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Increasing Acceptance Through Design: Review of Evaluation Methods for Interaction Design in Mixed Traffic

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Abstract: Communication in mixed traffic can have a major influence on the acceptance of automated vehicles (AV). In order to gain the deep trust of road users, it is not enough to consider individual factors in the development of external human-machine interfaces (eHMI). A holistic view of the design is necessary, which also includes vehicle design and aesthetics. To identify requirements and suitable methods for design evaluation, this paper presents an overview of eHMI evaluation methods based on an analysis of 40 papers. Using criteria such as study settings, stimulus patterns and deficits, recommendations for further research on the development and evaluation of eHMI are derived. The current study highlights the narrow perspective in existing research on eHMI, revealing a more holistic view on the topic. By including the vehicle design and its evaluation in the design of eHMI, the acceptance of automated vehicles in mixed traffic could be increased.

Keywords: eHMI, Automated Vehicle, Mixed Traffic, Automotive Design Engineering, Acceptance of Automated Vehicles

1 Introduction

Automated driving is currently a highly researched field with the potential to profoundly impact road traffic. The introduction of automated vehicles (AV) poses new challenges for all involved parties. Experts predict that achieving full traffic automation will take several years, if not decades (Tabone et al., 2021). During the transition phase towards full automation, a mixed traffic environment emerges, comprising both automated and non-automated vehicles, along with other (vulnerable) road users. In this mixed traffic, conflict situations are inevitable. They can be addressed through communication and interaction methods. However, traditional interaction among road users is expected to undergo significant changes due to the drivers in automated vehicles being out-of-the-loop (temporary), eliminating crucial non-verbal communication channels (e.g., gestures, facial expressions or eye contact) between road users. To address this emerging communication gap, researchers and developers are working on external Human-Machine Interfaces (eHMI).

eHMI aims to facilitate communication between automated vehicles and surrounding road users. Issues such as pedestrian crossings, right-of-way questions at intersections, or narrow passages can be resolved through this communication. The effectiveness and reliability of this new interaction method play a crucial role in gaining acceptance among novel automated road users (Habibovic et al., 2019; Lau et al., 2022; Lim and Kim, 2022). Trust in automation and the associated behavior of human road users are pivotal for the future of automated vehicles. If automated vehicles fail to sustainably gain the trust, particularly of vulnerable road users, achieving market penetration and the path to fully autonomous traffic may become challenging. Ensuring acceptance beyond early adopters and reaching a broad audience is crucial.

Various factors influence the acceptance of automated vehicles, both positively and negatively (Habibovic et al., 2019). These factors have been predominantly explored from psychological and technical perspectives.

Psychologically, the focus is on the manner (e.g., Ackermann et al., 2019; Eisma et al., 2023; Guo et al., 2022; Colley and Rukzio, 2020) and content of communication (e.g., Faas et al., 2020; Schieben et al., 2019; Colley and Rukzio, 2020; Dey et al., 2022) that can enhance trust in automated vehicles. Key questions include: What information should eHMI convey? When and how should it be displayed for maximum clarity? What perspective should the information take? All of these aspects influence trust-building and can quickly ruin trust in automated vehicles and thus their acceptance in case of malfunction or suboptimal solutions.

Meanwhile, from a technical perspective, the focus is primarily on the placement on the vehicle (Ackermann et al., 2019; Eisma et al., 2020; Guo et al., 2022; Lingam et al., 2023), implementation using LED strips (e.g., Benderius et al., 2018; Eisma et al., 2023; Faas et al., 2020; Horn et al., 2023; Wilbrink et al., 2021), or displays (e.g., Holländer et al., 2019; Joisten et al., 2020; Rettenmaier et al., 2020), as well as vehicle behavior (e.g., Dey et al., 2019; Ekman 2020; Miller et al., 2022), which can be seen as implicit communication (Lau et al., 2022). Technical implementation involves critical points to ensure the function and consistency of external communication. However, the design of the vehicle, including the design of eHMI and its integration into the vehicle exterior, significantly contributes to trust-building and acceptance (Gadermann et al., 2023a; Fischer et al., 2023). The aesthetics of a product influence its acceptance (Schiekofer and Weber, 2020), and the design already shapes users' attitudes towards the product or vehicle even before use (Reichelt et al., 2020;

Mandel et al., 2015). Due to this preconditioning of the users, induced by vehicle design, eHMI should also be considered from the perspective of vehicle design and aesthetics.

