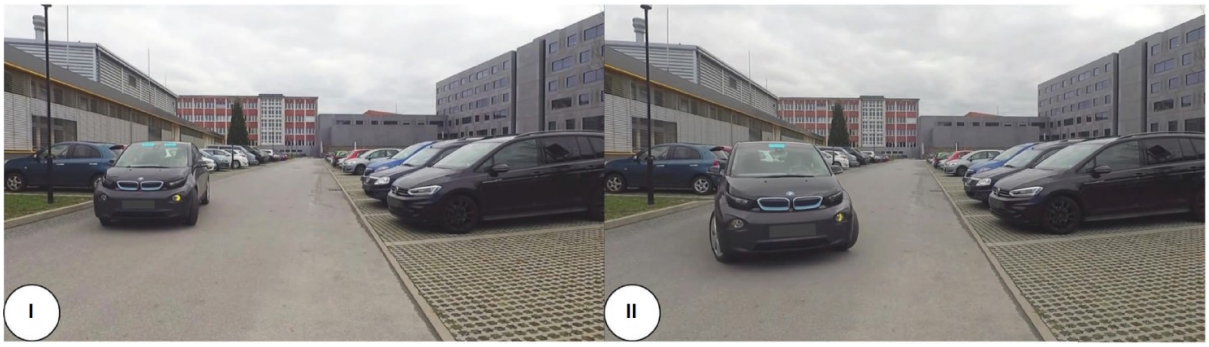
Note. (A) The footprints represent the pedestrians' perspective (i.e., the camera's position), (a) displays the participants' instructed trajectory for crossing the empty parking space (i.e., dashed area). (B) The vehicle indicates the approaching interaction vehicle including an augmented light-based eHMI in the windscreen, (b) displays the respective trajectory of the interaction vehicle that was recorded in the videos. The displayed distances of the interaction vehicle to video start, the transition of eHMI signals (when crossing mode was presented), and the initiation of the turning maneuver are displayed with respect to the camera's position (i.e., the pedestrians' perspective). (I and II) Valid system functions; (III and IV) invalid system functions.

Figure 2

Screenshot of the applied video material displaying the encountering interaction vehicle driving straight ahead the parking lot with the augmented light-based eHMI (signal: automation mode) from the pedestrians' perspective standing in front of an empty parking space the participants were instructed intending to cross

Figure 3

Screenshots of the applied video material displaying the interaction vehicle initiating a left-turn maneuver into the empty parking space in front of the participants with the augmented light-based eHMI (signal: crossing mode) and the activated turn indicator



Note. (I) The interaction vehicle initiated a left-turn maneuver (including deceleration, changes in trajectory, and steering of tires); (II) the interaction vehicle further conducted left-turn maneuver, video stop.

Table 1

Overview of the valid and invalid eHMI functions resulting from the vehicle's movements as implicit communication signals and the eHMI signals

		Vehicle movement	
		Driving straight ahead	Left-turn maneuver
eHMI signal	Automation mode	Valid system function *(F I; see also Figure 1 (I))*	System malfunction *(F IV; see also Figure 1 (IV))*
	Crossing mode	System malfunction *(F III; see also Figure 1 (III))*	Valid system function *(F II; see also Figure 1 (II))*

The moment of transition between automation mode and crossing mode was selected as a trade-off considering an unrealistically early presentation of the crossing mode and providing a sufficient display duration of the signal that participants could recognized the crossing mode signal. When the crossing mode was displayed by the eHMI, the turn signal of the interaction vehicle was activated simultaneously, to act in line with the road traffic regulations and to highlight the initiation of the upcoming left-turn maneuver into the empty parking space.

Both videos started displaying the interaction vehicle approaching to the camera's position (i.e., the pedestrians' position) and either:

- Driving straight ahead: the vehicle went with a constant speed straight ahead the parking lot and passed the pedestrians' position without interfering the instructed hypothetical trajectory of the pedestrian (video duration: 18.95 s; Figure 1 (I); example screenshot of the maneuver see Figure 2) or
- Left-turn maneuver: the vehicle approached and initiated a left-turn maneuver into the empty parking space in front of the camera's position (including changes in trajectory and deceleration), resulting in an overlap of the vehicle's and the pedestrian's hypothetical trajectories. This maneuver would have required the interaction vehicle to stop and give the pedestrian the priority of way to hypothetically cross the parking space in front of the vehicle [video duration: 18.10 s; Figure 1 (II); example screenshots of the maneuver see Figure 3].

Thus, the two light-based eHMI signals and the two movement conditions of the vehicle resulted in the following experimental conditions [for an overview see Figure 1 and Table 1]:

- (F I) Valid system function: eHMI displayed automation mode; vehicle went straight ahead the parking lot [Figure 1 (I)].
- (F II) Valid system function: eHMI displayed automation mode at the beginning of the video, transition to crossing mode and turn signal activated; vehicle initiated left-turn maneuver into empty parking space [i.e., dashed area; Figure 1 (II)].
- (F III) Invalid system function: eHMI displayed automation mode at the beginning of the video, transition to crossing mode and turn signal activated; vehicle went straight ahead the parking lot [Figure 1 (III)].
- (F IV) Invalid system function: eHMI displayed automation mode; vehicle initiated left-turn maneuver into empty parking space [i.e., dashed area; Figure 1 (IV)].

2.2.2 Questionnaires

All questionnaires were presented computer-based. Before the experimental blocks, a questionnaire was applied collecting socio-demographic information, such as participants' specific age and gender. This questionnaire also contained standardized scales collecting participants' affinity for technology interaction (ATI; Franke et al., 2019) and propensity to trust (Körber, 2019). The 9-item affinity for technology interaction scale according to Franke et al. (2019) was used to assess participants' ATI. Participants indicated their agreement to the items on a 6-point Likert scale from [1] *"completely disagree"* to [6] *"completely agree"* that were aggregated to an overall score (Cronbach's α = 0.86). Moreover, participants' propensity to trust was collected with the trust in automation scale (Körber, 2019; subscale: propensity to trust). The participants stated their agreement to the three items on a 5-point Likert scale from [1] *"strongly disagree"* to [5] *"strongly agree."* Afterward, the scores were averaged to an overall score (Cronbach's α = 0.51, which however depicts a rather low reliability; Field, 2009).

To draw a valid picture of the development of participants' assessment of the eHMI, trust, acceptance as well as feeling of safety during the interaction and participants' vigilance toward the eHMI were repeatedly collected. For trust, the trust in automation scale according to Jian et al. (2000) was applied at t0 to t2, comprising 12 items, which were answered on a 7-point Likert scale ranging from [1] *"not at all"* to [7] *"absolutely."* The items were afterward averaged, resulting in an overall trust score (Cronbach's α = 0.86-0.96). Moreover, the Van der Laan acceptance scale (Van Der Laan et al., 1997) was applied during the initial measurement and after each experimental block (t0-t2) since participants' acceptance of the eHMI was investigated during the study. The scale comprises two subscales: The subscale *usefulness*, which covers practical aspects of the system (5 items) and the subscale *satisfaction*, which describes comfort aspects when interacting with the system (4 items, Van Der Laan et al., 1997). Participants indicated their answers to the respective items on a five-

point semantic differential (e.g., useful vs. useless) that was coded from [−2] to [+2] (*usefulness*: Cronbach's α = 0.78–0.91; *satisfaction*: Cronbach's α = 0.78– 0.89). Moreover, participants' feeling of safety during the interaction was collected with a single item measurement at t1 and t2 ("I felt safe when interacting with the vehicle"; adapted from Hensch et al., 2019a). The participants indicated their agreement on a 7-point Likert scale from [1] *"I completely disagree"* to [7] *"I completely agree.* In addition, the vigilance toward the eHMI was collected at t1 and t2 by a single item measurement ("I am vigilant towards the eHMI and its functions"; self-designed) on a scale ranging from [0] *"not at all"* to [100] *"totally."*

2.3 Procedure

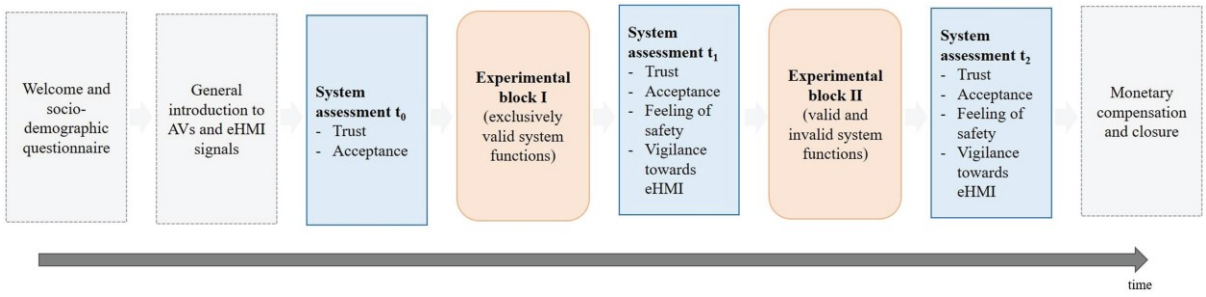
At first, participants were welcomed and informed about the scope of the study. Moreover, informed consent was obtained. Afterward, participants completed an initial questionnaire comprising questions regarding socio-demographics as well as ATI and propensity to trust. Written instructions that contained information about AVs in general and the concept of eHMIs as potential means of communication in AVs were provided to standardize the given information. Additionally, the applied eHMI signals were presented and their general meaning was explained to the participants by pictures and short videos. The written explanations and pictures regarding the meaning of the applied eHMI signals were available during the entire study, so that participants could reassure regarding the signals' meaning. There was no information about potential malfunctions of the eHMI provided to the participants. To ensure for participants' comprehension of the concept of eHMIs, a control questions had to be answered. In case the control question was not answered correctly, participants received an additional explanation about the applied eHMI concept.

