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Interaction between automated vehicles and other road users

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Interaction between automated vehicles and other road users

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Editorial: Interaction between automated vehicles and other road users

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Editorial on the Research Topic
Interaction between automated vehicles and other road users

1 Summary

An increasing number of automated vehicles will pervade our traffic systems in the future. The absence of a human driver requires these vehicles to communicate and interact with other traffic participants, such as vulnerable road users (VRUs; pedestrians, cyclists, and emerging mobility forms like eBikes or scooters) or drivers of manual vehicles. In this regard, various studies and concepts demonstrating so-called "external Human-Machine Interfaces" (eHMIs) have been presented in the past couple of years. Many of these works have investigated comparably simple scenarios, such as a single pedestrian aiming to cross the street when an automated vehicle is approaching. In the future, research in this area will have to take more complex situations into account. This drives the need for research addressing other situations involving groups of vulnerable road users and traffic participants, different demographics with different accessibility needs, and different scenarios including roundabouts or urban shared spaces, but also exploring the potential of communication and interaction beyond such classical situations to improve cooperation in traffic.

It is critical to contribute to a more systematic investigation of such communication and interaction systems while providing a forum for thought-provoking ideas and concepts on how automated vehicles and "Internet of Things" (IoT) technology can be utilized to increase safety, cooperation, comfort, empathy, and understanding between a wide range of traffic participants.

This Research Topic aims to address the before-mentioned aspects, but also goes beyond by asking questions like: What does ideal communication between traffic participants look like? What characterizes "good" interaction in traffic? Which ideas and principles should guide communication in the future? Are we just eliminating current problems, or are we ready to develop as-yet-uncovered ideas that may shape interaction in the future?

Within this Research Topic, nine articles have been accepted, which are briefly introduced in the following:

- Fabricius et al. discuss interactions between VRUs and heavy trucks. The authors present a systematic literature review of studies addressing empirical research on the interaction between heavy ground vehicles and VRUs and propose to conduct additional studies to get a deeper understanding of such interactions.
- Loew et al. present the results of a eHMI study in real-world crossing situations. Using the wizard-of-oz method, the authors compared three different eHMI concepts to a baseline and found that all eHMI concepts were rated positively regarding acceptance and perceived safety.
- Zhang et al. studied the interaction between right-turning motorists and crossing cyclists at a traffic-light-controlled urban intersection and identified three common communication patterns. Their results provide insights for implementing a communication strategy for automated driving functions that contributes to both traffic efficiency and ensuring safety when interacting with vulnerable road users.
- Hoggenmueller et al. report on the design and evaluation of an eHMI for a real AV in a pedestrianized urban space. The work presents insights from a human-centered design process and results of s study in virtual reality. The authors argue that the design of eHMIs in complex mobility scenarios requires a more holistic approach.
- Hensch et al. compared 19 younger and 17 elderly peoples' impressions of eHMIs. In their study, participants experience both well-working and malfunctioning eHMI systems. The authors report that elderly participants assessed eHMIs more positive than younger participants. The authors argue that designing understandable eHMIs demands addressing the requirements of specific user groups.
- Tran et al. present novel wearable augmented reality concepts to assist pedestrians in scenarios where multiple automated vehicles (AVs) travel the road from both directions. The authors evaluated these concepts in a virtual reality experiment. Their results show that wearable AR may reduce pedestrian cognitive load by providing individual AV responses and a clear signal to cross. However, pedestrians' willingness to adopt a wearable AR solution depends on various factors.
- Lau et al. investigated how the interplay of vehicle kinematics and eHMIs affects pedestrians crossing behavior. They conducted an online study with different eHMI status (static, dynamic, and a baseline) and kinematics (yielding and non-yielding). The results demonstrate that eHMIs can lead to negative effects when not matching vehicle dynamics.
- Sahin et al. present a study conducted in a gamified virtual reality environment, which aimed at revealing how vehicle type, social control, and monetary benefit influences participants' jaywalking behavior. The results suggest that pedestrians jaywalk more frequently when encountering AVs, and that this behavior is depending on associated risks.
- Mirnig et al. summarize the results of seven studies on eHMIs, which were conducted in three European countries. They discuss the investigation of a great variety of external communication solutions that aim at facilitating the exchange between automated shuttles and other motorized and non-motorized road users.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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.

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SYSTEMATIC REVIEW
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Interactions Between Heavy Trucks and Vulnerable Road Users—A Systematic Review to Inform the Interactive Capabilities of Highly Automated Trucks

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This study investigates interactive behaviors and communication cues of heavy goods vehicles (HGVs) and vulnerable road users (VRUs) such as pedestrians and cyclists as a means of informing the interactive capabilities of highly automated HGVs. Following a general framing of road traffic interaction, we conducted a systematic literature review of empirical HGV-VRU studies found through the databases Scopus, ScienceDirect and TRID. We extracted reports of interactive road user behaviors and communication cues from 19 eligible studies and categorized these into two groups: 1) the associated communication channel/mechanism (e.g., nonverbal behavior), and 2) the type of communication cue (implicit/explicit). We found the following interactive behaviors and communication cues: 1) vehicle-centric (e.g., HGV as a larger vehicle, adapting trajectory, position relative to the VRU, timing of acceleration to pass the VRU, displaying information *via* human-machine interface), 2) driver-centric (e.g., professional driver, present inside/outside the cabin, eye-gaze behavior), and 3) VRU-centric (e.g., racer cyclist, adapting trajectory, position relative to the HGV, proximity to other VRUs, eye-gaze behavior). These cues are predominantly based on road user trajectories and movements (i.e., kinesics/proxemics nonverbal behavior) forming implicit communication, which indicates that this is the primary mechanism for HGV-VRU interactions. However, there are also reports of more explicit cues such as cyclists waving to say thanks, the use of turning indicators, or new types of external human-machine interfaces (eHMI). Compared to corresponding scenarios with light vehicles, HGV-VRU interaction patterns are to a high extent formed by the HGV's size, shape and weight. For example, this can cause VRUs to feel less safe, drivers to seek to avoid unnecessary decelerations and accelerations, or lead to strategic behaviors due to larger blind-spots. Based on these findings, it is likely that road user trajectories and kinematic behaviors will form the basis for communication also for highly automated HGV-VRU interaction. However, it might also be beneficial to use additional eHMI to compensate for the loss of more social driver-centric cues or to signal other types of information. While controlled experiments can be used to gather such initial insights, deeper understanding of highly automated HGV-VRU interactions will also require naturalistic studies.

Keywords: truck, cyclist, pedestrian, interaction, automated driving system (ADS), heavy goods vehicle (HGV), vulnerable road user (VRU)

1 INTRODUCTION AND BACKGROUND

How road space has been used, perceived, and designed has changed throughout history in response to new transportation technologies (e.g., trams, bicycles, and motorcars). Following each transition, a new set of rules and societal norms have emerged, which in turn has affected how road users are expected to behave within the traffic environment. The possible introduction of highly automated driving systems (ADS, i.e., level 3–5 in the Driving Automation taxonomy, Society of Automotive Engineers On-Road Automated Driving ORAD committee 2021), would arguably be one of the more impactful mobility innovations to influence the traffic environment. There are multiple scenarios in which these automated vehicles (AVs) could operate, including within: 1) Segregated AV networks, 2) Motorway or expressway networks, 3) Urban networks, or 4) Shared spaces (Parkin et al., 2018). While the first scenario could include occasional AV-human interactions (e.g., within a terminal- or construction area), it is the public contexts that highlight significant challenges in terms of AVs co-existing with humans. Consequently, there have been increasing research efforts to address how these novel road agents should behave around other road users.

However, while an automated driving system may be implemented for all types of vehicles, much of the research has focused on passenger cars (Dey et al., 2020). This paper extends the scope by including trucks, which due to their common use in a professional setting and the transportation of goods instead of passengers could be among the first AVs to reach widespread deployment (Illya Verpraet, 2021). More specifically, this study focuses on encounters and interactions between heavy goods vehicles (HGVs) (i.e., trucks in line with the European classification of a maximum permissible gross vehicle weight of over 3.5 tons) and vulnerable road users (VRUs). Current HGVs operate in diverse settings, and drivers are generally highly skilled at managing the rich set of situations they encounter in traffic. However, HGV related accidents still cause almost 4,000 fatalities every year in Europe (European Commission, 2016). Of these fatal accidents, 32% are reported to include VRUs and the majority involve pedestrians or cyclists (Kockum et al., 2017), which is also the reason for focusing this study on this particular group of VRUs.

While the safety perspective is generally one of the leading arguments for introducing AVs, these vehicles must also support appropriate traffic interactions in terms of traffic flow and road user experience. Since highly automated HGVs are not widespread in traffic today, there is a limited opportunity of studying their encounters and interactions with VRUs. Instead, this paper focuses on existing HGV-VRU studies, with the aim of understanding potential implications for future interactions between highly automated HGVs and VRUs. By conducting a systematic literature review, this paper addresses the following research questions:

- What interactive road user behaviors and communication cues can be identified in empirical HGV-VRU studies?
- What are potential implications for future interactions between highly automated HGVs and VRUs?

Before presenting the methodology, general findings, and synthesis from the review process, the following sections provide a background to the notion of road traffic interaction and (some of) its related theory and concepts.

1.1 Framing Road Traffic Interaction

It is important to highlight that many traffic situations involving two or more road users (i.e., traffic encounters) can unfold without resulting in interaction. Domeyer et al. (2020) use the more general term encounter to indicate when road users have a possibility of accommodating one another, with only one or neither adjusting their behavior. Similarly, they use the term interaction to indicate when both road users send signals that could be interpreted as their intent to accommodate one another or not. Markkula et al. (2020) trace existing theoretical perspectives of road traffic interaction to the following four categories: 1) traffic conflict and safety, 2) game theory, 3) sociology, and 4) communication and linguistics. Connected to these categories, researchers have studied road traffic interaction using different perspectives including collision avoidance, order of access, coordination, reciprocity, and communication. In an attempt to provide a more cross-theoretical framing of the notion, the authors first define the following two terms:

- **Space-sharing conflict:** An observable situation from which it can be reasonably inferred that two or more road users intend to occupy the same region of space at the same time in the near future.
- **Interactive behavior:** Road user behavior that can be interpreted as being influenced by a space-sharing conflict.