This aspect has been underexplored. While design studies and visions from Original Equipment Manufacturers (OEMs) showcase integrated displays or LED strips (Bazilinskyy et al., 2019; Dey et al., 2020a), they lack scientific description and evaluation. The first prototypes or production vehicles such as the Audi Q6 e-tron (Audi AG, 2023) or the Hiphi-Z (Human Horizons, 2021) include external communication displays. However, crucial scientific insights from the perspective of industrial design engineering or automotive design engineering are missing to combine knowledge from psychology, ergonomics, technology, and design. Synthesizing knowledge from all these domains allows for statements on optimizing and aesthetically integrating eHMI into vehicle design. The goal of vehicle design should be to enhance acceptance of automated vehicles through consistent, understandable, and clear communication, while preserving the aesthetics of the vehicles. The significant impact of design must necessarily be considered in the psychological and technical design of eHMI. We are therefore pursuing an in-depth investigation into the integration of the design and its evaluation.

To conduct a meaningful design evaluation, appropriate evaluation methods are required. This article presents a detailed meta-study based on a literature review to provide an overview of common evaluation methods for eHMI and communication in mixed traffic. We examined various studies with regard to selected factors and compared the possibilities of the evaluation methods. The result identifies deficiencies and optimization potential for design evaluation and derives well-founded recommendations for further research on the design and design integration of eHMI. The contribution aims to provide a structured list of suitable evaluation methods for evaluating eHMI design while demonstrating how targeted design can increase acceptance of this communication form and, consequently, automated vehicles in mixed traffic.

2 Related Research

The current state of technology and relevant research is explored, with a focus on the connection between eHMI and vehicle design. In their classification taxonomy on design principles of eHMI, Dey et al. (2020a) have already gathered some knowledge about the state of the art in research and technology. This taxonomy systematically presents research work on eHMI, examining and classifying 70 eHMI concepts across 18 different dimensions. The authors present extensively researched areas such as communication strategy, HMI placement, or the nature of messages, as well as less explored factors like special needs communication or addressing multiple road users. The conclusion drawn is that there is still considerable disagreement in the design of eHMI, with no optimal solution identified in many areas (Dey et al., 2020a).

Regarding vehicle design, Dey et al. (2020a) provide insights relevant to this contribution. The fidelity levels of examined concepts vary widely and are generally low. Furthermore, there is a dependency of eHMI design on vehicle design, which, according to past studies (see Dey et al., 2019), makes interaction in mixed traffic even more tentative in futuristic vehicle designs. Due to the significant impact of vehicle design on the interaction of automated vehicles with pedestrians (see Dey et al., 2019), the authors emphasize the importance of incorporating vehicle design into the consideration of the external interface design (Dey et al., 2020a).

Ekman (2020) identifies factors influencing trust in automated vehicles, including information about the personality of the automated vehicle. The vehicle's exterior design is decisive for creating an acceptance-promoting overall appearance, providing the vehicle with character (Schiekofer and Weber, 2020). Anthropomorphism is another way to increase trust and acceptance by giving the vehicle a personality (Ekman, 2020). This can be implemented through the design of eHMI and vehicle exteriors, such as integrating moving eyes (Chang et al., 2017; Jaguar Land Rover, 2018). Thus, trust in automation and the acceptance of automated vehicles can be influenced by the design of the vehicle.

However, studies directly describing the integration of eHMI into the exterior of automated vehicles are limited. Gadermann et al. (2023a) compare methods of integrating eHMI in the exterior-design and their interaction with visible sensors using an eye-tracking study. Similarly, Ackermans et al. (2020) investigate the effects of eHMI with noticeable exteriors featuring visible sensors on pedestrian behavior in a VR study. Presentation methods of stimulus patterns are of great importance in design-focused studies, as they can influence evaluations (Janotta, 2023; Reid, 2013). Therefore, the following literature review presents possible evaluation methods and presentation styles of eHMI concepts, considering deficiencies and recommendations from the authors.