In a next step, all participants received a short repetitive explanation of the applied eHMI signals by videos and assessed the eHMI regarding trust and acceptance without any further instructions and without being introduced in the scenario at the parking lot (t0). Then, the scenario of the study in the parking lot was described and participants were instructed to take the perspective of a pedestrian intending to cross an empty parking space in front (Figure 1). The applied eHMI signals (i.e., automation mode and crossing mode) were explained with respect to the specific scenario in the parking lot. To prevent from fatigue, participants were instructed to indicate when they would no longer cross the empty parking space in front of the encountering vehicle by pressing the enter key. Moreover, a potential revision of this decision (i.e., crossing the empty parking space again) could have been also indicated by pressing the enter key again. To provide feedback to the participants regarding the decision, a green or red symbol in the simulation environment displayed the current state of the crossing decision (default setting: crossing the empty parking space, represented by a green symbol). To

become familiarized with the eHMI signals in the parking area scenario and the instructed task, participants experienced six test trials including exclusively valid system functions. Afterward, participants experienced experimental block I comprising 18 randomized trials displaying the oncoming vehicle and the eHMI with exclusively valid system functions of the eHMI (nine trials of each valid system function, respectively; Table 1). Subsequently, participants evaluated the system regarding trust, acceptance, feeling of safety during the interaction and their vigilance toward the eHMI (t1). Again, to support the participants' comprehension of the signals' meanings, they received a reminder of the eHMI signals. Then, experimental block II with further 18 trials followed. Experimental block II comprised twelve valid (six trials of each valid system function, respectively; Table 1) and six invalid system functions (three trials of each type of malfunction, respectively; Table 1). The trails were presented in a balanced, determined order to control for influencing effects on the subsequent system assessment. Again, participants assessed the system afterward regarding trust, acceptance, feeling of safety, and vigilance toward the eHMI (t2). In the end, questions may had arisen were answered and all participants received a monetary compensation of 15€ for contributing to the study, which in sum lasted about one hour. See Figure 4 for an overview of the study's procedure.

Figure 4

Procedure of the current study



2.4 Sample

Since one aim of the current study was to compare the eHMI assessment of different age groups, participants were divided into an elderly (≥ 65 years) and a younger group (18 - 40 years). In total, $N = 37$ participants contributed to the study. Due to answering the control question incorrect, one participant had to be excluded for further analysis. This resulted in a final sample of $n = 36$ participants (19 women, 17 men) across both age groups. In the group of younger participants ($n = 19$), $n = 8$ participants reported that no vision correction was

required, whereas n = 11 participants reported corrected vision. Among the group of elderly participants (n = 17), all participants reported corrected vision. Further details of the sample and both experimental groups are provided in Table 2. To check for the age groups' comparability and to control for other systematic group differences, the ATI scores and propensity to trust scores were compared between the groups. There was no difference for ATI between the age groups [$t(34) = -0.02$, $p = 0.983$, $d = -0.01$]. In addition, there was also no difference in propensity to trust between the two groups [$t(34) = 0.02$, $p = 0.984$, $d = 0.01$].

Table 2

Overview of the sample characteristics

Age group	*N*	*n* female	*n* male	*M* age	*SD* age	*Min* age	*Max* age	M_{ATI} score	SD_{ATI} score	$M_{propensity}$ to trust	$SD_{propensity}$ to trust
Younger participants (18-40 years)	19	12	7	30.47	4.65	23	38	4.22	0.82	3.83	0.74
Elderly participants (≥ 65 years)	17	7	10	71.00	3.87	65	77	4.23	1.02	3.82	0.82

3 Results

In the current study, mixed ANOVAs were applied. The assessment of the eHMI during the initial measurement of the system (t0), after experiencing valid system functions (t1), and after experiencing valid system functions and malfunctions (t2) served as within-subject factors. Participants' age groups were applied as between-subjects factor (younger: 18 - 40 years vs. elderly: ≥ 65 years). Participants' trust in and acceptance of the system, reported feeling of safety during the interaction and vigilance toward the eHMI served as dependent variables. The assumptions for parametric analysis (i.e., normal distribution, homogeneity of variances, and assumption of sphericity) were tested for each dependent variable and were given in most cases. In cases where the assumption of sphericity (Mauchly's test) had been violated ($p < 0.05$), Greenhouse–Geisser corrected (Greenhouse–Geisser $\mathcal{E} \leq 0.75$) or Hyunh-Feldt corrected (Greenhouse–Geisser $\mathcal{E} > 0.75$) F-values and degrees of freedom are reported. Extreme outliers were identified using boxplots (i.e., ≥ three interquartile ranges over the third or under the first quartile). During the visual analysis, two outliers were identified in vigilance

toward the eHMI and were therefore excluded for further analysis. An overview of the ANOVA results can be found in Table 3.

3.1 Trust in automation

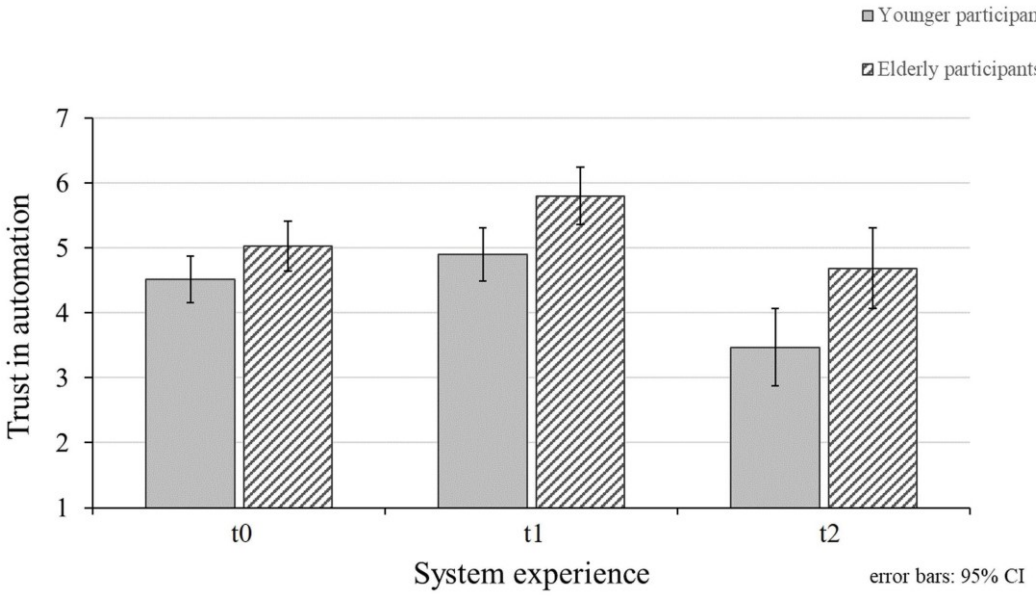
The effect of the initial measurement (t0), after interacting with a valid system (t1), and after experiencing valid and invalid system functions (t2) on participants' trust in the eHMI was examined (RQ1). Figure 5 displays the mean values and standard deviations for participants' trust ratings for the different measurements and for both age groups. The conducted ANOVA revealed significant differences in trust ratings for the points of measurement (Table 3). Participants' initial trust ratings of the eHMI are above the midpoint of the rating scale representing a rather moderate trust in the eHMI (M_{t0} = 4.75; SD_{t0} = 0.81). Data revealed an increase of trust after interacting with a reliable system (M_{t1} = 5.32, SD_{t1} = 0.99; Bonferroni-corrected pairwise comparison t0 and t1: $p < 0.001$), which supports H1a. Moreover, the ratings significantly decreased beyond the initial trust level after experiencing eHMI malfunctions (M_{t2} = 4.04, SD_{t2} = 1.39; Bonferroni-corrected pairwise comparisons t0 and t2: $p = 0.004$; t1 and t2: $p < 0.001$). Therefore, the data support H1b. In addition, a significant effect in trust ratings was found for the age groups (Table 3). In detail, elderly participants indicated significantly higher trust ratings toward the eHMI ($M_{elderly}$ = 5.17, $SD_{elderly}$ = 0.66) than younger participants did ($M_{younger}$ = 4.29, $SD_{younger}$ = 0.85). No significant interaction effect of trust ratings for the different points of measurement and participants' age could be shown (Table 3).