Based on this, they subsequently define road traffic interaction as follows:

- **Road traffic interaction:** A situation where the behavior of at least two road users can be interpreted as being influenced by a space-sharing conflict between the road users.

These are the definitions that are adopted for this study. However, it is acknowledged that the term interaction can be used in a variety of ways (Hornbæk and Oulasvirta, 2017;

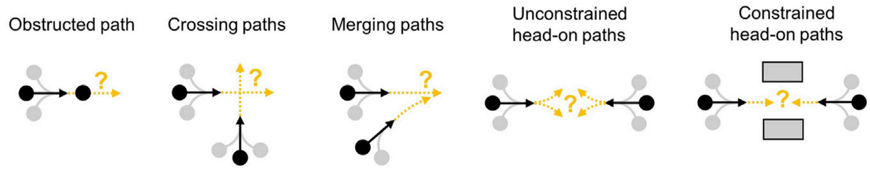

FIGURE 1 | Prototypical space-sharing scenarios based on Markkula et al. (2020).

Hornbæk et al., 2019), suggesting that these definitions should be subject for future discussions.

1.1.1 Interactive Scenarios in Road Traffic

By focusing on space-sharing conflicts/scenarios as a basis for traffic interaction, interactive behaviors (and interactions) are more likely to occur in conjunction with two or more road users' order of access to some shared region of space (Markkula et al., 2020). The authors argue that there is a limited number of ways two road users can approach a conflict space and that such situations can be generalized into five prototypical space-sharing scenarios, including obstructed paths, merging paths, crossing paths, and unconstrained and constrained head-on paths (**Figure 1**). Notably, when more than two road users are involved, multiple prototypes can apply simultaneously. While the simplicity of these prototypical scenarios support generalizations, other researchers have proposed more extensive taxonomies of scenes, situations, and scenarios that include more attributes and value facets (Ulbrich et al., 2015; Fuest et al., 2017).

1.1.2 Road User Behavior and Communication

Observable behaviors in traffic are situated within a highly dynamic context. Domeyer et al. (2020b) adapted the transactional model of communication where road users are viewed as existing within "fields of experience" and relying on common ground (Clark and Brennan, 1991) as a basis for interaction and communication. They suggest that the degree of interdependence between road users will affect the need for interactive behaviors and communication. In earlier research (Johnson et al., 2014), interdependence has been defined as "the set of complementary relationships that two or more parties rely on to manage required (hard) or opportunistic (soft) dependencies in joint activity". Here, the term joint activity is a generalization of joint action (Clark, 1996) and describes situations when what one party does depend on what another party does (and vice-versa) over a sustained sequence of actions. Johnson et al. (2014) suggest a "coactive design framework" (leveraging seminal work on teamworking principles) as an approach for supporting these hard and soft dependencies during joint activity. In brief, it has to do with supporting observability, predictability, and directability (OPD) between agents.

In their synthesis based on existing road traffic interaction literature, Markkula et al. (2020) highlight the tasks "moving" and "perceiving" as (the) two fundamental high-level tasks that road users perform to maneuver successfully in traffic. Furthermore, they state three basic types of behavioral effects in relation to these two tasks ("achieve", "signal", "request"), causing actions to have six different effects/impacts on the traffic situation. On top of this, they also identify a seventh (socially motivated) category of effects/impacts when road users signal appreciation. In terms of communication, road users' various actions and behaviors can be classified into the following two main categories (International Organization for Standardization ISO, in progress):

- **Implicit communication:** Behavior that can be interpreted as serving the purpose of conveying information to another road user, but also as serving some other purpose (e.g., locomotion).
- **Explicit communication:** Behavior that can be interpreted as serving the exclusive purpose of conveying information to another road user.

Indeed, the mechanisms through which road users communicate are diverse and include both explicit cues, such as hand gestures and turning indicators, and more implicit cues, commonly conveyed *via* road users' kinematic behaviors. These cues and signals can be further classified using theories of communication, such as the communicative aspect associated with nonverbal behavior (Domeyer et al., 2020b). Nonverbal behavior is a well-studied area with roots leading back to the 19th century (Darwin, 1873). While the exact definition may vary between research contexts, categories of nonverbal behavior include body movements and gestures, managing space and territory, touch, tone of voice, and appearance (Cowan et al., 1997). **Table 1** summarizes these categories, where nonverbal behavior becomes nonverbal communication if another person interprets the behavior as a message and attributes meaning to it (Stefanov, 2018). Since this can be difficult to distinguish, we will use nonverbal behavior/communication interchangeably and include such sub-categories as part of a broader spectrum of possible channels/mechanisms that may also include modalities such as spoken language or text, signs, and symbols (e.g., various human-machine interfaces). While theories of nonverbal communication were originally developed for human (face-to-face) interactions, mechanisms such as vehicle turning signals have been likened to human facial expressions (Norman in Thomassen, 1994). Ultimately, universal questions of communication are concerned with accuracy, meaning, and effect of communication (Shannon, 1948).

The more recently sparked interest in interactions between AVs and other road users has influenced additional research to investigate existing traffic interaction practices (e.g., Dey and Terken, 2017; Lee et al., 2021), as well as the potential implications of introducing AVs

TABLE 1 | Categories of nonverbal behavior/communication as summarized by Stefanov (2018).

Categories of nonverbal behavior/ communication	Description
Gestures and movement	This type of behavior is often called body language, and the study of the communicative aspects of all gestures, eye behaviors, facial expressions, posture, and movements of the hands, arms, body, head, legs, feet, and fingers is called kinesics
Space	The study of the communicative aspects of space and distance is called proxemics. Proxemic distances can be grouped into several categories including, public, social, personal, and intimate distance. The concept of territoriality groups spaces into several categories, including primary, secondary, and public spaces
Time	The study of the communicative aspects of time is called chronemics. Time can be grouped into several categories including, biological, personal, physical, and cultural time
Voice	Paralanguage refers to the vocalized but nonverbal part of the communication. The study of the communicative aspects of voice including, pitch, volume, rate, vocal quality, and verbal fillers, is called vocalics
Face and eyes	We also communicate through eye behaviors, primarily eye contact and face behaviors, primarily facial expressions. While face and eye behaviors are often studied under the category of kinesics, communicative aspects of eye behaviors have their own branch of studies called oculesics
Touch	The study of the communicative aspects of touch is called haptics. Touch is important for human social development, and it can be grouped into several categories including, welcoming, threatening, and persuasive touch
Appearance	Appearance involves physical characteristics and artifacts. There are many aspects of physical appearance that can potentially produce messages including, attractiveness, body size, body shape, facial features, hair, skin color, height, weight, clothing, watches, and necklaces
Environment	Environmental factors include architecture, interior spatial arrangements, music, color, lighting, temperature, scent, and smell. The study of the communicative aspects of scent and smell is called olfactics

into the public traffic environment (e.g., Lundgren et al., 2017; Rettenmaier and Bengler, 2021; Tabone et al., 2021).

1.1.3 Factors Influencing Vehicle-VRU Interactions

Road user behavior is influenced by elements such as infrastructure, traffic rules, and cultural expectations (Renner and Johansson, 2006) and can include actions that are more strategic in nature (aligning with a game-theoretic perspective) or that arise in less calculated ways. Based on a meta-analysis of pedestrian negotiation and decision-making in roadway crossings, Rasouli and Tsotsos. (2019) synthesized a figure depicting a complex web of influential factors and sub-factors including pedestrian-centric factors (speed, attention, past experiences), and environmental factors (traffic flow, weather conditions, road infrastructure). Similarly, Madigan et al. (2019) concluded that the level and criticality of interactions between vehicles and VRUs is influenced by three broad factors—environmental/situational characteristics, road user characteristics, and vehicle characteristics. While the interrelationship within and between these factors will vary depending on situation and studied phenomena (e.g., crossing decision, gap acceptance, yielding behavior), they clearly range across the interactional, relational, and societal level illustrated in the adapted transactional model of communication proposed by Domeyer et al. (2020b).

1.1.4 Summary and Implications for This Study

This brief theoretic background suggests that road traffic interactions may be viewed as short episodes of joint activity with the (subjectively assessed) presence of interactive behaviors aimed at resolving space-sharing conflicts between at least two road users. In these highly dynamic and context-dependent situations, actor may use implicit and explicit communication to seek various effects/impacts connected to the tasks of moving and perceiving in the traffic environment. Road users can also signal appreciation. Coordination devices such as rules, norms, and traffic control devices limit the degree of interdependence (and need for communication) among road users, while more ambiguous situations include negotiation and coordination. Interactive behaviors and communication cues can be linked to established theory of communication, where actions sometimes are intended and interpreted as signals and sometimes available as less deliberate cues for other road users to judge (or possibly misjudge). The following part of the paper leverages these theoretical concepts and definitions to guide the HGV-VRU literature review process and to structure the findings.

2 METHODS

The literature search and selection process was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis statement (Moher et al., 2015).

2.1 Literature Sources and Search Strategy

The search for studies was conducted through the databases Scopus, ScienceDirect and Transport Research International Documentation (TRID), using the search string ("truck" OR "HGV" OR "lorry") AND ("behavior" OR "interaction" OR "communication" OR "conflict") AND ("pedestrian" OR" cyclist" OR "vulnerable") based on title, abstract, and keywords. The search was conducted in May 2021, with alerts

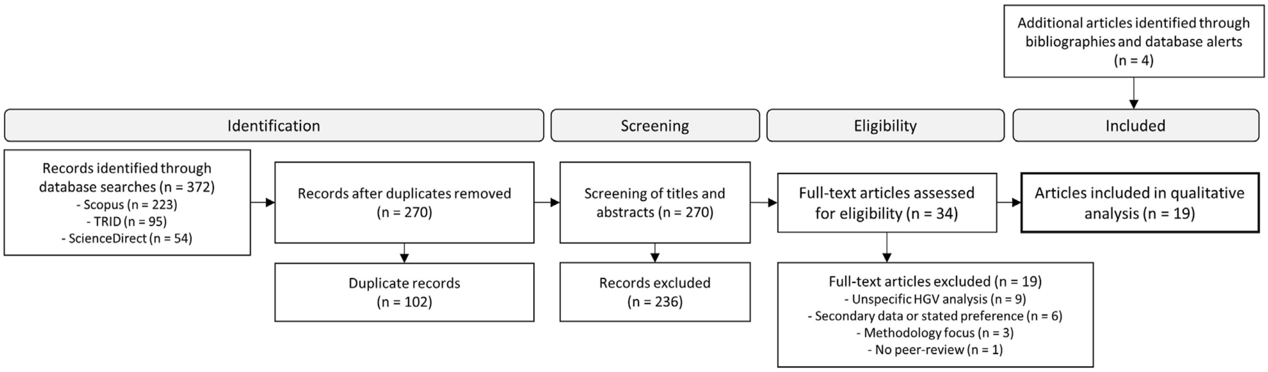

FIGURE 2 | Search and selection flow diagram.

for new publications continuing through to September 2021. Only documents published in English were considered, resulting in a total of 372 records (223 Scopus, 54 ScienceDirect, 95 TRID).