3 Methods

To gain an overview of potential evaluation methods for external Human-Machine Interfaces (eHMI), this contribution presents a literature review. Publications encompassing evaluations of eHMI concepts were compiled through scoping literature research, focusing on fundamental works in the eHMI domain. Employing a snowball approach, starting from foundational papers, a pre-selection of 70 papers was made on the research question: “How can eHMI be evaluated?”. The following criteria were then applied to assess their relevance for this meta-study:

- Evaluation of an eHMI-concept,
- Scientific study, no OEM concept presentation,
- Description of the evaluation (study setting, vehicle type, point of view (POV), scenario),
- Visualisation of the stimulus pattern available,
- Up to date: 2017 or newer.

From this filtering, 40 papers were identified as relevant and used for the meta-study. The selected study sample represents a cross-section of relevant literature regarding the evaluation possibilities of eHMI concepts. For further examination, the following analysis categories were used to analyze the selected papers:

1. **Author(s):** Who are the contributors of the paper?
2. **Year:** When was the paper published?
3. **Title:** What is the title of the publication?
4. **Study Setting:** What type of study design was used in the paper for evaluation? (Online survey, online interview, real study dynamic/static, VR study dynamic/static, screen study dynamic/static, driving simulator study dynamic/static)
5. **Vehicle Type:** What type of vehicle was examined in the evaluation? (Car, truck, shuttle, bus)
6. **POV:** What perspective does the participant take in the study for the evaluation of eHMI? (Pedestrian, cyclist, driver of a manually controlled vehicle (MV), …)
7. **Scenario:** Which scenario was investigated in the evaluation? (Road-crossing, signal-less intersection, parking lot, narrow passage, ...)
8. **Content/Objective:** What is examined in the study or what is the goal of the study?
9. **Stimulus Pattern:** How were the stimulus patterns visualized? → Analysis of visualization on positioning, representation, and design integration.
10. **Deficiencies:** What deficiencies are mentioned in the publication in terms of limitations and in the outlook for future research? What improvements in studies are recommended for further research on the evaluation of eHMI?

The 40 selected papers were examined based on the mentioned criteria, and the results were documented in a tabular form. The quality and extent of the results depend on the level of detail provided in the paper. Similarly, the analysis of visualization depends on the graphics of stimulus patterns included in the paper. All insights gained in the meta-study are thus based on the respective representations and information from the original papers. The following section presents the results of the meta-analysis graphically and evaluates them.

4 Results

In this meta-analysis, evaluations of eHMI concepts were examined with regard to the methods used. The following section presents and describes the results of the analyses of the above-mentioned criteria for the following 40 papers examined: Ackermann et al., 2019; Ackermans et al., 2020; Bauer, 2021; Bazilinskyy et al., 2023; Bazilinskyy et al., 2019; Böckle et al., 2017; Bonneviot et al., 2023; Burns et al., 2019; Chang et al., 2017; Clamann et al., 2017; Clercq et al., 2019; Colley et al., 2023; Colley et al., 2020a; Colley et al., 2020b; Dey et al., 2022; Dey et al., 2021a; Dey et al., 2021b; Dey et al., 2020b; Dey et al., 2020c; Eisma et al., 2023; Eisma et al., 2020; Faas et al., 2020; Gadermann et al., 2023a; Guo et al., 2022; Hensch et al., 2022; Hoggenmueller et al., 2022; Holländer et al., 2019; Horn et al., 2023; Hübner et al., 2022; Joisten et al., 2021; Joisten et al., 2020; Lau et al., 2022; Lim and Kim, 2022; Lingam et al., 2023; Loew et al., 2022; Mahadevan et al., 2018; Rettenmaier et al., 2020; Troel-Madec et al., 2019; Verstegen et al., 2021; Wilbrink et al., 2021.