3.2 Acceptance of the eHMI

Participants' acceptance (i.e., comprising the subscales *usefulness* and *satisfaction*) of the eHMI (RQ2) was investigated during the initial measurement (t0), when interacting with the eHMI exclusively comprising valid system functions (t1) and after experiencing valid and invalid system functions (t2). Descriptive measures of participants' acceptance ratings divided by age group are displayed in Figure 6 (subscale *usefulness*) and Figure 7 (subscale *satisfaction*).

Figure 5

Mean values for younger and elderly participants' trust in the eHMI for the points of measurement (t0 = initial measurement; t1 = valid system functions; and t2 = valid and invalid system functions). Higher values represent higher trust ratings

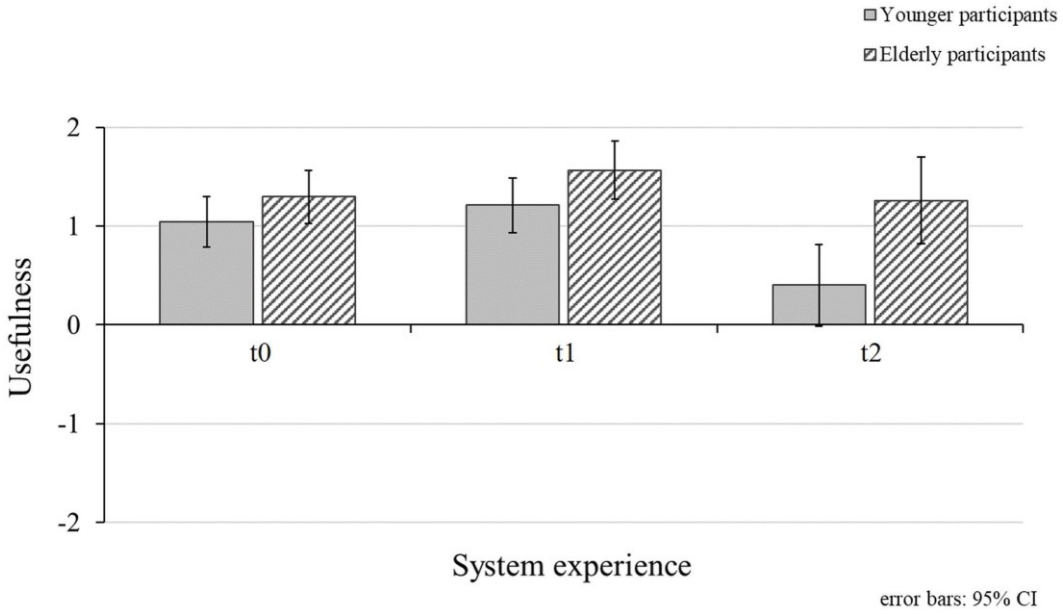


3.2.1 Usefulness

For the eHMI *usefulness* ratings at the different points of measurements, the ANOVA uncovered a significant main effect (Table 3). Participants initially evaluated the investigated eHMI as rather useful (M_{t0} = 1.16; SD_{t0} = 0.55). Post-hoc comparisons (Bonferroni-corrected) showed that the *usefulness* ratings for the eHMI significantly increased when interacting with a valid system (M_{t1} = 1.38; SD_{t1} = 0.61) compared to the initial measurement (t0 and t1: p = 0.036; Bonferroni-corrected). After experiencing invalid system functions, participants' *usefulness* ratings declined significantly in comparison with a valid system (M_{t2} = 0.81; SD_{t2} = 0.98; t1 and t2: p < 0.001; Bonferroni-corrected), which supports H2. However, there was no significant difference in participants' usefulness ratings between the initial measurement and after experiencing system malfunctions (t0 and t2: p = 0.073). The investigated age groups evaluated the eHMI as significantly different regarding its *usefulness* (RQ5; Table 3). Specifically, elderly rated the eHMI as more useful ($M_{elderly}$ = 1.37, $SD_{elderly}$ = 0.60) than younger participants ($M_{younger}$ = 0.88, $SD_{younger}$ = 0.52). In addition, a significant interaction effect was obtained (Table 3). In this context, the stronger decline of younger participants' usefulness ratings after experiencing eHMI malfunction compared to the elderly group should be highlighted (Figure 6).

Figure 6

Mean values for younger and elderly participants' usefulness ratings for the different points of measurement (t0 = initial measurement; t1 = valid system functions; and t2 = valid and invalid system functions). Higher values represent higher usefulness ratings

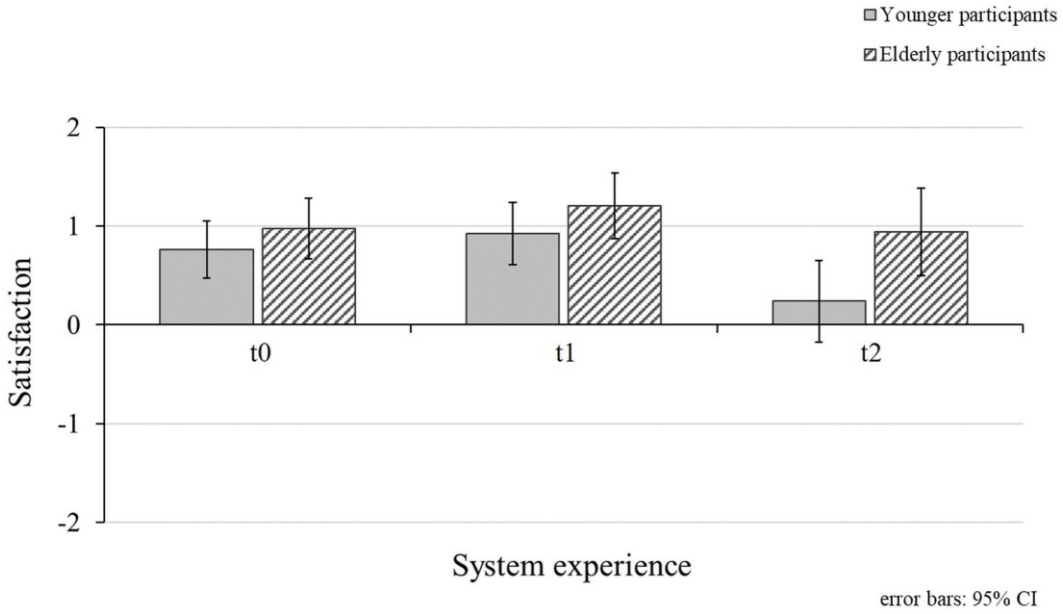


3.2.2 Satisfaction

A significant main effect for participants' *satisfaction* with the eHMI was shown for the different points of measurement (Table 3). Participants assessed the investigated eHMI as rather satisficing during the initial measurement (M_{t0} = 0.86; SD_{t0} = 0.62). Bonferroni-corrected pairwise comparisons revealed a significant decrease of the ratings after experiencing system malfunctions (M_{t2} = 0.57; SD_{t2} = 0.95) compared to valid system functions (M_{t1} = 1.06; SD_{t1} = 0.68; t1 and t2: $p < 0.001$; Bonferroni-corrected). Based on the results, H2 could be confirmed. There was no significant difference in ratings between the other points of measurement (t0 and t1: $p = 0.086$; t0 and t2: $p = 0.131$; Bonferroni-corrected). Participants' age group did not appear to influence the *satisfaction* ratings of the investigated eHMI significantly (RQ5; Table 3). However, there was a significant interaction effect between participants' age group and *satisfaction* ratings for the different measurements (Table 3). Similar to the effect obtained for usefulness, this result was mainly driven by the stronger decline of *satisfaction* scores of younger participants after experiencing invalid eHMI functions compared to the ratings by the elderly participants (Figure 7).