2.2 Study Selection Process

After removing duplicate entries, the records (n = 270) were screened for relevance by evaluating titles and abstracts, after which the exclusion process continued by evaluating full-text articles (n = 34) for eligibility. Both steps were guided by the following exclusion criteria:

- Studies with an unspecific type of heavy vehicle/driver or other than HGV (e.g., "drivers", "heavy vehicles", "vans", "buses", "forklift trucks").
- Studies not focusing on road traffic encounters/interactions between road users (e.g., vehicle emissions, road infrastructure, driver health issues)
- Studies focusing on safety measures (e.g., blind-spot detection, front-end/sideguard design, VRU high-visibility clothing).
- Studies on accident frequencies and injury severity.
- Studies on methods, simulations, and modelling (e.g., simulator development, data collection techniques, traffic models/simulations).
- Studies with an unspecific type of VRU or other than pedestrians or cyclists (e.g., "motorcycles", "mopeds", "e-bikes").
- Studies based on secondary data or stated preference (e.g., database analysis, meta-analysis, focus groups, surveys).

Apart from the more obvious criteria when searching for HGV-VRU interaction/behavioral studies (e.g., excluding other types of vehicles, studies on driver health issues, method development etc.), this list include additional delimitations. The choice was made to focus on pedestrians and cyclists, even if the term VRU sometimes refers to other groups such as motorcycles and powered two-wheelers (PTWs). In addition, we excluded studies based on secondary data or stated preferences. This was done due to the subjective nature of investigating interactive behaviors and communication (highlighted in the theoretical background) motivating first-hand sources with observations and analyses by researchers of the individual studies. The full-text eligibility step yielded 15 studies, and after additions from bibliographies and database alerts (n = 4), the selection included a total of 19 empirical HGV-VRU studies (see flow diagram in **Figure 2**).

2.3 Data Extraction and Analysis

After summarizing the basic characteristics of the included studies, they were categorized according to the type of investigated prototypical space-sharing scenario (presented in **Section 1.1.1**). From here, the analysis was of a qualitative nature summarizing study insights and extracting reports of interactive behaviors and communication cues of the included road users. Three of the paper authors (VF, DR, AH) independently reviewed the sample and later consolidated their findings, where the analysis relied on the theoretic background provided in **Section 1.1**, including the definition of the term interactive behavior as "road user behavior that can be interpreted as being influenced by a space-sharing conflict". The first author also categorized the extracted interactive behaviors and communication cues according to the type of communication channel/mechanism (e.g., nonverbal communication sub-category) as well as the general type of communication (i.e., more implicit or explicit), adhering to the theoretical background under **Section 1.1**.

3 RESULTS

This section presents the main findings from the systematic literature review and qualitative data extraction. A description of the sample is followed by three sections structured according to the type of interaction scenario (i.e., prototypical space-sharing conflict) addressed in the included study.

3.1 Description of the Sample

Table 2 lists the 19 empirical HGV-VRU interaction/behavioral studies that met the eligibility criteria for this review. The studies

TABLE 2 | Basic characteristics of the included studies.

Author(s), year, location	Title	Objective	Method/data collection	Sample size	Interactants
Abadi et al. (2019), US	Factors impacting bicyclist lateral position and velocity in proximity to commercial vehicle loading zones: Application of a bicycling simulator	Do engineering treatments (markings and signs) and truck maneuver have any effect on the bicyclists' velocity and lateral position in the bicycling environment?	Bicycle simulator experiment	48 participants	HGV-cyclist
Beck et al. (2019), AU	How much space do drivers provide when passing cyclists? Understanding the impact of motor vehicle and infrastructure characteristics on passing distance	Quantify passing distance and assess the impact of motor vehicle and road infrastructure characteristics	Naturalistic riding study	60 participants, 379 overtakes by trucks	HGV-cyclist
Beck et al. (2021), AU	Subjective experiences of bicyclists being passed by motor vehicles: The relationship to motor vehicle passing distance	Explore the relationship between cyclists' subjective experiences and the lateral passing distance of motor vehicles	Naturalistic riding study	60 participants, 379 overtakes by trucks	HGV-cyclist
Chuang et al. (2013), TW	The use of a quasi-naturalistic riding method to investigate bicyclists' behaviors when motorists pass	Investigate how motorized vehicle-related factors, road-related factors, and bicyclist-related factors influence passing events	Instrumented bicycle experiment	34 participants	HGV-cyclist
Colley et al. (2020), DE	Evaluating Highly Automated Trucks as Signaling Lights	Investigate interactions and external communication when an automated truck is blocking a sidewalk	Virtual Reality experiment	20 participants	Highly automated HGV-pedestrian
Dozza et al. (2016), SE	How do drivers overtake cyclists?	Explore overtaking scenarios and quantify the corresponding driver comfort zones	Instrumented bicycle experiment	10 overtakes by trucks	HGV-cyclist
Garcia et al. (2020), ES	Influence of peloton configuration on the interaction between sport cyclists and motor vehicles on two-lane rural roads	Investigate risks associated to the interaction with motor vehicles of cyclists riding in a peloton	Instrumented bicycle experiment	73 overtakes by trucks	HGV-cyclist
Jashami et al. (2020), US	The Impact of Commercial Parking Utilization on Cyclist Behavior in Urban Environments	Evaluate the impact of commercial vehicle loading and unloading activities on safe and efficient bicycle operations in a shared urban roadway environment	Bicycle simulator experiment	48 participants	HGV-cyclist
Kircher and Ahlström (2020), SE	Truck drivers' interaction with cyclists in right-turn situations	Investigate truck drivers' speed choice, gaze behaviour, and interaction strategies in relation to VRUs when turning right in signalized and non-signalised intersections	Semi-controlled naturalistic experiment	29 participants	HGV-Cyclist
Kircher et al. (2020), SE	Effects of training on truck drivers' interaction with cyclists in a right turn	Explore the effects of training truck drivers in anticipatory driving to improve their interaction with cyclists	Semi-controlled naturalistic experiment	15 participants	HGV-Cyclist
Petzoldt. (2016), DE	Size speed bias or size arrival effect—How judgments of vehicles' approach speed and time to arrival are influenced by the vehicles' size	Clarify the relationship between size speed bias and size arrival effect	Video experiment	39 participants	HGV-VRU
Petzoldt et al. (2017), DE	Time to Arrival Estimates, (Pedestrian) Gap Acceptance and the Size Arrival Effect	Investigate whether the size arrival effect that is prevalent in time to arrival estimates can explain the variations in gap acceptance	Video experiment	27 participants	HGV-pedestrian
Pitera et al. (2017), NO	The complexity of planning for goods delivery in a shared urban space: a case study involving cyclists and trucks	Examine issues related to freight delivery on a street section with a high volume of cyclists	Video observational study	1,358 observations	HGV-cyclist
Pokorny and Pitera (2019), NO	Observations of truck-bicycle encounters: A case study of conflicts and behaviour in Trondheim, Norway	Exploring the behaviors and conflicts surrounding truck–bicycle encounters	Video observational study	979 encounters, 31 conflicts	HGV-cyclist
Richter and Sachs (2017), DE	Turning accidents between cars and trucks and cyclists driving straight ahead	Investigate driving and gaze behavior during right turning	Truck simulator experiment	48 participants	HGV-cyclist

(Continued on following page)

TABLE 2 | (*Continued*) Basic characteristics of the included studies.

Author(s), year, location	Title	Objective	Method/data collection	Sample size	Interactants
Schindler and Bianchi Piccinini (2021), SE	Truck drivers' behavior in encounters with vulnerable road users at intersections: Results from a test-track experiment	Assess how HGV drivers negotiate the encounters with VRUs in two scenarios	Test-track experiment	13 participants	HGV-VRU
Thorslund and Lindström (2020), SE	Cyclist strategies and behaviour at intersections. Conscious and un-conscious strategies regarding positioning	Examine the typical behavior among cyclists in terms of positioning themselves when passing an intersection	Bicycle simulator experiment	33 participants	HGV-cyclist
Twisk et al. (2018), NL	Higher-order cycling skills among 11- to 13-year-old cyclists and relationships with cycling experience, risky behavior, crashes and self-assessed skill	Assess the level of higher-order cycling skill among children	Video experiment	335 participants	HGV-cyclist
Walker (2007), United Kingdom	Drivers overtaking bicyclists: Objective data on the effects of riding position, helmet use, vehicle type and apparent gender	Present behavioral data on drivers' overtaking around bicyclists	Instrumented bicycle experiment	A total of 2,355 vehicle overtakes	HGV-cyclist

originate from Europe (n = 14), the United States (n = 2), Australia (n = 2), and Asia (n = 1), and the majority are published during the last decade. The studies address HGVs in scenarios with cyclists (n = 15), pedestrians (n = 2), or both cyclists and pedestrians (n = 2). The methodologies and data collection approaches include controlled experiments (n = 9) (e.g., test track/simulator/virtual reality VR experiments), semi-controlled experiments (n = 6) (e.g., instrumented vehicle/bicycle field experiments), and naturalistic studies (n = 4) (e.g., naturalistic driving/riding studies, observational studies).