The most frequently utilized **study setting**, see Figure 1, is the dynamic VR study (11). The advantages of this approach lie in the straightforward design of reproducible and immersive scenarios, with a cost-effective implementation of the respective eHMI concepts. The virtual environment enables the dynamic animations of eHMI, moving vehicles, pedestrians, and other road users. The second most used method is the online survey (9), providing a simple and economical way to conduct studies with questionnaires and, if applicable, video sequences, reaching a large number of users quickly and independent of location. The third most employed type of study is the dynamic screen study (8), which offers similar advantages to VR simulation without the need for expensive hardware. However, screen studies may compromise on immersion or realism. Dynamic real studies (8) were used as frequently as dynamic screen studies. Real studies represent the evaluation approach with the highest level of realism but are also associated with high effort and costs, not least due to the use of real prototypes. Static screen studies (2), static real studies (1), and studies in static driving simulators (1) were rarely utilized.

In terms of **vehicle type**, it is evident that the majority of studies investigate eHMI on passenger cars, as shown in Figure 1. In this case, passenger cars were examined 37 times, once in comparison to a bus. Additionally, there were studies involving trucks (1) and shuttles (2). A similar clarity emerges when considering the **POV** of the studies, as depicted in Figure 2. In 39 out of 40 studies considered, an investigation from the perspective of a pedestrian was conducted, with the pedestrian view being the sole perspective in 35 cases. Four studies examined both the pedestrian perspective and the perspective from a manually controlled vehicle (MV), while one study focused additionally on the perspective of a cyclist and one of a passenger. A single study exclusively explored the perspective from a manually controlled vehicle. A clear pattern also emerges regarding the **scenario**, as shown in Figure 2. In the 40 studies examined, the road-crossing scenario was investigated 32 times, with 29 instances being exclusive to this scenario. In eleven studies, scenarios deviated from road-crossing or complemented the investigation with additional scenarios, such as static examination of eHMI from the sidewalk (3), scenarios at intersections (2), or in parking lots (2). One study examined 20 different scenarios, including road-crossing. This is listed separately under “various scenarios”.