Figure 7

Mean values for younger and elderly participants' satisfaction ratings for the different points of measurement (t0 = initial measurement; t1 = valid system functions; and t2 = valid and invalid system functions). Higher values represent higher satisfaction ratings

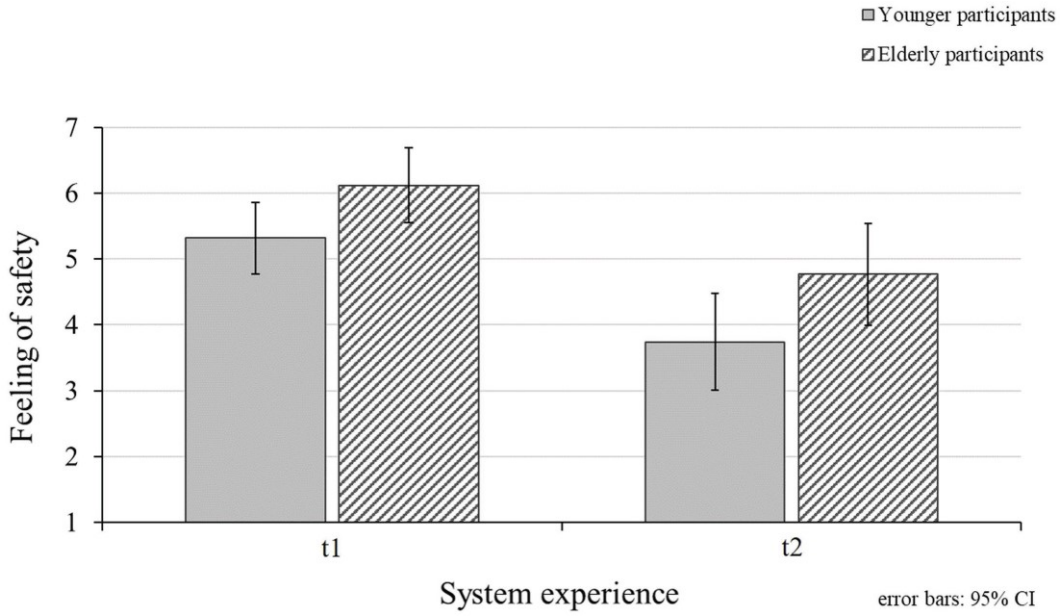


3.3 Feeling of safety during the interaction

Besides assessing the eHMI, participants indicated their feeling of safety during the encounters with the vehicle (RQ3; Figure 8) after interacting with a valid system (t1) and after experiencing invalid eHMI functions (t2). During the interactions with valid system functions, participants indicated to feel rather safe (M_{t1} = 5.69; SD_{t1} = 1.22). However, feeling of safety declined significantly after interacting with an invalid system (M_{t2} = 4.22; SD_{t2} = 1.64; Table 3). Moreover, a significant difference between the age groups for feeling of safety during the encounter with the vehicle was revealed (RQ5; Table 3). In detail, elderly participants indicated a higher feeling of safety during the interactions ($M_{elderly}$ = 5.44, $SD_{elderly}$ = 1.01) compared to younger participants ($M_{younger}$ = 4.53, $SD_{younger}$ = 1.40). There was no significant interaction effect between participants' feeling of safety ratings for the different points of measurements and the investigated age groups (Table 3).

Figure 8

Mean values for younger and elderly participants' feeling of safety ratings during the interaction for the different points of measurement (t1 = valid system functions; t2 = valid and invalid system functions). Higher values represent higher feeling of safety

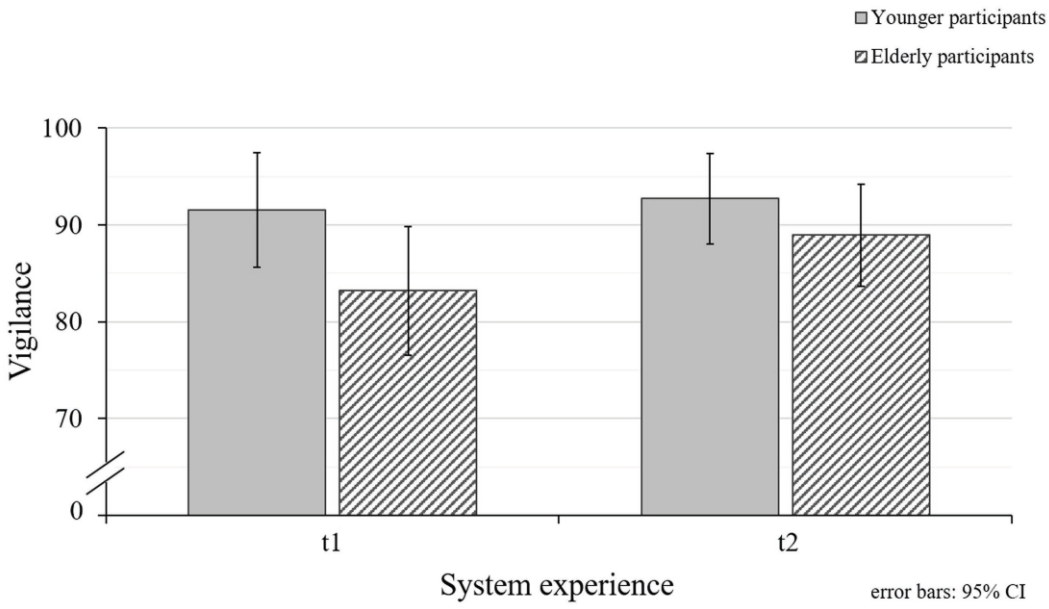


3.4 Vigilance toward the eHMI

In addition, participants' vigilance toward the eHMI (RQ4) was examined after experiencing valid eHMI functions (t1) and after interacting with an invalid system (t2) as an indicator for participants' awareness of potential system malfunctions (RQ4). Generally, participants' indicated to be rather observant regarding the eHMI signals (Figure 9). However, the ratings even increased significantly when experiencing eHMI malfunctions (M_{t2} = 91.06, SD_{t2} = 10.03) compared to valid system functions (M_{t1} = 87.85, SD_{t1} = 13.16; Table 3). The impact of eHMI malfunctions showed to be relevant for both age groups, since there was neither a significant main effect for participants' age groups (RQ5; Table 3) nor an interaction effect between vigilance ratings for the different points of measurement and participants' age groups found (Table 3).

Figure 9

Mean values for younger and elderly participants' vigilance toward the eHMI for the different points of measurement (t1 = valid system functions; t2 = valid and invalid system functions). Higher values represent higher indicated vigilance toward the system



4 Discussion

The present study investigated the effects of eHMI malfunctions (i.e., mismatches between vehicle's movements as implicit communication cues and explicit eHMI signals) on younger and elderly participants' assessment of the system. Previous research reported that participants indicated higher feeling of safety (de Clercq et al., 2019) and trust (Faas et al., 2020) during interactions with AVs when eHMI signals were presented compared to interactions comprising exclusively implicit communication signals. Therefore, participants' overtrust in case of eHMI malfunctions could display a potential safety issue in AVs (Tabone et al., 2021). Due to ambiguous findings regarding elderly users' attitudes toward technology (Czaja et al., 2006; Schaefer et al., 2016), age-related differences of eHMI assessment and potential system malfunctions were investigated within the present study. Participants indicated their trust and acceptance of the eHMI, feeling of safety during the interaction and vigilance toward the eHMI across different points of measurement including valid and invalid system functions. Results showed that participants' assessment of the eHMI increased with experience regarding trust and acceptance (i.e., usefulness ratings) compared to the initial measurement. Participants' trust, acceptance, and feeling of safety declined significantly after experiencing eHMI malfunctions, whereas participants' vigilance toward the eHMI increased after the experienced malfunctions. Moreover, elderly participants indicated significantly

Table 3

Mixed ANOVA results displaying the main and interaction effects of the investigated factors points of measurement (within-subject factor) and participants' age groups (between-subjects factor)

Measurement	Effect	*df1, df2*	*F-value*	*p*	η^2_p
Trust	**Point of measurement [b]**	**1.66, 57.91**	**23.78**	**< .001**	**.400**
	Age group	**1, 34**	**10.73**	**.002**	**.240**
	Point of measurement x age group [b]	1.69, 57.57	1.71	.193	.048
Acceptance: usefulness	**Point of measurement [a]**	**1.43, 50.12**	**11.26**	**< .001**	**.243**
	Age group	**1, 34**	**6.33**	**.017**	**.157**
	Point of measurement x age group [a]	**1.49, 50.80**	**4.54**	**.024**	**.118**
Acceptance: satisfaction	**Point of measurement [b]**	**1.65, 57.60**	**8.69**	**.001**	**.199**
	Age group	1, 34	2.95	.095	.080
	Point of measurement x age group [b]	**1.77, 60.03**	**3.36**	**.047**	**.090**
Feeling of safety	**Point of measurement**	**1, 35**	**49.68**	**< .001**	**.587**
	Age group	**1, 34**	**4.43**	**.043**	**.115**
	Point of measurement x age group	1, 34	0.43	.518	.012
Vigilance towards the eHMI	**Point of measurement**	**1, 33**	**4.89**	**.034**	**.129**
	Age group	1, 32	3.86	.058	.108
	Point of measurement x age group	1, 32	2.89	.099	.083

Note. Statistically significant results are highlighted in bold.