3.2 Interactive Behaviors in Obstructed Path Scenarios

From the 19 identified empirical HGV-VRU studies, 10 could be linked to obstructed path scenarios such as the road being blocked by trucks or overtaking situations. Several researchers have analyzed HGV encounters as part of wider data collection on vehicle-cyclist passing events. Using an instrumented bicycle, Walker (2007) found that large vehicles pass cyclists significantly closer as compared to smaller vehicles (reporting a mean overtaking proximity of 1.15 m). Owing to their length and poor acceleration, large trucks take much longer to pass a cyclist than shorter vehicles. To pass safely, a driver must encroach onto the oncoming traffic lane for an extended period (even with a cyclist riding towards the road edge). It is suggested that cyclists should acknowledge the overtaking limitations of long vehicles in urban environments and assist their overtaking efforts where practicable. Chuang et al. (2013) found that longer passing times caused the cyclists to exhibit more cautious and less stable cycling behavior while the motorists passed. In another study using instrumented bicycles, Dozza et al. (2016) investigated how drivers overtake cyclists on rural roads. During this maneuver, drivers regulate speed and lateral position, negotiating with potential oncoming traffic to stay within their comfort zones while approaching and passing cyclists. They identified four overtaking phases (approaching, steering away, passing, and returning) and quantified the corresponding driver comfort zones. Three overtaking strategies were considered: 1) the flying strategy, where drivers overtake cyclists while keeping their speed relatively constant, 2) the accelerative strategy where drivers slow down and follow the cyclists for some time before passing, and 3) the piggybacking strategy adopted by drivers who follow a lead vehicle. While the sample size of HGVs was small, comfort zone boundaries were found to be longer for trucks than cars only in the approaching phase, and the trucks spent more time in the passing phase. Garcia et al. (2020) found that passing vehicle speeds were lower when cyclists (racers) were riding in a group, and that HGVs had lower lateral clearance. Cyclists' subjective risk perception was negatively affected by increased vehicle speed, decreased clearance, and larger vehicle size (referencing the aerodynamic forces that an overtaking vehicle produces). Beck et al. (2019) instrumented participants' own bicycles in their naturalistic riding study. Overall, one in every 17 passing events was a close (<100 cm) passing event, and they identified that road infrastructure (specifically on-road cycle lanes) had a substantial influence on the distance that motor vehicles provide when passing cyclists. Based on the same dataset, Beck et al. (2021) also investigated the subjective experiences of cyclists being passed by motor vehicles. Using a "panic button" on the instrumented bicycles, they found that the proportion of passing events with a recorded button press were over three-fold higher in events where the cyclist was passed by an HGV (3.7%) compared to a sedan (0.9%). Across all conditions, the predicted probability of a button press was 1% at a passing distance of 140 cm, 6% at 100 cm and 23% at 60 cm, and the study concluded an increased perceived risk in events where cyclists were passed by large vehicles such as HGVs.

In an observational study, Pitera et al. (2017) found that cyclists tended to adapt their behavior and trajectory

TABLE 3 | Reported interactive road user behaviors/communication cues from HGV-VRU obstructed path scenarios, including their motivation/effect, communication channel/mechanism, type of cue, and reference.

Road user behavior/communication cue	Motivation/effect	Communication channel/mechanism	Type of communication cue	References
HGV characteristics (large/heavy vehicle often driven by a professional driver). VRU characteristics (e.g., unprotected, wearing helmet, gender)	Sets expectations and may affect interaction capabilities and patterns	Appearance	More implicit cue	Walker (2007)
Adopting a “flying”, “accelerative”, or “piggybacking” strategy when overtaking the cyclist	The driver seeking to stay within their comfort zone	Kinesics, proxemics, chronemics	More implicit cue	Dozza et al. (2016)
HGV passing VRU in close proximity	Passing distance below 1 m considered a close passing event	Kinesics, proxemics	More implicit cue	Chuang et al. (2013), Garcia et al. (2020), Beck et al. (2019), Beck et al. (2021)
Cyclists adapting their trajectory depending on the position of the blocking truck in relation to the infrastructure (loading zone, cycle lane, sidewalk)	Anticipating people or objects emerging	Kinesics, proxemics, environment	More implicit cue	Pitera et al. (2017), Jashami et al. (2020)
Pedestrian passing the obstructing truck by stepping onto the roadway	Movement-achieving	Kinesics, proxemics, chronemics	More implicit cue	Colley et al. (2020)
Truck external human-machine interface (eHMI) displaying colors, symbols, and text	Provide information to VRUs	Human-machine interface	More explicit cue	Colley et al. (2020)
Cyclist selecting a more visible position when HGV is present	Avoid blind-spot (i.e., perception-requesting behavior)	Proxemics	More explicit cue	Pokorny and Pitera (2019)

depending on the position of a parked HGV in relation to the cycle lane. More specifically, when passing an HGV parked in a loading zone, the cyclists adopted one of the following behaviors: 1) continue using the cycle lane, 2) riding around using the sidewalk, or 3) riding around using the road. The two latter behaviors occurred when the truck was blocking the cycle lane; half of the cyclists adopted behavior b) and half of them adopted behavior c). Similar behavioral adaptations were observed in situations when the HGV was reversing, which made nearly half of the cyclists react in some way (e.g., riding in the opposite traffic lane, going around the reversing truck, waiting in the cycle lane while the truck was reversing). Related insights are provided by Jashami et al. (2020), who concluded that larger loading zones for trucks in the proximity of cyclists resulted in the cyclists adopting slower speed and greater lateral distances from the loading zone even when the zone size was not directly obstructing the trajectory of the cyclists. Pokorny and Pitera (2019) reported that in a scenario where HGVs and cyclists will continue after having stopped at the red phase at traffic lights, cyclists accelerated faster than and thus “escaping” the trucks' proximity. The study further noted that cyclists' waiting positions in these static scenarios varied, and that cyclists in the presence of HGVs tended to select the most visible positions.

Colley et al. (2020) conducted a virtual reality VR experiment with a scenario where a highly automated HGV was blocking a sidewalk. They tested different types of explicit communication (*via* external human-machine interfaces, eHMI) to provide supporting information for approaching pedestrians, using symbols, text, colors, auditory signals, and other displayed features on the HGV. Based on their experiment they concluded that the information of being able to walk safely past the truck was highly appreciated by the test participants.

To summarize, from the reviewed studies on obstructed path scenarios, we identified several examples of HGV-VRU interactive behaviors and communication cues (**Table 3**). A great majority of these were classified as implicit communication as defined in Section 1.2.1. More specifically, two of these implicit cues are related to the appearance and characteristics of HGVs (e.g., large/heavy, often driven by a professional driver) and VRUs (e.g., unprotected, wearing helmet, gender) that may set expectations and affect behavior in terms of clearance and acceleration (Walker, 2007). The rest of the implicit cues reflect communication *via* movement, position, and timing (kinesics, proxemics, and chronemics nonverbal behavior): HGV driver adopting a “flying”, “accelerative”, or “piggybacking” strategy when overtaking a cyclist (Dozza et al., 2016), HGV passing a VRU in close proximity (Chuang et al., 2013; Beck et al., 2019; Garcia et al., 2020; Beck et al., 2021), cyclists adapting their trajectory depending on the position of the HGV (Pitera et al., 2017; Jashami et al., 2020), pedestrian passing the obstructing HGV by stepping onto the roadway (Colley et al., 2020). When it comes to explicit communication, one of the cues identified is based on strategic positioning (proxemics) to request perception and involves cyclists selecting a more visible position when the HGV is present (Pokorny and Pitera, 2019), while the other one involves HGVs displaying colors, symbols, and text to VRUs in their vicinity *via* eHMI (Colley et al., 2020). Notably, several of the HGV-VRU interaction patterns might differ from corresponding interactions between VRUs and light vehicles: as compared to light vehicles, HGVs (and other large vehicles associated with professional drivers) displayed closer proximity when overtaking cyclists (Walker, 2007; Beck et al., 2019), took longer to overtake (Walker, 2007; Dozza et al., 2016), and made cyclists feel less safe (Garcia et al., 2020; Beck et al., 2021).

3.3 Interactive Behaviors in Crossing Paths Scenarios

Nine of the empirical HGV-VRU studies could be linked to crossing paths scenarios such as road crossings. In an observational study from signalized intersections in Norway, Pokorny and Pitera (2019) showed that most HGV drivers (78%) selected "safer" positions further back from the stop line (distance >1 m) when a cyclist was present. This behavior was explained by the HGV drivers' aspiration for gaining a better overall view of the area while considering potential blind-spots. Results also showed that HGV drivers are used to stopping for cyclists even if the drivers hold the right of way. This was even more common for passenger cars, possibly explained by the fact that decelerating and accelerating is more demanding for HGVs. In addition, cyclists would more often dismount their bicycle (leading to priority at a pedestrian crossing) where the road was wider and the speed of the HGV was higher, and any negotiations would typically end with the cyclist waving their arm to thank the truck driver. In a semi-controlled study where HGV drivers used eye-tracking equipment and an instrumented vehicle, Kircher and Ahlström (2020) reported that glances towards cyclists in right turn intersection scenarios were more frequent when the intersection included greater distances than shorter distances. In situations where there was free-flowing traffic, the HGV drivers glanced less towards the cyclist, possibly due to having better chances to choose safer interaction strategies such as staying behind the cyclist. The authors describe typical ways of how an HGV-VRU turning/crossing scenario might unfold depending on various situational aspects (e.g., road user trajectories, infrastructure layout, traffic control devices, presence of other traffic), and where the interaction ends with "either the truck or cyclist going first". In another study with a similar methodology (Kircher et al., 2020), improved driver behavior from before and after training could be observed, such as better speed management, strategic/tactical positioning strategies, and more intensive monitoring of cyclists. The authors state that adopting such anticipatory driving techniques can improve interactions with VRUs. Richter and Sachs (2017) also studied right-turning HGVs and cyclists going straight, finding that HGV driver's relative gaze frequency to the cyclist through the right window increased when the distance between the lanes decreased.