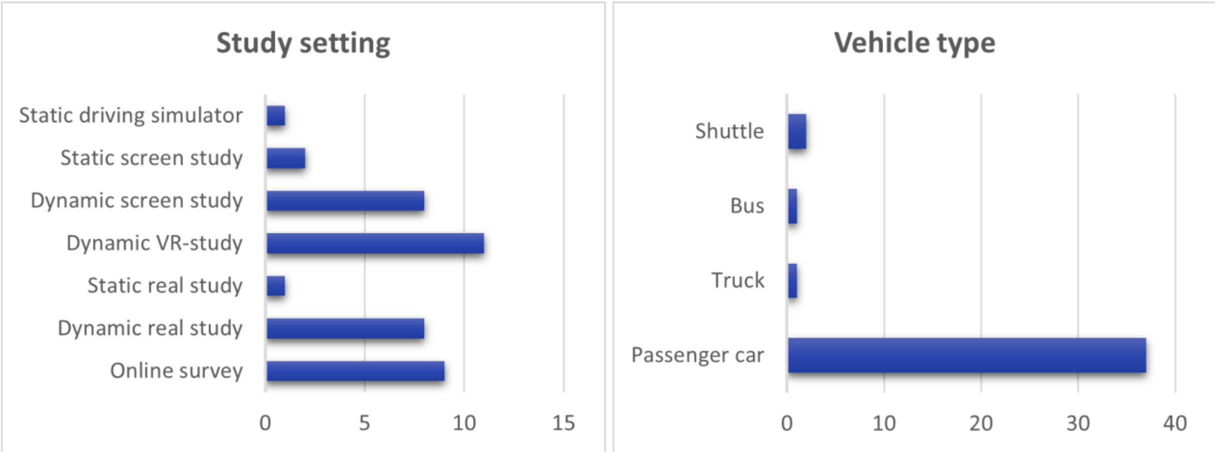

Figure 1. Study settings used and vehicle types examined

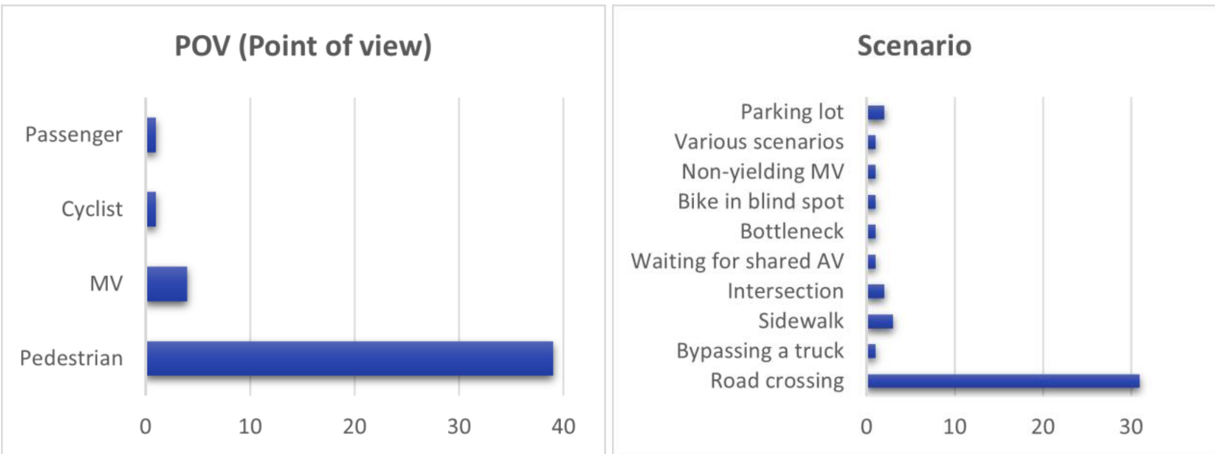

Figure 2. Perspectives taken and scenarios used

The **content** of the studies is distributed almost equally among three major thematic areas, as depicted in Figure 3. Firstly, the impact of eHMI on the interaction between automated vehicles and pedestrians (14) is explored. This involves investigating whether eHMI, as a form of explicit communication, positively influences decision-making during planned road crossings in terms of timing or content. Pedestrian behavior is a focal point, as well as their perception of safety and trust in automated vehicles. The second examined thematic area focuses on the design of eHMI on the vehicle (14). This includes attention to positioning, technical implementation (LED strip vs. display), color, and modality. Additionally, the emphasis is on the content of information—what the vehicle should display or convey in various situations. The third examined thematic area deals with the evaluation of developed eHMI concepts (11). In this area, eHMI concepts previously developed are tested for their suitability in participant trials. Questions about visibility, comprehensibility, and clarity are frequently examined. Only one paper in the selected sample of the meta-analysis primarily addresses the importance of exterior vehicle design in eHMI development. Gadermann et al. (2023a) investigate the integration of eHMI into vehicle design and the resulting interactions with visible sensors. Statements about visible sensors can also be found in the publication by Ackermans et al. (2020).

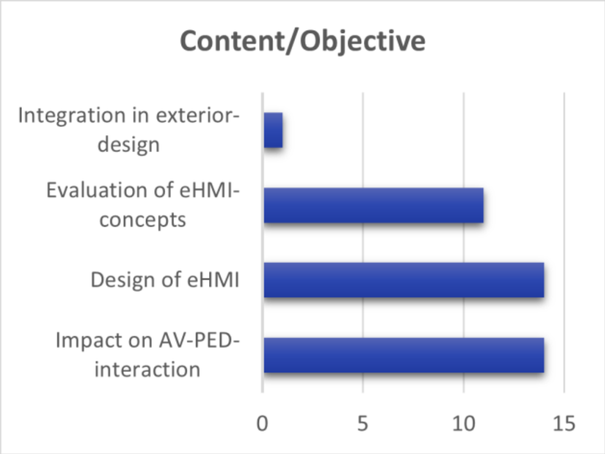

Figure 3. Content of the analysed studies

As part of the analysis, the **stimulus patterns** used in the studies were also examined. Statements in this regard are based on the visualizations provided in the papers. The analysis results of visual eHMI were cumulatively transferred to a neutral vehicle to make overarching statements. The vehicle is shown in Figure 4. Upon examination, it is noticeable that most concepts pertain to the front of the vehicle. This can be attributed to the scenarios examined, mostly road-crossing scenarios where pedestrians see the approaching vehicle from the front. Some studies also consider positioning on the side, on the door area, or on the roofline. However, eHMI is predominantly located on and around the grille or the windshield. Few concepts are also placed on the roof or projected onto the road in front of the vehicle. Significant gaps are found on the hood and on the side mirrors. Possible reasons for this could be the high variability in the shape of the hood or the current elimination of side mirrors due to camera systems.