[a]Greenhouse-Geisser corrected degrees of freedom are reported.

[b]Hyunh-Feldt corrected degrees of freedom are reported. *N* = 36.

higher trust, acceptance (i.e., usefulness ratings), and feeling of safety ratings across all conditions compared to younger participants.

Generally, participants assessed eHMI signals as useful means of communication in AVs. This is reflected in rather high levels of trust and acceptance ratings during the initial measurement. The results are in line with previous findings (Rouchitsas and Alm, 2019). As expected, participants' trust in the system increased after interacting with a valid system (H1a), since system experience can be described as an influencing factor of users' *learned trust* according to Hoff and Bashir (2015). Despite a rather short period of achieving system experience in the current study, a similar development was also shown in previous research that included a longer period of three weeks to gain system experience with the investigated eHMI (Faas et al., 2020). However, participants' trust and acceptance ratings of the system declined significantly when experiencing eHMI malfunctions as an additional component of *learned trust* (Hoff and Bashir, 2015). In line with the assumptions and previous studies

considering eHMI malfunctions in crossing scenarios (Kaleefathullah et al., 2020; Faas et al., 2021), participants indicated lower trust ratings when experiencing invalid system functions (H1b). The current study applied a shared space scenario that comprised lower speed levels of the interaction vehicle. Therefore, implicit communication cues, such as the vehicle's deceleration, might be more difficult to recognize due to lower encountering speeds and thus lower speed differences during deceleration maneuvers. However, despite the lower speed levels, participants seem to be sensitive regarding mismatches of implicit communication cues and eHMI signals. This awareness might potentially be necessary in shared space settings due to ambiguous encounters and a diversity of traffic participants that need to interact (Hamilton-Baillie, 2008).

As expected, participants' acceptance of the eHMI as means of communication in AVs also declined significantly after experiencing invalid system functions that were not announced beforehand compared to exclusively valid system functions (H2). The investigated eHMI malfunctions might be comparable to omitted system failures of driving assistance systems as investigated by Beggiato and Krems (2013). The authors reported a decline of users' acceptance when experiencing omitted system failures (Beggiato and Krems, 2013), as also shown in the current study with eHMI malfunctions. On the other hand, participants' acceptance ratings remained rather moderate despite experiencing multiple eHMI malfunctions in the current study.

In addition, eHMI malfunctions also impaired participants' feeling of safety during the interaction with the vehicle (RQ3). The results are in line with findings by Holländer et al. (2019) and developed similar to participants' trust and acceptance ratings of the eHMI. Moreover, the participants indicated rather high vigilance ratings toward the eHMI, even when experiencing exclusively valid system functions. Moreover, the vigilance ratings increased after experiencing eHMI malfunctions (RQ4). This might be constituted in reduced trust in the eHMI due to the experienced malfunctions (Lee and See, 2004). The participants seem to be aware of additional monitoring requirements resulting in increased vigilance ratings in case of eHMI malfunctions to ensure traffic safety (Warm et al., 2008).

Regarding age effects (RQ5), an overall impact in terms of generally higher trust and perceived usefulness ratings, as one aspect of users' acceptance, in the eHMI was found for elderly compared to younger participants. Moreover, elderly participants indicated a higher feeling of safety during the interaction with the vehicle. The results are in line with previous studies that reported higher trust ratings (Schaefer et al., 2016) and a more positive attitude toward automated systems of elderly users compared to younger users (Hartwich et al., 2019; Hensch et al., 2019b). However, within the current study, there were no differences in satisfaction ratings, as another factor of acceptance, between the investigated age groups.

The result might be related to a general low intuitiveness of the applied eHMI signals that required an acquisition of the signals' meanings (Hensch et al., 2019a). Considering repeated malfunctions of the eHMI, elderly participants indicated a tendency of overreliance in the eHMI. In particular, elderly participants still indicated higher trust and acceptance ratings (i.e., usefulness ratings) than younger participants when evaluating the eHMI after experiencing malfunctions. In addition, elderly users also indicated higher feeling of safety during the interaction with the vehicle when experiencing an invalid eHMI than younger users did. Despite experiencing repeated malfunctions of the eHMI, elderly participants adjusted their acceptance assessment of the system less when experiencing malfunctions, which was also shown for elderly users' trust adjustment in previous research considering an automated decision aid (Ho et al., 2005). One explanation might be given by declines in working memory capacity of elderly (Salthouse, 1992). For the system assessment that was conducted block wise after 18 trails respectively, information about the frequency of malfunctions needed to be integrated in a mental representation of the system and recalled from working memory. Moreover, elderly may have difficulty in interpreting stochastic information, such as the probability of valid system functions and system malfunctions. Considering these aspects, the block wise system assessment might have led to a more positive assessment of the system by elderly participants (i.e., overestimating valid system functions in the overall mental representation of the system, since more trials displayed valid eHMI functions; Ho et al., 2005). Prospective studies should therefore collect participants' assessment of the system in case of malfunctions in shorter time intervals (e.g., after each single trial) to prevent from distortion of the system assessment. It should be noted that participants of the current study did not perform ability checks (e.g., sensory and cognitive ability checks) that could support the given explanations of the current findings. However, the results are worrisome, since elderly pedestrians might be particularly imperiled by eHMI malfunctions, including possible safety issues, that are constituted in longer response and execution times to conduct actions in traffic scenarios (Stelmach and Nahom, 1992). Therefore, further studies are necessary to gain more information about the rationales of the obtained effects.

For ethical and safety reasons and to standardize the data collection process, the current study was conducted as a laboratory study with a therefore rather limited external validity. Moreover, the participants' task to indicate their hypothetical crossing decisions by pressing a button to prevent from fatigue might have been rather artificial. It should be also mentioned that the current study neither conducted manipulation checks that controlled for participants' adequate responses during the interaction with the investigated eHMI signals nor collected additional explanations for participants' decisions to cross or not to cross. Therefore, the collection of additional behavioral measures, corresponding assessments, and

explanations would be of interest in further studies. Moreover, the current study investigated two types of eHMI malfunctions that differed in the resulting criticality for pedestrians' safety. In particular, the investigated malfunction F IV potentially impaired traffic safety, since the trajectories of the vehicle and the pedestrian hypothetically overlapped. Whereas malfunction F III did not directly impair traffic safety, since the participants' instructed intention to cross the parking space was not compromised by the vehicle's driving behavior (i.e., movement straight ahead the parking lot) or the displayed eHMI signal (i.e., crossing mode). Thus, the revealed declines in participants' trust, acceptance, and feeling of safety ratings might be mainly driven by the examined safety critical malfunctions (i.e., F IV). However, even the experience of not directly safety relevant eHMI malfunctions might have affected the assessment and interaction with eHMIs to some extent, for instance in terms of a general acceptance and feeling of safety, since the participants experienced an unreliable system (Lee and Moray, 1992). When investigating the effects of malfunctions on participants' eHMI assessment in further studies, the effect of safety critical malfunctions and non-critical malfunctions should be considered in a between-subjects design. In addition, the development of users' system assessment over additional points of measurement, such as trust recovery, should prospectively be considered.

The findings of the current study showed that participants seem to be generally sensitive regarding eHMI malfunctions. Participants adjusted their assessment of the system due to the experienced malfunctions of the system. Since the vehicle's driving behavior also represented a source of information in form of a dynamic HMI (Bengler et al., 2020), the results imply that participants considered the vehicle's motion behavior as implicit communication cues in addition to the provided eHMI signals during the encounters with the vehicle. When applied as means of communication in AVs, eHMI signals are required to be in line with vehicle's movements as implicit communication signals to benefit of the additional signals that could enhance traffic safety and support the interaction with surrounding traffic participants (Tabone et al., 2021). Moreover, the additional explicit signals could improve pedestrians' situational awareness by supporting the predictability of prospective driving maneuvers conducted by the encountering AV (Endsley, 1995; Habibovic et al., 2018). To support traffic safety, an appropriate level of trust in eHMI signals, preventing for distrust and also overtrust, needs to be calibrated even system malfunctions are rare events (Lee and See, 2004). An appropriate system usage could be supported by preliminary information about the signals' meanings. For instance, providing detailed information about the specific meaning of the applied eHMI signals can facilitate surrounding traffic participants to detect system malfunctions. Additional information, provided by eHMI signals, might also support the system's transparency, which in turn could support traffic safety and the users' acceptance of AVs (Faas et al., 2021).