Thorslund and Lindström (2020) used a cycle simulator to investigate cyclists' conscious and unconscious strategies regarding positioning at intersections in mixed traffic. With the HGV present, participants rode slower, kept more to the left, as well as stopped farther from the stop line. The most frequent strategic considerations were to obtain a good overview, visibility, avoid blind-spots, and be prepared for the vehicle turning right without the use of turning indicators. As part of a longer video-based experiment, Twisk et al. (2018) investigated 11- to 13-year-old cyclists' preferred behaviors during encounters with an HGV waiting at a signalized intersection. They found that the participants often selected dangerous positions (i.e., blind-spots) relative to the HGV. Furthermore, the authors argue that limitations in higher-order skills may be detrimental for the safety of youngsters, and these children appear to overestimate their level of skill, which may contribute to over confidence, violations, and errors. In a test track experiment, Schindler and Bianchi Piccinini (2021) found that truck drivers adapted their kinematic and visual behavior in a crossing when pedestrians and cyclists were present. Compared to the baseline (no VRU), the speed profiles of the drivers diverged approximately 30 m from the intersection and glances were directed more often towards front right and right when the cyclist was present. For the scenario with a pedestrian crossing, the drivers changed their speed about 14 m from the intersection and glances were directed more often towards the front center.

The aim of Petzoldt's (2016) experiment was to clarify the relationship between the contradicting size speed bias (i.e., the phenomenon that observers underestimate the speed of larger objects) and size arrival effect (i.e., that larger objects are judged as arriving earlier than smaller ones). The results confirmed the size speed bias for the speed judgments, with the HGV being perceived as travelling slower than a car. Referencing several sources that have found motorists to be consistently more conservative when confronted with larger vehicles, it was suggested that factors other than perceived speed or time-to-collision TTA play an important role for the differences in gap acceptance between different types of vehicles such as expected cost/consequence of an accident. In a following controlled video experiment, Petzoldt et al. (2017) found that vehicle size and perceived threat correlated substantially. However, it was unclear to what degree these factors contributed to pedestrian's crossing decisions or perceived TTA.

To summarize, from the reviewed empirical studies on crossing path scenarios, we identified several examples of HGV-VRU interactive behaviors and communication cues (**Table 4**). Like the obstructed path scenarios (**Section 3.2**), a great majority of these fall into the category implicit communication. More specifically, two of them are related to the appearance and characteristics of HGVs that either contribute to poor situation awareness of cyclists in terms of choosing to stop in blind-spots of the HGV driver (Twisk et al., 2018), or affect expectations and behavior of cyclists in terms of gap acceptance (Petzoldt, 2016). Furthermore, one of the implicit cues reflects communication *via* relative position (chronemics): an HGV driver choosing to stop further from the stop line when a cyclist is present in order to ensure a sufficient safety margin to the cyclist (Pokorny and Pitera, 2019; Kircher and Ahlström, 2020). Three other implicit cues that we identified reflect communication *via* movements and proximity (kinesics and proxemics): pedestrians accepting a gap and deciding to cross the street (Petzoldt et al., 2017), an HGV driver considerably reducing the speed when encountering a VRU to signal his/her willingness to give way (Schindler and Bianchi Piccinini, 2021), and cyclists dismounting their cycles to get priority at a zebra crossing (Pokorny and Pitera, 2019). The rest of the implicit cues reflect a combination of eye/body language (oculesics/kinesics)

TABLE 4 | Reported interactive road user behaviors/communication cues from HGV-VRU crossing paths scenarios, including their motivation/effect, communication channel/mechanisms, type of cue, and references.

Road user behavior/ communication cue	Motivation/effect	Communication channel/mechanism	Type of communication cue	References
HGV characteristics (large/ heavy vehicle)	Sets expectations and may affect road users' behavior such as gap acceptance	Appearance	More implicit cue	Petzoldt, (2016)
Cyclist approaching an HGV at an intersection	Cyclist aware/unaware of HGV blind-spots	Appearance	More implicit cue	Twisk et al. (2018)
Driver stopping farther from the stop line when a cyclist is present	Driver seeking overview and greater safety margin to VRUs	Proxemics	More implicit cue	Pokorny and Pitera (2019), Kircher and Ahlström (2020)
Cyclist dismounting bicycle at zebra crossing	Get priority as a pedestrian	Kinesics/proxemics	More implicit cue	Pokorny and Pitera, (2019)
Driver/cyclist glances towards other road users	Monitor the environment (i.e., perception-achieving behavior). Possible signal/ request for movement or perception	Oculesics, kinesics	More implicit cue	(Kircher and Ahlström (2020), Kircher et al. (2020), Richter and Sachs (2017), Schindler and Bianchi Piccinini (2021)
Driver approaching cyclist and remaining behind	Leaving an opportunity for a cyclist to cross first	Kinesics, proxemics, chronemics	More implicit cue	Kircher and Ahlström (2020)
Pedestrian deciding to cross the street (accepting a gap)	Movement achieving, Possible signal/ request for perception	Kinesics	More implicit cue	Petzoldt et al. (2017)
Driver considerably reducing speed when encountering a VRU	Movement achieving/signaling/requesting	Kinesics	More implicit cue	Schindler and Bianchi Piccinini (2021)
Cyclist waving arm	Thank driver after negotiation	Kinesics	More explicit cue	Pokorny and Pitera (2019)
Cyclist stopped earlier and more to the left in the lane	Avoid blind-spot (i.e., perception-requesting behavior)	Kinesics, proxemics	More explicit cue	Thorslund and Lindström (2020)
Driver using turning indicators	Movement signaling	Human-machine interface	More explicit cue	Thorslund and Lindström (2020)

TABLE 5 | Reported interactive road user behaviors/communication cues from HGV-VRU merging scenarios, including their motivation/effect, communication channel/ mechanism, type of cue, and reference.

Road user behavior/ communication cue	Motivation/effect	Communication channel/ mechanism	Type of communication cue	References
Cyclist slowing down and moving to the side in the lane	HGV maneuver had a decreasing effect on velocity and an increasing effect on lateral position	Kinesics, proxemics	More implicit cue	Abadi et al. (2019)
Loading zone painted in patterns/colors and outfitted with signs	Indicate specific infrastructure element and potential hazard	Environment	More explicit cue	Abadi et al. (2019)

(an HGV driver or cyclist directs his/her head and glances towards the interacting partner to get perception of the situation and possibly to signal a request for movement or perception, Kircher and Ahlström (2020), Kircher et al. (2020), Richter and Sachs (2017), and Schindler and Bianchi Piccinini (2021)), and a combination of kinesics, proxemics and chronemics [an HGV approaching a cyclist and choosing to remain behind in order to leave the opportunity for the cyclists to cross first, Kircher and Ahlström (2020)]. When it comes to the more explicit communication cues that we identified, one of them reflects selecting a strategic position (proxemics) to request perception: a cyclist stops earlier and more to the left in the lane to avoid blind-spots around the HGV and thereby enable the HGV driver to perceive him/her (Thorslund and Lindström, 2020). Cyclists will also wave their arm to say thanks (Pokorny and Pitera, 2019), and drivers use turning indicators to signal to cyclists in the vicinity (Thorslund and Lindström, 2020). It is also worth noticing that there seems to be a discrepancy in HGV-VRU interaction patterns in crossing path scenarios as compared to light vehicles. In particular, HGVs appear more threatening (Petzoldt et al., 2017), may be perceived as travelling slower (Petzoldt, 2016), and drivers will to a larger extent try to avoid decelerations and accelerations if they can (Pokorny and Pitera, 2019). Lastly, the biggest difference compared to most other vehicles is the more limited field of view causing larger blind-spots for the HGV driver.

3.4 Interactive Behaviors in Merging Scenarios

In a bicycle simulator experiment, Abadi et al. (2019) investigated interactions at loading zones incorporating different HGV behaviors (i.e., no truck, parked truck, truck pulling out) and infrastructure designs (varying road markings and warning signs). The results showed that truck presence does influence cyclist's performance (i.e., velocity and lateral position), and this effect varies based on the design treatments employed. When a truck was present, cyclists had a lower velocity and lower divergence from the edge of the bike lane on solid green pavement, and a higher divergence from the edge of the bike lane when a warning sign was present.

From the study by Abadi et al. (2019), which was the only one containing a merging scenario, we identified two examples of HGV-VRU interactive behaviors and communication cues (**Table 5**). One of them is linked to implicit communication and reflects communication *via* movements and position (kinesics and proxemics): the presence of an HGV in a loading zone next to a cyclist lane makes the cyclists slow down and choose a lateral placement in the lane further away from the HGV. The other one is linked to explicit communication *via* traffic environment elements/signs: an HGV in a loading zone that is painted in green makes the cyclists slow down more and diverge less from the edge, while the presence of a warning sign makes them to diverge more from the edge. Altogether, this exemplifies that cyclists might adjust their behavior not only to the presence and anticipated behavior of the HGV, but also to cues in the traffic environment.

4 DISCUSSION

This section contains a discussion based on the two research questions: 1) What interactive road user behaviors and communication cues can be identified in empirical HGV-VRU studies? 2) What are potential implications for future interactions between highly automated HGVs and VRUs?

4.1 Current HGV-VRU Interactive Behaviors

While we can observe behaviors and collect data using controlled, semi-controlled, and naturalistic studies, it is harder to interpret their influence or underlying motivation. Apart from the more general influencing factors described in **Section 1.1.3**, researchers have investigated factors based on HGV-VRU encounters. Influencing (safety) factors derived from HGV-cyclist literature include a lack of awareness regarding blind-spots, adopting risk taking behaviors (e.g., using phone while crossing/driving), and the lack of visual contact and communication between road users (Pokorny and Pitera, 2019). Examples of influencing factors derived from the reviewed studies on HGV-pedestrian interactions include blind-spot issues, size of traffic gap, and road users' individual characteristics such as vehicle size or observed pedestrian age (Petzoldt et al., 2017; Naser et al., 2017). In addition, there will also be contextual influences including interaction at unfamiliar locations, objects limiting visibility, unsafe infrastructure layouts, and adverse weather conditions (Pokorny and Pitera, 2019; Sheykhfard and Haghighi, 2020). From the reviewed studies, we found several examples of how HGV-VRU characteristics are affecting encounters and interactions (**Tables 3–5**). However, there are also conclusions that the combination of infrastructure design and surrounding traffic was reported to have a larger impact on the development of the interaction between HGV and cyclist than the truck driver had (Kircher and Ahlström, 2020). The interconnected relationships between these factors are what contributes to the complex (or wicked) reality of the traffic domain.