From a design perspective, the analysis reveals a lack of integration of concepts into the overall design. A generally low fidelity level is evident in the concepts, often added to the existing vehicle form. This applies to displays, which are typically mounted additively on the vehicle exterior. LED strips are also often added to existing joints or design lines. Only in digital concepts, such as in VR studies, the integration of displays into the existing grille can be observed. However, no emphasis was placed on the saliency of eHMI. The integration of eHMI-concepts into the exterior-design or a holistic new vehicle design with eHMI was almost neglected. This will be important in the future, as the exterior of the vehicle, especially the proportions of the bodywork, have changed constantly and will change more in the future. (see Holder, 2021).

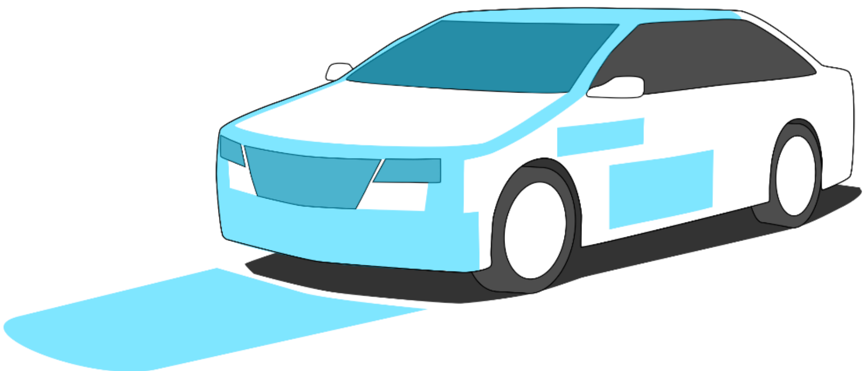

Figure 4. Neutral vehicle with eHMI positioning of the analysed stimulus patterns

When examining the outlooks and limitations of the analyzed papers, statements regarding optimization needs and further research requirements can be made. To gain an overview of frequently mentioned improvements and demands, the identified **deficiencies** were analyzed for their frequency of mention and categorized. The results are illustrated in Figure 5. The explicit demand for more reality (18) or a more realistic study setting is particularly common. According to the findings, this is attributed to the circumstances that, on the one hand, simulations (e.g., VR simulations or videos) do not fully approach reality in terms of immersion. On the other hand, the chosen scenarios and situations in the simulation do not fully approximate reality. In a similar vein, there are calls for more or more complex scenarios (9), increased traffic (6), more realistic or natural environmental conditions (13), such as lighting and weather conditions, and scalability or multi-user settings (16) with multiple participants. This applies to both more vehicles and more human participants in the scenario.

To consider more individuality in human factors (12) in the studies, such as age, gender, origin, culture, or faith, several authors recommend conducting studies with a broader and more diverse participant group (5). This recommendation explicitly applies to the inclusion of people with disabilities (4) and, relatedly, to multimodal eHMI concepts (4). In general, further research (13) in various areas of communication is recommended. The findings of the papers analysed do not yet contain optimal eHMI solutions that are helpful, clearly understandable, and unambiguous for all users (see e.g, Dey et al., 2020a). This includes demands for more empirical data and additional evaluation methods. From a technical perspective, many authors also suggest placing further focus on the design (6) in terms of displaying text or symbols, coloration, or the necessary content (see e.g., Dey et al., 2021a; Gadermann et al., 2023a; Verstegen et al., 2021). Due to the lack of consensus on the positioning of eHMI (5), further investigations should also be conducted in this area. The examination of the influence of vehicle design (6) is also mentioned multiple times, reinforcing the necessity of the mentioned design consideration.