5 CONCLUSION

EHMIs offer the potential to support the interaction between AVs and pedestrians (Habibovic et al. 2018). However, potential eHMI malfunctions cannot be excluded in AVs (Holländer et al., 2019). With regard to traffic safety, pedestrians need to be aware of potential failures and are required to react appropriately by considering the vehicles' implicit driving cues as a source of information in case of eHMI malfunctions. The findings of the current study imply that participants considered the vehicle's movements as implicit communication cues in addition to the provided eHMI signals in case of malfunctions, which is reflected in an adjusted assessment of the eHMI system. Thus, to support traffic safety and smooth interactions with surrounding traffic participants, eHMI signals are required to be in line with the vehicle's movements as implicit communication signals when applied as means of communication in AVs (Tabone et al. 2021). Moreover, the results underline the importance of calibrating an appropriate level of trust and expectations in eHMI signals among traffic participants. Thereby, the requirements of different user groups, such as elderly pedestrians, should be specifically considered. In order to develop an adequate understanding of the system, preliminary information about eHMI signals need to be provided if the systems are applied in AVs (Faas et al., 2021).

Data availability statement

The datasets presented in this article are not readily available because of the involvement of project partners and required confidentiality of data within the project. Requests to access the datasets should be directed to A-CH, ann-christin.hensch@ psychologie.tu-chemnitz.de.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

Author contributions

A-CH: conceptualization, methodology, formal analysis, investigation, writing-—original draft, and visualization. IK: conceptualization, methodology, formal analysis, investigation, writing—original draft, writing—review and editing, visualization, and supervision. MB: conceptualization, methodology, software, investigation, writing—original draft, writing—review and editing, and supervision. JK: investigation, writing—review and editing, supervision, and project administration. All authors contributed to the article and approved the submitted version.

Funding

The research was funded by the Bundesministerium für Verkehr und digitale Infrastruktur (BMVI, German Federal Ministry of Transport and Digital Infrastructure; grant no 16AVF2016A) - project “InMotion - Light-based communication between automated vehicles and other road users”; and by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) - Project-ID 416228727—SFB 1410.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

6 REFERENCES

Ackermann, C., Beggiato, M., Schubert, S., and Krems, J. F. (2019). An experimental study to investigate design and assessment criteria: what is important for communication between pedestrians and automated vehicles? *Appl. Ergon.* 75, 272–282. doi: 10.1016/j.apergo.2018.11.002

Adobe Inc. (2020). *Adobe After Effects.* Adobe Inc. PC.

Beggiato, M., and Krems, J. F. (2013). The evolution of mental model, trust and acceptance of adaptive cruise control in relation to initial information. *Transport. Res. F: Traffic Psychol. Behav.* 18, 47–57. doi: 10.1016/j.trf.2012.12.006

Bengler, K., Rettenmaier, M., Fritz, N., and Feierle, A. (2020). From HMI to HMIs: towards an HMI framework for automated driving. *Information* 11, 61. doi: 10.3390/info11020061

Böckle, M.-P., Brenden, A. P., Klingegård, M., Habibovic, A., and Bout, M. (2017). "SAV2P: exploring the impact of an interface for shared automated vehicles on pedestrians' experience." in *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*; September 24–27, 2017.

Clark, H. H., and Brennan, S. E. (1991). "Grounding in communication," in *Perspectives on Socially Shared Cognition*. eds. L. B. Resnick, J. M. Levine and S. D. Teasley (American Psychological Association), 127–149. doi: 10.1037/10096-006

Czaja, S. J., Charness, N., Fisk, A. D., Hertzog, C., Nair, S. N., Rogers, W. A., et al. (2006). Factors predicting the use of technology: findings from the center for research and education on aging and technology enhancement (create). *Psychol. Aging* 21, 333–352. doi: 10.1037/0882-7974.21.2.333

Czaja, S. J., and Sharit, J. (1998). Age differences in attitudes toward computers. *J. Gerontol. – Series B Psychol. Sci. Soc. Sci.* 53, P329–P340. doi: 10.1093/ geronb/53B.5.P329

de Clercq, K., Dietrich, A., Velasco, J. P. N., de Winter, J., and Happee, R. (2019). External human-machine interfaces on automated vehicles: effects on pedestrian crossing decisions. *Hum. Factors* 61, 1353–1370. doi: 10.1177/0018720819836343

Dey, D. and Terken, J. (2017). "Pedestrian interaction with vehicles: roles of explicit and implicit communication." in *AutomotiveUI 2017 - 9th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications, Proceedings*; September 24–27, 2017.

Dunbar, G., Holland, C. A., and Maylor, E. A. (2004). Older pedestrians: a critical review of the literature. Road Safety Research Report. (Department for Transport: London,

2004). Available at: https://publications.aston.ac.uk/id/eprint/24396/1/Older_pedestrians.pdf

Endsley, M. R. (1995). Toward a theory of situation awareness in dynamic systems. *Hum. Factors* 37, 32–64. doi: 10.1518/001872095779049543

European Commission (2020). Facts and Figures Pedestrians. European Road Safety Observatory. (Vias institute and SWOV Institute for Road Safety Research, 2020). Available at: https://ec.europa.eu/transport/road_safety/system/ files/2021-07/facts_figures_pedestrians_final_20210323.pdf

European Commission (2021). Road Safety Thematic Report – Fatigue. (Vias institute and SWOV Institute for Road Safety Research, 2021). Available at: https://ec.europa.eu/transport/road_safety/system/files/2021-07/asr2020.pdf

Faas, S. M., Kao, A. C., and Baumann, M. (2020). "A longitudinal video study on communicating status and intent for self-driving vehicle - pedestrian interaction." in *CHI'20: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*; April 25–30, 2020.

Faas, S. M., Kraus, J., Schoenhals, A., and Baumann, M. (2021). "Calibrating pedestrians' Trust in Automated Vehicles." in *CHI'21: Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*; May 8–13, 2021.

Faas, S. M., Mathis, L.-A., and Baumann, M. R. (2020). External HMI for self-driving vehicles: which information shall be displayed? *Transport. Res. F: Traffic Psychol. Behav.* 68, 171–186. doi: 10.1016/j.trf.2019.12.009

Field, Andy. (2009). *Discovering Statistics Using Spss*. Thousand Oaks: Sage Publications.

Franke, T., Attig, C., and Wessel, D. (2019). A personal resource for technology interaction: development and validation of the affinity for technology interaction (ATI) scale. *Int. J. Hum.-Comput. Interact.* 35, 456–467. doi: 10.1080/10447318.2018.1456150

Ghazizadeh, M., Lee, J. D., and Boyle, L. N. (2012). Extending the technology acceptance model to assess automation. *Cognit., Technol. Work* 14, 39–49. doi: 10.1007/s10111-011-0194-3

Habibovic, A., Lundgren, V. M., Andersson, J., Klingegård, M., Lagström, T., Sirkka, A., et al. (2018). Communicating intent of automated vehicles to pedestrians. *Front. Psychol.* 9:1336. doi: 10.3389/fpsyg.2018.01336

Hamilton-Baillie, B. (2008). Towards shared space. *Urban Des. Int.* 13, 130–138. doi: 10.1057/udi.2008.13

Hartwich, F., Witzlack, C., Beggiato, M., and Krems, J. F. (2019). The first impression counts – a combined driving simulator and test track study on the development of trust and acceptance of highly automated driving. *Transport. Res. F: Traffic Psychol. Behav.* 65, 522–535. doi: 10.1016/j.trf.2018.05.012

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., and Krems, J. F. (2019a). Effects of a light-based communication approach as an external HMI for automated vehicles – a wizard-of-Oz study. *Trans. Transport Sci.* 10, 18–32. doi: 10.5507/TOTS.2019.012

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., and Krems, J. F. (2019b). "Steady, flashing, sweeping – an exploratory evaluation of light signals as an EHMI in automated driving." in *HFES Europe Chapter Annual Meeting - Understanding Human Behavior in Complex Systems*; October 2–4, 2019.

Ho, G., Kiff, L. M., Plocher, T., and Haigh, K. Z. (2005). "A model of trust and reliance of automation technology for older users." in *AAAI Fall Symposium: Caring Machines*; November 3–6, 2005.

Ho, G., Wheatley, D., and Scialfa, C. T. (2005). Age differences in trust and reliance of a medication management system. *Interact. Comput.* 17, 690–710. doi: 10.1016/j.intcom.2005.09.007

Hoff, K. A., and Bashir, M. (2015). Trust in Automation: integrating empirical evidence on factors that influence trust. *Hum. Factors* 57, 407–434. doi: 10.1177/0018720814547570

Holländer, K., Wintersberger, P., and Butz, A. (2019). "Overtrust in external cues of automated vehicles: An experimental investigation." in *AutomotiveUI'19: Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*; September 22–25, 2019.