So, while acknowledging this complexity, we do conclude that HGV-VRU interactive behaviors are shaped by the general characteristics of these road users. HGVs are among the larger and heavier vehicles on public roads, affecting vehicle dynamics and increasing the risk of severe outcomes in the event of an accident. They most often have professional drivers who need to handle large visual blind-spots and unpredictable, possibly inattentive, VRUs. The safety imbalance between these road users is indicated by reported behaviors including cyclists being more cautious and selecting strategic positions in the presence of an HGV (Pokorny and Pitera, 2019; Thorslund and Lindström, 2020), and drivers selecting a position with better overview or giving up right of way (Pokorny and Pitera, 2019). The reviewed studies more frequently report on road users' kinematic behaviors, suggesting implicit communication to be the primary mechanisms facilitating HGV-VRU encounters and interactions. This is in line with more general vehicle-VRU literature (Dey and Terken, 2017; Lee et al., 2021), further suggesting a velocity threshold at approximately 25–35 km/h for the relevance of more explicit social cues such as driver gestures or eye contact (Dietrich et al., 2019). Above this threshold, road users will instead try to find appropriate gaps to either cross or merge with the traffic based on implicit cues. Unfortunately, this review did not reveal the more precise role or importance of truck driver-centric cues for facilitating HGV-VRU encounters and interactions.

4.2 Interactions Involving Highly Automated HGVs

The second research question has to do with implications of the review for the development of HGVs controlled by highly ADS. From the reviewed studies, we have examples of more fixed communication cues (e.g., more precise type of HGV and VRU characteristics) as well as interactive behaviors that will change rapidly (e.g., road user trajectories, body language). **Table 6** contains examples of such cues and behaviors, forming an overview of how information can be derived from a range of channels/mechanisms connected to the road users. More specifically, the table maps possible cues between established categories of communication and the source/origin of information (e.g., vehicle-centric vs. driver-centric). While

TABLE 6 | Communication channels/mechanisms in HGV-VRU interactions, including examples of extracted road user behaviors/communication cues (regular font) as well as complementary examples added by the authors (italic font).

	HGV		**VRUs**	
Communication channel/ mechanism	Vehicle-centric cues	Driver-centric cues	Pedestrian-centric cues	Cyclist-centric cues
Gestures and movement (kinetics)	HGV adapting trajectory	*Driver hand gesture*	Pedestrian stepping onto the roadway	Cyclist waving
Space (proxemics)	HGV position relative to VRU at an intersection	Driver present inside/outside the truck cabin at loading zone	Pedestrian proximity to other VRUs in the vicinity	Cyclists riding in group
Time (chronemics)	HGV timing acceleration to pass VRU	Driver sequence/order of gaze behavior	Pedestrian initiation of crossing (timing a gap)	Cyclist quickly leaving the near-truck zone
Voice (paralanguage)	*HGV horn sound*	*Driver vocal reaction*	*Pedestrian vocal reaction*	*Cyclist vocal reaction*
Face and eyes (e.g., oculesics)	—	Driver eye-gaze	*Pedestrian facial expression*	Cyclist eye-gaze
Touch (haptics)	HGV producing aerodynamic force on cyclist	—	—	—
Appearance	HGV as a larger vehicle	Professional driver	Young/old pedestrian	Casual cyclist vs. racer
Human-machine interface (HMI)	HGV displaying contents using external HMI (turning indication or other state/intent etc.)	—	—	—
Environment (e.g., olfactics)	*Engine/tire smell*	—	—	—

most of the examples are extracted from the reviewed studies (**Section 3**), some additions have been made by the authors to provide a more complete view of the possible range of cues these road users might produce and encounter in traffic. From the perspective of the road user, these cues can be classified as either spontaneous (i.e., provided on a nonvoluntary basis), symbolic (i.e., provided deliberately to communicate), or pseudo-spontaneous (seemingly spontaneous cues but with a concealed intentionality) (Buck and VanLear, 2002). This highlights how difficult it might be to differentiate between implicit and explicit communication, and that road users may adopt pseudo-spontaneous strategies to get ahead in traffic (e.g., VRU actively deciding not to look at oncoming traffic put the burden of responsibility on the driver). When considering highly ADS applied to HGVs, **Table 6** indicates that these systems will need to handle a wide range of interactive behaviors. Communication based on trajectories and kinematic behavior will form the basis for interaction, but developers of these systems could also find it necessary to compensate for the loss of more social driver-centric cues such as eye-gaze and body language.

While these are direct conclusions based on existing HGV-VRU studies, we also expect highly ADS to contribute to shaping future interactions. For example, the addition of this new type of road user could introduce ambiguity regarding who controls the vehicle. They could also lead to reduced perceived risk for interacting VRUs and enhance observability and predictability by providing information made possible by a more consistent and proactive behavior of an ADS compared to a human driver. So, while this review attempts to provide an overview of the current understanding of HGV-VRU interactive behavior, a future frame of reference (and common ground for communication) could be adjusted as VRUs and vehicles controlled by highly automated driving systems get increased experience of interacting with each other.

4.3 Limitations and Future Research

Road traffic interaction is challenging to review since it can be connected to multiple perspectives related to the process and outcomes of events in traffic (**Section 1.1**). For this review, we strictly included peer-reviewed empirical HGV-VRU interaction studies based on primary data sources, and the process was limited to three databases and a range of exclusion criteria (**Section 2.2**). While it was useful to leverage theoretical concepts and recent definitions of road traffic interaction, data extraction of "interactive behavior phenomena" were limited to a qualitative analysis of the existing studies. During this process, it was often difficult to fully evaluate the presence, motivation, and effect of reported behaviors since many studies had different research motives or units of analysis. Future research could add to our findings by more directly addressing the communicative components of HGV-VRU behaviors. The reviewed studies were linked to three out of the five prototypical interaction scenarios proposed by Markkula et al. (2020) (**Section 1.1.2**). This is explained by the fact that HGVs and VRUs often have dedicated infrastructure and are coordinated by traffic control devices, resulting in limited points of interaction. Broadening of the scope of the review to include other types of VRUs (e.g., powered two-wheelers) and vehicles could lead to a better understanding of what interaction practices are unique to different constellations of road users. However, to what extent we can generalize between different "types" of road users is not always clear, and discussions will continue of how such categories are best constructed (Holländer et al., 2021).

This study supports the view that traffic encounters and interactions predominantly are reliant on implicit communication, motivating that AV developers need to pay close attention to how even subtle changes in movement and trajectories can affect interactions. Our synthesis suggests that the more precise appearance and design features of a highly automated HGV could be important for how it is perceived by VRUs. Furthermore, while we only found a few examples of explicit driver-centric communication, more general research (e.g., Dietrich et al., 2019) show that such behaviors are primarily to facilitate social low-speed space-sharing scenarios. Future research should investigate the added value for automated HGVs to 1) explicitly signal movement, perception, and appreciation, or 2) request movement and perception from others during such scenarios. The way to support these various effects could be through existing communication mechanisms or by adding new channels such as eHMI based on visual, auditory, or haptic modalities (see eHMI overview in Dey et al., 2020). These modalities can communicate information such as ADS mode, intentions, perception, instructions, commands, advice, and predictions (Habibovic et al., 2018; Schieben et al., 2019; Colley and Rukzio, 2020; Faas et al., 2020).

However, research and development of the interactive capabilities of AVs is complex. The reviewed studies leveraged various controlled and naturalistic approaches to collect both qualitative and quantitative data, and it is evident that the study of road traffic interaction is (and should continue to belong to) a pluralistic research discipline. Within the HGV-VRU delimitation we found only one study addressing highly automated HGV encounters, resulting in the findings being predominantly based on human drivers interacting with (human) VRUs. This indicates that there is need for additional perspectives from fields such as human-computer interaction (HCI). Though HCI research and concepts have been widely used for the in-vehicle experience, AV technology has extended the scope to include traffic interactions. Unfortunately, there are no well-established practices when it comes to investigating or designing for interactions with "AI-infused technology" (Amershi et al., 2019), which at least vehicles controlled by higher levels of driving automation could be based on. Initially, AV-VRU interaction research have largely had to rely on insights from (controlled) experiments using Wizard-of-Oz and VR/simulator approaches, or experiences of early deployments of highly rule-based systems (e.g., AV shuttle buses). However, depending on the architecture of highly automated driving system (and the possible limits in transparency/explainability), any deeper understanding on AV-VRU encounters/interactions could require more naturalistic studies. Analogous to how we study human (or animal) behavior, we might need to study emergent machine behavior (Rahwan et al., 2019) in naturalistic traffic studies. Still, any new perspectives should go together with a deep understanding of existing traffic practices as well as the development of rigorous ways of gathering insights on the subtleties of road traffic interactions (e.g., Markkula et al., 2020; Madigan et al., 2021). In addition, more discussion is needed about what constitutes appropriate road traffic interactions in mixed traffic environments and how those encounters and interactions should be evaluated.

5 CONCLUSION

This systematic review helps to generate an understanding of how drivers of heavy goods vehicles (HGVs) and vulnerable road users (VRUs) interact and communicate with each other, and what it might mean for interactions and communication between highly automated HGVs and VRUs. Overall, it is concluded that discernable interactive behaviors and communication cues from existing HGV-VRU behavioral studies can be categorized in line with concepts from communication theory and the field of road traffic interaction. However, further methodological efforts should be made to support a continued cross-disciplinary understanding of road traffic interaction. Based on our research questions, we conclude the following:

What interactive road user behaviors and communication cues can be identified in empirical HGV-VRU studies?