Less frequently but still repeatedly demanded are studies on malfunctions and limits of eHMI (4), the driving behavior of automated vehicles (3), as well as bidirectional communication (3). Additionally, there is a call for the consideration of habituation and learning effects in long-term studies (3) and recommendations for the standardization of eHMI (3) across manufacturers and national borders.

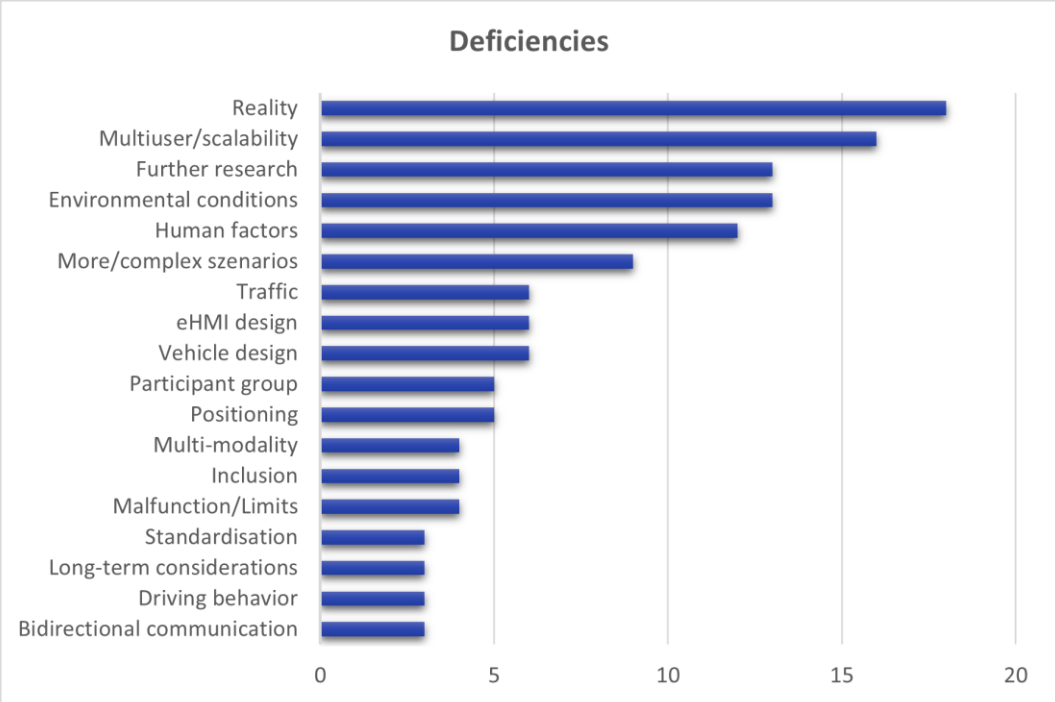

Figure 5. Deficits mentioned in the limitations and outlooks

5 Discussion and limitations

Considering the results of the conducted meta-analysis, it becomes evident that previous evaluations in the field of eHMI predominantly focus on the interaction between automated passenger cars and pedestrians in the scenario of road crossing from the pedestrian's perspective. Similar observations were made by Dey et al. (2020a). The limited number of users in the studies and consequently the lack of studies with multi-user scenarios are also confirmed. Although there are emerging approaches that address multi-user scenarios and their effects on the evaluation of eHMI concepts (Colley et al., 2023; Dey et al., 2021; Hübner et al., 2022; Verstegen et al., 2021; Wilbrink et al., 2021; Miller et al., 2022), the deficiencies identified in the analyzed studies make it clear that the topic of multi-user scenarios in realistic traffic situations has not been adequately explored.