Jian, J.-Y., Bisantz, A. M., and Drury, C. G. (2000). Foundations for an empirically determined scale of trust in automated systems. *Int. J. Cogn. Ergon.* 4, 53–71. doi: 10.1207/S15327566IJCE0401_04

Kaleefathullah, A. A., Merat, N., Lee, Y. M., Eisma, Y. B., Madigan, R., Garcia, J., et al. (2020). External human–machine interfaces can be misleading: an examination of trust development and misuse in a CAVE-based pedestrian simulation environment. *Hum. Factors*. doi: 10.1177/00187208209 70751

Körber, M. (2019). "Theoretical considerations and development of a questionnaire to measure trust in automation." in *Proceedings of the 20th Congress of the International*

Ergonomics Association. IEA 2018. Advances in Intelligent Systems and Computing; August 26–30, 2018.

Körber, M., Schneider, W., and Zimmermann, M. (2015). “Vigilance, boredom proneness and detection time of a malfunction in partially automated driving.” in *2015 International Conference on Collaboration Technologies and Systems, CTS 2015*; 1–5 June 2015.

Krems, J. F., and Baumann, M. R. (2009). “Driving and situation awareness: a cognitive model of memory-update processes.” in *Lecture Notes in Computer Science*; July 19-24, 2009.

Lee, J. D., and Moray, N. (1992). Trust, control strategies and allocation of function in human-machine systems. *Ergonomics* 35, 1243–1270. doi: 10.1080/00140139208967392

Lee, J. D., and See, K. A. (2004). Trust in automation: designing for appropriate reliance. *Hum. Factors* 46, 50–80. doi: 10.1518/ hfes.46.1.50_30392

Lundgren, V. M., Habibovic, A., Andersson, J., Lagström, T., Nilsson, M., Sirkka, A., et al. (2017). “Will there be new communication needs when introducing automated vehicles to the urban context?” in *Advances in Human Aspects of Transportation. Advances in Intelligent Systems and Computing*; July 27–31, 2016.

Merat, N., Louw, T., Madigan, R., Wilbrink, M., and Schieben, A. (2018). What externally presented information do VRUs require when interacting with fully automated road transport systems in shared space? *Accid. Anal. Prev.* 118, 244–252. doi: 10.1016/j.aap.2018.03.018

Muir, B. M., and Moray, N. (1996). Trust in automation. Part II. Experimental studies of trust and human intervention in a process control simulation. *Ergonomics* 39, 429–460. doi: 10.1080/00140139608964474

National Instruments (2015). *LabView*. National Instruments. PC.

Nordhoff, S., Kyriakidis, M., van Arem, B., and Happee, R. (2019). A multi-level model on automated vehicle acceptance (MAVA): a review-based study. *Theor. Issues Ergon. Sci.* 20, 682–710. doi: 10.1080/1463922X.2019. 1621406

Othersen, I., Conti-Kufner, A. S., Dietrich, A., Maruhn, P., and Bengler, K. (2018). “Designing for automated vehicle and pedestrian communication: perspectives on EHMIs from older and younger persons.” in *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2018 Annual Conference*; October, 8-10, 2018.

Polders, E., Brijs, T., Vlahogianni, E., Papadimitriou, E., Yannis, G., Leopold, F., et al. (2015). Eldersafe risk and countermeasures for road traffic of elderly in Europe. ElderSafe:

final report. (European Commission. Directorate general for mobility and transport, 2015). Available at: http://ec.europa.eu/transport/road_safety/pdf/studies/eldersafe_final_report.pdf

Portouli, E., Nathanael, D., and Marmaras, N. (2014). Drivers' communicative interactions: on-road observations and modelling for integration in future automation systems. *Ergonomics* 57, 1795–1805. doi: 10.1080/00140139. 2014.952349

Rasouli, A., and Tsotsos, J. K. (2019). Autonomous vehicles that interact with pedestrians: a survey of theory and practice. *IEEE Trans. Intell. Transp. Syst.* 21, 900–918. doi: 10.1109/TITS.2019.2901817

Rödel, C., Stadler, S., Meschtscherjakov, A., and Tscheligi, M. (2014). "Towards autonomous cars: the effect of autonomy levels on acceptance and user experience." in *AutomotiveUI'14: Proceedings of the 6th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*; September 17–19, 2014.

Rouchitsas, A., and Alm, H. (2019). External human-machine interfaces for autonomous vehicle-to-pedestrian communication: a review of empirical work. *Front. Psychol.* 10:2757. doi: 10.3389/fpsyg.2019.02757

SAE International's new standard J3016 (2018). Levels of Driving Automation. SAE International. 2018.

Salthouse, T. A. (1992). Why do adult age differences increase with task complexity? *Dev. Psychol.* 28, 905–918. doi: 10.1037/0012-1649.28.5.905

Schaefer, K. E., Chen, J. Y. C., Szalma, J. L., and Hancock, P. A. (2016). A meta-analysis of factors influencing the development of trust in automation: implications for understanding autonomy in future systems. *Hum. Factors* 58, 377–400. doi: 10.1177/0018720816634228

Schieben, A., Wilbrink, M., Kettwich, C., Madigan, R., Louw, T., and Merat, N. (2019). Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognit., Technol. Work* 21, 69–85. doi: 10.1007/s10111-018-0521-z

Schindler, J., Herbig, D. L., Lau, M., and Oehl, M. (2020). "Communicating issues in automated driving to surrounding traffic." in *HCI International 2020 – Late Breaking Posters. HCII 2020. Communications in Computer and Information Science*; July 19–24, 2020.

Stelmach, G. E., and Nahom, A. (1992). Cognitive-motor abilities of the elderly driver. *Hum. Factors* 34, 53–65. doi: 10.1177/001872089203400107

Tabone, W., de Winter, J., Ackermann, C., Bärgman, J., Baumann, M., Deb, S., et al. (2021). Vulnerable road users and the coming wave of automated vehicles: expert perspectives. *Transport. Res. Interdisc. Perspect.* 9:100293. doi: 10.1016/j.trip.2020.100293

Van Der Laan, J. D., Heino, A., and De Waard, D. (1997). A simple procedure for the assessment of acceptance of advanced transport telematics. *Transport. Res. Part C: Emerg. Technol.* 5, 1–10. doi: 10.1016/S0968-090X(96)00025-3

Venkatesh, V., Morris, M. G., Davis, G. B., and Davis, F. D. (2003). User acceptance of information technology: toward a unified view. *MIS Q.* 27, 425–478. doi: 10.2307/30036540

Warm, J. S., Parasuraman, R., and Matthews, G. (2008). Vigislance requires hard mental work and is stressful. *Hum. Factors* 50, 433–441. doi: 10.1518/001872008X312152

Wilde, G. J. S. (1976). Social interaction patterns in driver behavior: an introductory review. *Hum. Factors: J. Hum. Factors Ergon. Soc.* 18, 477–492. doi: 10.1177/001872087601800506

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PUBLICATIONS

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Hensch, A.-C., Kreißig, I., Beggiato, M., & Krems, J. F. (2022). The effect of eHMI malfunctions on younger and elderly pedestrians' trust and acceptance of automated vehicle communication signals. *Frontiers in Psychology, Section Human-Media Interaction, 13*. https://doi.org/10.3389/fpsyg.2022.866475

Hensch, A.-C., Rauh, N., Schmidt, C., Hergeth, S., Naujoks, F., Krems, J. F., & Keinath, A. (2020). Effects of secondary tasks and display position on glance behavior during partially automated driving. *Transportation Research Part F: Traffic Psychology and Behaviour, 68*, 23–32. https://doi.org/10.1016/j.trf.2019.11.014

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems J. F. (2019). Effects of a light-based communication approach as an external HMI for Automated Vehicles — a Wizard-of-Oz Study. *Transactions on Transport Sciences, 10*(2)*,* 18–32. https://doi.org/10.5507/tots.2019.012

CONFERENCE CONTRIBUTIONS

Hensch, A.-C., Beggiato, M., & Krems, J. F. (2023). Comparing accepted gaps in traffic flow for conducting left turn actions in different intersection scenarios - A driving simulator study. In D. de Waard, V. Hagemann, L. Onnasch, A. Toffetti, D. Coelho, A. Botzer, M. de Angelis, K. Brookhuis, & S. Fairclough (Eds.), *Proceedings of the Human Factors and Ergonomics Society Europe Chapter 2023 Annual Conference* (pp. 83–94). Online. http://hfes-europe.org.

Hensch, A.-C., Beggiato, M., Mandl, S., Strobel, A., & Krems, J. F. (2022). The interplay of personality traits with drivers' gap acceptance. In K. Plant & G. Praetorius (Eds.), *Human Factors in Transportation. AHFE (2022) International Conference. AHFE Open Access (vol. 60)* (pp. 329–337). AHFE International. doi:10.54941/ahfe10024641.