- Like encounters and interactions between other types of road users, HGV-VRU interactions are influenced by interrelated vehicle, individual, and contextual factors.
- Focusing on the road users, we found the following examples of interactive behaviors and communication cues: a) vehicle-centric (e.g., HGV as a larger vehicle, adapting trajectory, positioning relative to the VRU, timing acceleration to pass the VRU, producing aerodynamic force on VRU, displaying information *via* HMI), b) driver-centric (e.g., professional driver, being present inside/outside the cabin, eye-gaze behavior), and c) VRU-centric (e.g., professional vs. casual cyclist, adapting trajectory, positioning relative to the HGV, proximity to other VRUs in the vicinity, timing a gap, gaze behavior, waving to driver).
- Most of the cues that we identified are linked to implicit communication. While it indicates that this is the primary mechanisms for interactions, it could also suggest that the role/importance of communication from HGV driver- and VRU-centric cues (e.g., eye-gaze, facial expressions and vocal reactions) requires additional research. Based on more general literature, such research should focus on low-speed scenarios where this type of communication is more common.
- Another important insight is that HGV drivers commonly adjust their behavior (i.e., gazing, positioning) in areas with VRUs and yield to VRUs even if they have priority. Similarly, VRUs may experience HGVs as threatening, underestimate their speed and adjust (or fail to adjust) their behavior due by blind-spots around HGVs.
- Compared to corresponding scenarios with light vehicles, HGV-VRU interaction patterns are generally formed by the HGV's size, shape and weight. For example, this can cause VRUs to feel less safe, drivers to seek to avoid unnecessary decelerations and accelerations, or lead to strategic behaviors due to larger blind-spots.

What are potential implications for future interactions between highly automated HGVs and VRUs?

- Our conclusions from the first research question indicate that highly automated HGVs might need to handle a wide range of interactive behaviors and communication cues. Road user trajectories and kinematic behavior are likely to form the basis for communication also for highly automated HGV-VRU interaction. However, it might also be beneficial to use additional eHMI to compensate for the loss of more social driver-centric cues or to signal other types of information.
- In particular, developers of highly automated HGVs can try to design their vehicles to appear less threatening. Added eHMI can be used to differentiate them from manually driven HGVs with bigger blind-spots, or to more explicitly signal their perception of VRUs. Also, eHMI could be used to make it easier for VRUs to estimate the speed and distance of the HGV, or to indicate their yielding intentions. The latter might be especially important since it can also reduce the need for abrupt decelerations and accelerations. While this is largely in line with the current knowledge on eHMI for highly automated passenger vehicles, this study provides indications that the value for HGV-VRU interactions could be more pronounced.
- Lastly, these conclusions are based on the existing HGV-VRU studies. We should, however, expect interaction practices to be updated as VRUs and highly automated HGVs get increased experience of interacting with each other.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization: VF, AH, DR, PW, and JA. Methodology and analysis: VF, AH, DR, PW, and JA. Writing—original draft: VF, AH, and DR. Writing—review and editing: VF, AH, DR, PW, and JA. Funding acquisition: AH.

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Designing Wearable Augmented Reality Concepts to Support Scalability in Autonomous Vehicle-Pedestrian Interaction

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Wearable augmented reality (AR) offers new ways for supporting the interaction between autonomous vehicles (AVs) and pedestrians due to its ability to integrate timely and contextually relevant data into the user's field of view. This article presents novel wearable AR concepts that assist crossing pedestrians in multi-vehicle scenarios where several AVs frequent the road from both directions. Three concepts with different communication approaches for signaling responses from multiple AVs to a crossing request, as well as a conventional pedestrian push button, were simulated and tested within a virtual reality environment. The results showed that wearable AR is a promising way to reduce crossing pedestrians' cognitive load when the design offers both individual AV responses and a clear signal to cross. The willingness of pedestrians to adopt a wearable AR solution, however, is subject to different factors, including costs, data privacy, technical defects, liability risks, maintenance duties, and form factors. We further found that all participants favored sending a crossing request to AVs rather than waiting for the vehicles to detect their intentions—pointing to an important gap and opportunity in the current AV-pedestrian interaction literature.

Keywords: autonomous vehicles, vehicle-to-pedestrian communication, external human–machine interfaces, user-initiated communication, vulnerable road users, wearable augmented reality, scalability

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1. INTRODUCTION

The ability of autonomous vehicles (AVs) to effectively interact with vulnerable road users (VRUs), such as pedestrians, is crucial to ensuring safe operations and public confidence. While pedestrians mainly rely on implicit cues (e.g., motion and motor sounds) from a vehicle to interpret its intention (Risto et al., 2007; Moore et al., 2019), explicit signals from a driver, including verbal exchanges, eye contact, and hand gestures, help resolve impasses and instill trust in interactions (Rasouli and Tsotsos, 2019). Once humans relinquish control to an AV, these informal signals may become less prevalent or possibly disappear altogether. External human-machine interfaces (eHMIs) (Dey et al., 2020a) are currently being investigated as a possible way to compensate for the lack of driver cues, allowing for intention transparency, which is a desirable quality in almost every intelligent system (Zileli et al., 2019).

In order to understand key factors influencing pedestrian behavior and experiences, most external communication research has evaluated eHMIs in the fundamental traffic setting involving one pedestrian and one vehicle (Colley et al., 2020b). However, for eHMIs to become an effective mediator in real-world traffic situations, it is critical for external communication research to take into account scalability factors (i.e., vehicular and pedestrian traffic volumes) and their associated challenges. For example, pedestrians may experience an increased cognitive load when interpreting signals from multiple AVs (Mahadevan et al., 2018; Dey et al., 2020a) or mistakenly believe a message intended for another is directed to them (Dey et al., 2021).

One promising solution to the scalability issues is incorporating augmented reality (AR). This technology has been explored in the automobile industry to improve driving safety and comfort (Riegler et al., 2021). In-car AR, such as heads-up and windshield displays, offer diverse opportunities to aid navigation, highlight potential hazards, and allow for a shared perception between a driver and an automated driving system (Wiegand et al., 2019). The application of AR outside of vehicles to assist AV-pedestrian interaction is also of increasing interest in academia (Tabone et al., 2021a). As with smartphones, the personal nature of wearable AR[1] allows their connected eHMI concepts to address an unlimited number of road users simultaneously with notable precision and resolution (Dey et al., 2020a). In addition, tailored communication based on user preferences and characteristics may contribute to eHMIs becoming more inclusive. Notably, AR has been investigated as an accessibility tool for visually impaired people (Coughlan and Miele, 2017). Most significantly, wearable AR enables digital content to be displayed within the physical environment, allowing users to retain situational awareness and react rapidly to safety alerts (Tong et al., 2021).

Various AR concepts have been designed to convey road-crossing information (Hesenius et al., 2018; Pratticò et al., 2021; Tabone et al., 2021b) and provide collision warnings to pedestrians (Tong et al., 2021). However, to our knowledge, no studies have been undertaken to date to evaluate AR concepts in a complex traffic setting where pedestrians must consider the intentions of several AVs in making crossing decisions. Our driving assumption is that a multi-vehicle situation necessitates the understanding of an appropriate communication approach to provide pedestrians with pertinent cues without overwhelming them. Furthermore, the literature has focused on determining the efficacy of various AR concepts in conveying AV intent rather than pedestrians' preferences for using wearable AR in daily interactions with AVs. Given the novel AR experiences and the shift away from using public crossing facilities and toward using personal devices, it is important to gauge pedestrians' acceptance of wearable AR solutions.

To address these research gaps, we designed three AR eHMI concepts with different ways to signal responses from multiple AVs: a visual cue on each vehicle, a visual cue that represents all vehicles, and both the aforementioned types of visual cues. We used virtual reality (VR) to simulate and test wearable AR prototypes against a pedestrian push button baseline. Our overall research goal was to answer the following research questions: **(RQ1)** *To what extent, if any, do pedestrians prefer using wearable AR to interact with AVs?* **(RQ2)** *How do different communication approaches influence pedestrians' perceived cognitive load and trust?*

Our study makes the following contributions: we (1) present novel AR eHMI concepts that assist the crossing of pedestrians in heavy traffic scenarios, (2) identify factors influencing pedestrians' preferences for wearable AR solutions, and (3) determine the effect of three distinct communication approaches on pedestrians' crossing experiences.

2. RELATED WORK

2.1. External Communication of AVs

The vast majority of car crashes are caused by human error (Treat et al., 1979; Hendricks et al., 2001); therefore, advanced driver assistance systems have been developed to assist drivers in a variety of driving tasks (e.g., active cruise control, collision warnings) or relieve them fully from driving. Without active drivers, future vehicles may be outfitted with additional interfaces that communicate clearly with pedestrians and other VRUs regarding their intentions and operating states. For instance, Waymo has submitted a patent stating that cars may inform pedestrians using "a physical signaling device, an electronic sign or lights, [or] a speaker for providing audible notifications" (Urmson et al., 2015). Meanwhile, Uber has further proposed using a virtual driver and on-road projections (Sweeney et al., 2018). Potential implementations of eHMI also include approaches in which communication messages are detached from the vehicles. The urban technology firm Umbrellium has prototyped an LED-based road surface capable of dynamically adapting its road markings to different traffic conditions to prioritize pedestrians' safety (Umbrellium, 2017). In addition, Telstra has trialed a technology enabling vehicles to deliver early-warning collision alerts to pedestrians *via* a smartphone (Cohda Wireless, 2017).

The locus of communication—*Vehicle*, *Infrastructure*, and *Personal Device*—is one of the key dimensions in the eHMI design space (Colley and Rukzio, 2020a). According to a review of 70 different design concepts from industry and academia, vehicle-mounted devices have accounted for the majority of research on the external communication of AVs thus far (Dey et al., 2020a). However, urban infrastructure and personal devices are promising alternatives for facilitating complex interactions involving multiple road users and vehicles due to their high scalability and communication resolution (Dey et al., 2020a).

2.2. Scalability

In the context of AV-pedestrian interaction, scalability refers to the ability of eHMIs to be employed in situations with a large number of vehicles and pedestrians without compromising on efficacy (Colley et al., 2020b). In this case, the communication relationship goes beyond the simple one-to-one encounters and includes one-to-many, many-to-one, and many-to-many interactions (Colley and Rukzio, 2020b). Although scalability research is still in its early stages (Colley et al., 2020b), potential

[1] In this article, we use the term *wearable AR* to refer to all types of near-eye displays regardless of their form factor. These displays include head-mounted AR devices (e.g., Microsoft HoloLens), monocular and binocular AR glasses (e.g., Google Glass), and contact lenses (e.g., Mojo Lens).

scaling limitations of eHMIs, including low communication resolution and information overload, have been noted in several research articles (Robert Jr, 2019; Dey et al., 2020a, 2021).