Multi-user traffic scenarios enhance the reality of evaluations. However, solely introducing multiple users to the evaluation environment is insufficient to achieve a higher level of realism. About half of the analyzed papers explicitly call for more reality in scenarios, while others indirectly address more realistic traffic conditions or environmental settings. According to the analyzed papers, more realistic lighting and weather conditions, natural environments, and increased traffic with additional persons and vehicles are essential for more accurate results (see e.g., Ackermann et al., 2019; Ackermans et al., 2020; Dey et al., 2020c; Horn et al., 2023; Rettenmaier et al., 2020). How exactly such scalability is achieved remains open, apart from a few recommendations from scalability studies (Colley et al., 2023; Dey et al., 2021). Real environmental and presentation conditions, lighting conditions, and scenarios are crucial for a design evaluation as well (Reid et al., 2013; Oberhofer, 2021; Gadermann et al., 2023b). Thus, to ensure comprehensive acceptance of automated vehicles, ways must be found to increase realism in studies while maintaining reproducibility.

Based on the results of the meta-study, general deficiencies in current research can also be identified. The focus of the studies conducted so far is too narrow. The examination of conventional passenger cars should be expanded. A comprehensive examination of trucks and buses is just as important for further research as the inclusion of novel vehicle designs. The question also arises whether eHMI is really only relevant for automated vehicles or whether non-automated vehicles could also benefit from an external interface for explicit communication. The overly restrictive focus of current research on few or almost only one scenario, the pedestrian road-crossing scenario, is also not sustainable and effective. Alongside manually controlled vehicles, other traffic stakeholders should be included, such as cyclists, scooter, or motorcycle riders. Each of these road users has different communication requirements in mixed traffic (see Dey et al., 2020a). Paired with the individuality of each person and the inclusion of older individuals, children, or people with disabilities, a large field of unresolved questions emerges, far beyond current research.

Upon critical examination, this meta-analysis is not without limitations. The selected papers do not claim to be exhaustive in representing the state of the art in eHMI science. The selection provides a cross-section of currently available studies on the evaluation of eHMI concepts and demonstrates their impact on communication in mixed traffic. The examined perspectives are shaped by the field of Human Factors. Additional publications with different focuses would expand the insights of this study and strengthen its validity. A detailed view from the perspective of OEMs' vehicle design would be highly interesting for this purpose. Unfortunately, comprehensive, scientific descriptions of design studies and visions from vehicle manufacturers are not very common or publicly accessible. Insights into the design processes at OEMs and the associated decisions regarding the design of vehicles and HMI are also limited (Reichelt et al. 2023). The present study offers recommendations from the perspective of automotive design engineering for further evaluation. It emphasizes the need for empirical studies in real environments, as described by Dey et al. (2020a). Furthermore, this study underscores the importance of realistic environment design even in simulated settings. The study particularly highlights the necessity of a holistic approach to ensure the acceptance of automated vehicles and their communication forms in mixed traffic.

6 Conclusion and future work

In general, it can be noted that eHMI is predominantly studied from psychological and technical perspectives in research. The conducted meta-study provides evidence that a viewpoint from automotive design engineering is rarely or not at all considered. Additionally, many studies only examine individual aspects, lacking a comprehensive analysis of eHMI with a focus on design and its interaction with other vehicle components such as sensors or lighting. With the absence of a realistic environment, a meaningful design assessement of eHMI in vehicle exteriors seems nearly impossible at the current state of research. So far, statements can only be made from a technical-functional perspective or evaluations of content comprehensibility on a psychological level. However, design evaluation is crucial to make further statements about the design of eHMI from an aesthetic point of view. The aspects of design and the associated acceptance of automated vehicles are of great importance for designing eHMI. Design features contribute to gaining a holistic view for the optimal design of eHMI. Accordingly, they should be considered equally in development and research on communication in mixed traffic, alongside psychological and technical factors.

In further research, we aim to investigate how eHMI can be evaluated more realistically and holistically. To achieve a realistic visualization of concepts without necessarily relying on real prototypes, it should be clarified which parameters of visualization need to be adjusted to efficiently enhance the quality of representation (see Gadermann et al., 2023b). It is also important to understand which sub-factors of eHMI design influence perception, quality, and trust-building to improve them systematically. With knowledge about the various sub-factors of design, the concept development of eHMIs can be scientifically optimized. Conducting studies on design evaluation, considering all necessary factors, in an immersive environment with realistic visualization is crucial. Following this, statements can be made about the impact of vehicle design on the acceptance of automated vehicles with eHMI, and design recommendations from the perspective of automotive design engineering can be provided.

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