Hensch, A.-C., Beggiato, M., & Krems J. F. (2022). Should I wait or should I go? - Deciphering Implicit Communication Cues for Cooperative Interactions in Left-Turn Scenarios. In

2022 IEEE International Conference on Computational Intelligence & Virtual Environments for Measurement Systems and Applications (CIVEMSA), Chemnitz, Germany (pp. 1–5). doi: 10.1109/CIVEMSA53371.2022.9853676

Hensch, A.-C., Kreißig, I., Beggiato, M., & Krems, J. F. (2022). The effects of eHMI failures on elderly participants' assessment of automated vehicle communication signals. In Ahram T. & Taiar R. (Eds.), *Human Interaction, Emerging Technologies and Future Systems V. IHIET 2021. LNNS 319* (pp. 355–363). Springer. https://doi.org/10.1007/978-3-030-85540-6_45

Hensch, A.-C., Beggiato, M., Schömann, M. X., & Krems, J. F. (2021). Different types, different speeds – The effect of interaction partners and encountering speeds at intersections on drivers' gap acceptance as an implicit communication signal in automated driving. In H. Krömker (Ed.), *HCI in Mobility, Transport, and Automotive Systems. HCII 2021. Lecture Notes in Computer Science*, *vol 12791. LNCS 12791* (pp. 517–528). Springer. https://doi.org/10.1007/978-3-030-78358-7_36

Hensch, A.-C., Beggiato, M., Krems, & J. F. (2021). Predicting lane changes by identifying sequence patterns of implicit communication cues. In N. Stanton (Ed.), *Advances in Human Aspects of Transportation. AHFE 2021. LNNS 270* (pp. 3–10). Springer. https://doi.org/10.1007/978-3-030-80012-3_1

Kreißig, I., Hensch, A.-C., Beggiato, M., Halama, J., & Krems J. F. (2021). Enlightening communication – An exploratory study on light-based signals in automated driving. *Proceedings of the 7th HUMANIST Conference, Rhodes, Greece*. ISBN 978-2-9531712-6-6. https://www.humanist-vce.eu/_files/archives/ace9ed_64d1f0cf8a164dd185a50e52238fa1a4.zip?dn=Rhodes-2021.zip

Hensch, A.-C., Beggiato, M., & Krems J. F. (2021). Drive safely and comfortably – Gap Acceptance as a Basis for a user-centred Design of Driving Styles in Automated Vehicles. *Proceedings of the 7th HUMANIST Conference, Rhodes, Greece*. ISBN 978-2-9531712-6-6. https://www.humanist-vce.eu/_files/archives/ace9ed_64d1f0cf8a164dd185a50e52238fa1a4.zip?dn=Rhodes-2021.zip

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems J. F. (2020). How should automated vehicles communicate? – Effects of a light-based communication approach in a Wizard-of-Oz study. In: N. Stanton (Ed.), *Advances in Human Factors of Transportation. AHFE 2019. Advances in Intelligent Systems and Computing (vol. 964)* (pp. 79–91). Springer. https://doi.org/10.1007/978-3-030-20503-4_8

Hensch, A.-C., Halama, J., Ackermann, C., Beggiato, M., Neumann, I., & Krems, J. F. (2018). Kommunikation zwischen Fußgängern und Fahrzeugen. Querungsintentionen und Interaktionsverhalten im Niedriggeschwindigkeitsbereich [Communication between pedestrians and vehicles. Crossings and interactions in a shared space setting]. In VDI (Eds.), *Fahrerassistenzsysteme und automatisiertes Fahren 2018 [Driver Assistance Systems and Automated Driving], VDI-Berichte 2335* (pp. 323–336). VDI-Verlag GmbH. ISBN 978-3-18-092335-2.

Hensch, A.-C., Rauh, N., Schmidt, C., Hergeth, S., Naujoks, F., Krems, J. F., & Keinath, A. (2018). Effects of secondary tasks and display position on glance behavior during partially automated driving. In N. Van Nes & C. Voegelè (Eds.), *Proceedings of the 6th HUMANIST Conference* (pp. 40–45). Humanist Publications. ISBN 978-2-9531712-5-9.

OTHER (ABSTRACTS, POSTER, ETC.)

Hess, S., Hensch, A.-C., Beggiato, M., & Krems, J. F. (2023, September 21-22). *Effects of rearward displays in highly automated shuttles on following traffic* [Poster presentation]. HUMANIST Conference, Berlin, Germany. https://www.tu-chemnitz.de/hsw/psychologie/professuren/fgaap/media/230922_Poster_humanist.pdf

Beggiato, M., Hensch, A.-C., & Krems, J. F. (2022). Sollen automatisierte Fahrzeuge bei Dämmerung Manöverentscheidungen anpassen, um sich erwartungskonform zu verhalten? [Should automated vehicles adapt their maneuvering decisions during twilight to provide intuitive driving behavior?]. In S. Malejka, M. Barth, H. Haider, & C. Stahl (Eds.), *Abstracts of the 64th Conference of Experimental Psychologists* (pp. 216-217). Pabst Science Publishers. ISBN: 978-3-95853-768-2.

Hensch, A.-C., Kreißig, I., Beggiato, M., & Krems, J. F. (2022, April 20-22). *To trust or not to trust - Comparing two trust in automation scales when assessing an external HMI in automated vehicles* [Poster presentation]. Annual Meeting of the Human Factors and Ergonomic Society Europe Chapter, Turin, Italy. https://www.hfes-europe.org/wp-content/uploads/2022/04/PosterAnn-ChristinHensch2022.pdf

Kreißig, I., Hensch, A.-C., Beggiato, M., Krems, J., Wolter, S., Pahlke, D. (2021). *Abschlussbericht InMotion - Entwicklung von lichtbasierten Kommunikationskonzepten zwischen automatisierten Fahrzeugen und anderen Verkehrsteilnehmern [Final report InMotion – Development of light based*

communication concepts between automated vehicles and other traffic participants]. Technische Universität Chemnitz. doi:10.2314/KXP:1750576813

Beggiato, M., Hensch, A.-C., & Krems, J. (2021). "Hey automatisiertes Fahrzeug: park mich sicher und komfortabel ein ohne andere zu irritieren." Weglückenakzeptanz als Basis menschzentrierter automatisierter Fahrstile [„Hey automated vehicle: park me safe and comfortable without irritating others.“ Gap acceptance as a basis for human-centered driving styles]. In A. Huckauf, M. Baumann, M. Ernst, C. Herbert, M. Kiefer, & M. Sauter (Eds.)*, Abstracts of the 63th Conference of Experimental Psychologists*. Pabst Science Publishers. ISBN: 978-3-95853-694-4.

Hensch, A.-C., Beggiato, M., & Krems J. F. (2020). Better safe than sorry – Gap Acceptance related to Participants' Age, Vehicle Types and Speed. In C. Dobel, C. Giesen, L. A. Grigutsch, J. Kaufmann, G. Kovács, F. Meissner, K. Rothermund, & S. R. Schweinberger (Eds.), *Abstracts of the 62nd Conference of Experimental Psychologists* (p. 95). Pabst Science Publishers. https://dryfta-assets.s3.eu-central-1.amazonaws.com/assets/teap2020/eventdocs/1583451218Abstracts_TeaP2020.pdf

Neumann, I., Hensch, A.-C., Beggiato, M., Halama, J., Krems, J. F. (2019). Einleuchtend?! Evaluation lichtbasierter Kommunikation zwischen automatisierten Fahrzeugen und anderen Verkehrsteilnehmern [Plausible?! An evaluation of light-based communication signals between automated vehicles and other traffic participants]. In M. Vollrath & Deutsche Gesellschaft für Psychologie (Eds.), *"Mehr Mensch im Verkehr?" [Human and Traffic]: 3. Kongress Fachgruppe Verkehrspsychologie, Saarbrücken* (p. 25). Universitätsbibliothek Braunschweig.

Hensch, A.-C., Neumann, I., Beggiato, M., Halama, J., & Krems, J. F. (2019, October 2-4). *Steady, flashing, sweeping – An exploratory evaluation of light signals as an eHMI in automated driving* [Poster presentation]. Annual Meeting of the Human Factors and Ergonomic Society Europe Chapter, Nantes, France. doi:10.13140/RG.2.2.33925.29922

EIDESSTATTLICHE ERKLÄRUNG

Hiermit erkläre ich, Ann-Christin Hensch, geb. 29.08.1992 in Gera, dass ich die vorliegende Arbeit selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel verwendet habe.

Ann-Christin Hensch

Chemnitz, 03.11.2023