In terms of communication resolution, i.e., "the clarity of whom the message of an eHMI is intended" (Dey et al., 2020a), a message broadcasted to all road users in a vehicle's vicinity, e.g., from an on-vehicle LED display, might result in misinterpretation. This issue is particularly apparent when co-located road users have conflicting rights of way (Dey et al., 2020a), which may lead to confusion or even unfortunate outcomes in real-world traffic situations. Dey et al. (2021) tested four eHMI designs with two pedestrians and observed that non-specific yielding messages increased the participants' willingness to cross even when the vehicle was stopping for another person. To address this possible communication failure, Verstegen et al. (2021) prototyped a 360-degree disk-shaped eHMI featuring eyes and dots that acknowledge the presence of multiple (groups of) pedestrians. Other proposed alternatives include nomadic devices, the personal nature of which inherently enables targeted communication, and smart infrastructures (e.g., responsive road surfaces) (Dey et al., 2020a). However, more research is required to determine user acceptance and the (cost-) effectiveness of such solutions.

Information overload may occur when pedestrians are presented with an excessive number of cues. In the study by Mahadevan et al. (2018), a mixed interface of three explicit cues situated on the automobile, street infrastructure, and a pedestrian's smartphone was viewed as time-consuming and perplexing by many participants. Hesenius et al. (2018) reported a similar finding, where participants disliked the prototype that visualizes safe zones, navigation paths, and vehicle intents simultaneously. In the case of multiple AVs, an increase in the number of external displays was expected to impose a high cognitive load onto pedestrians (Robert Jr, 2019) and turn street crossing into "an analytical process" (Moore et al., 2019). According to Colley et al. (2020a), when multiple AVs communicate using auditory messages, pedestrians' perceived safety and cognitive load improve; however, it is uncertain whether the same observation can be made with visual messages. Our study aims to close this knowledge gap by examining three different approaches to displaying visual responses from multiple AVs.

2.3. Wearable AR Concepts

Globally, smartphone uptake has increased at a very swift pace. Together with advances in short-range communication technologies, the devices have been investigated for their potential to improve pedestrian safety, such as aiding individuals in crossing streets (Holländer et al., 2020; Malik et al., 2021) and providing collision alerts (Wu et al., 2014; Hussein et al., 2016). Smartphones' close proximity to users allows them to access reliable positioning data for collision estimations and deliver adaptive communication messages based on users' current phone activity (e.g., listening to music) (Liu et al., 2015).

Wearable AR, as the next wave of computing innovation, has similar advantages to smartphones. However, its ability to combine the virtual and real worlds enables a more compelling and natural display of information and improved retention of situational awareness (Azuma, 2019). Context-aware and pervasive AR applications (Grubert et al., 2016) also present an opportunity to aid users in more diverse ways. They are envisioned to become smart assistants that can semantically understand the surrounding environment, monitor the user's current states (e.g., gaze and visual attention), and adjust to their situational needs (Starner et al., 1997; Azuma, 2019). This has led to a growing discussion on the application of wearable AR for AV-pedestrian communication. In a position paper where 16 scientific experts were interviewed, it was partially agreed that wearable AR might resolve scalability issues of AV-VRU interaction (Tabone et al., 2021a). Recent work has explored several different AR eHMI concepts but has yet to examine the scalability aspect. Tong and Jia (2019) designed an AR interface to warn pedestrians of oncoming vehicles while other studies have presented navigational concepts (Hesenius et al., 2018; Pratticò et al., 2021) and theoretically-supported prototypes (Tabone et al., 2021b) offering crossing advice. Our study attempts to extend this body of work through an empirically based investigation of wearable AR design concepts in a multi-vehicle situation.

Currently, various technical issues exist that make it challenging to prototype and evaluate wearable AR interfaces outdoors (Billinghurst, 2021): (1) a narrow field of view (FOV) that covers only a portion of the human field of vision, limiting what users can see to a small window; (2) an unstable tracking system that is affected by a wide range of environmental factors (e.g., lighting, temperature, and movement in space); and (3) low visibility of the holograms in direct sunlight. For these reasons, we utilized VR simulations to overcome the shortcomings of wearable AR and the limitations of AV testing in the real world, following a similar approach to Pratticò et al. (2021).

3. DESIGN PROCESS

3.1. Crossing Scenario

Similar to most studies on AV-pedestrian interaction, we selected an ambiguous traffic situation, i.e., a midblock location without marked crosswalks or traffic signals, requiring pedestrians to cross with caution and be vigilant of oncoming vehicles. To assess the design concept's scalability, the crossing scenario featured many vehicles driving in both directions on a two-way street. This situation is prevalent in urban traffic, typically requiring pedestrians to estimate the time-to-arrival of vehicles and select a safe gap to cross. However, the ability to correctly assess the speed and distance of approaching cars varies with different environmental conditions and across demographic groups (Rasouli and Tsotsos, 2019). Inaccurate judgments may lead to unsafe crossing decisions, causing pedestrian conflicts with vehicular traffic. On the premise that not all road users can chart their best course of action, we sought to create a design concept to aid their crossing decisions.

3.2. Design Concepts

Our wearable AR concepts were inspired by the widely used pedestrian push button, which enables pedestrians to request a crossing phase. The buttons are typically installed at locations with intermittent pedestrian volumes, where an automatic pedestrian walk phase has not been implemented. The installment is intended to improve vehicle mobility by reducing unnecessary waiting times (Lee et al., 2013) and promote pedestrian compliance with traffic signals (Van Houten et al., 2006). Moreover, accessible push buttons that incorporate audio-tactile signals may be especially beneficial to blind and vision-impaired pedestrians (Barlow and Franck, 2005). In the advent of autonomous driving, the pedestrian push button remains an effective solution to mediate conflicts and improve pedestrian safety; however, the system may not be available at every intersection and midblock location. Furthermore, pedestrians tend to cross at convenient locations that present shorter delays (Ravishankar and Nair, 2018). Therefore, we followed an iterative design process to devise a concept where pedestrians can utilize the AR glasses to negotiate a crossing opportunity with approaching AVs. Prototypes of varying fidelities were created and improved through internal discussions among the authors. Additionally, two pilot studies (with a total of four participants) were conducted prior to the main investigation. User interactions were modeled after those used with the pedestrian button, comprising three stages, as illustrated in **Figure 1** and described in greater detail as follows.

Sending a crossing request: As a safety prerequisite, predicting pedestrian crossing intentions based on parameters such as the pedestrian dynamics, physical surroundings, and contextual scene information is one of the most critical tasks of AVs (Ridel et al., 2018). However, many challenges remain to be overcome in achieving a reliable and robust solution. For this reason, we implemented a user-initiated communication approach with pedestrians explicitly indicating their crossing intents for a greater sense of control. Users can send a crossing request to all nearby AVs by quickly tapping a touch surface on the temples of AR glasses. While various methods for controlling the AR glasses exist, the tapping gesture was selected for its simplicity and ease of prototyping. Additionally, it is widely employed in wireless earphones, smart glasses, and smart eyewear (e.g., Ray-Ban Stories).

Waiting for crossing signals: Analogous to how the pedestrian push buttons offer visual and audible feedback when pressed, the AR glasses displayed a text prompt acknowledging the crossing request. According to media reports on push-button usage in the United States, many people are unsure if the system is of value and even regard them as placebo buttons, with their presence only offering an "illusion of control" (Prisco, 2018). The confusion has arisen mainly because the push buttons are inoperative during off-peak hours or have been supplanted by more advanced systems (e.g., traffic sensors) and kept only for accessible features (Prisco, 2018). Considering these user frustrations stemming from a lack of understanding regarding how a system works, we ensured that the text prompt briefly explains the workings of the AR glasses.

Receiving crossing signals: We developed three communication approaches to visually convey AVs' responses to the crossing request. The first approach involves placing a visual cue on each vehicle ("distributed response;") specifically, the AR glasses render a green overlay that covers a vehicle's surface to indicate a yielding intent. The idea of an overlay is based on the futuristic digital paints that may be incorporated in automobiles by 2050 (AutoTrader, 2020). Given the lack of consensus regarding the optimal placement of visual cues on a vehicle's body, an overlay offers the advantage of being noticeable and visible from various angles. Green was chosen as the color to indicate "go" because of its intuitiveness (Dey et al., 2020b); we also assumed that possible confusion in perspectives (Bazilinskyy et al., 2019) is less likely to occur when the user initiates the communication. The second approach entails the use of a single visual cue, in this case, an animated forward-moving pedestrian crossing, to convey the intentions of all cars ("aggregated response.") The zebra crossing is a widely recognized traffic symbol that numerous eHMI studies have investigated (Löcken et al., 2019; Nguyen et al., 2019; Dey et al., 2021; Pratticò et al., 2021; Tabone et al., 2021b); its forward movement indicates the crossing direction (Nguyen et al., 2019), and the markings have high visibility (Löcken et al., 2019). The third approach combines both types of visual cues by displaying car overlays and an animated zebra crossing simultaneously. This approach was implemented based on study findings from Hesenius et al. (2018), taking into account the possibility of participants having different preferences regarding different combinations of cues.

4. EVALUATION STUDY

4.1. Study Design

Given that the AR eHMI concepts were designed for a multi-vehicle traffic situation, a comparison to a currently implemented system would yield relevant insights into pedestrian preferences and crossing experiences. Therefore, we decided on a within-subjects study design with four experimental conditions: a baseline pedestrian push button and three wearable AR concepts with different communication approaches—aggregated response (AR crosswalk), distributed response (AR overlay), and both the aforementioned types (refer to **Figure 2**). To minimize carryover effects, we changed the order of presenting the concepts from one participant to another using a balanced Latin Square. We kept factors that might influence pedestrian behavior, such as vehicle speed, deceleration rates, and gaps between vehicles the same across all conditions. The participants' experimental task was to stand on the sidewalk, several steps away from traffic, and cross the street with the assistance of a given design concept.

4.2. Participants

To determine the required sample size, an a priori power analysis was performed using G*Power (Faul et al., 2009). With an alpha level of .05, a sample of 24 participants was adequate to detect a medium effect sizes (Pearson's $r = 0.25$) with a power of .81 (Cohen, 2013) for our measures.

We recruited 24 participants (62.5% female; 18–34 age range) through social media networks and word of mouth. The participants included working professionals and university students who had been living in the current city for at least 1 year and who could speak English fluently. All participants were required to have normal or corrected-to-normal eyesight,

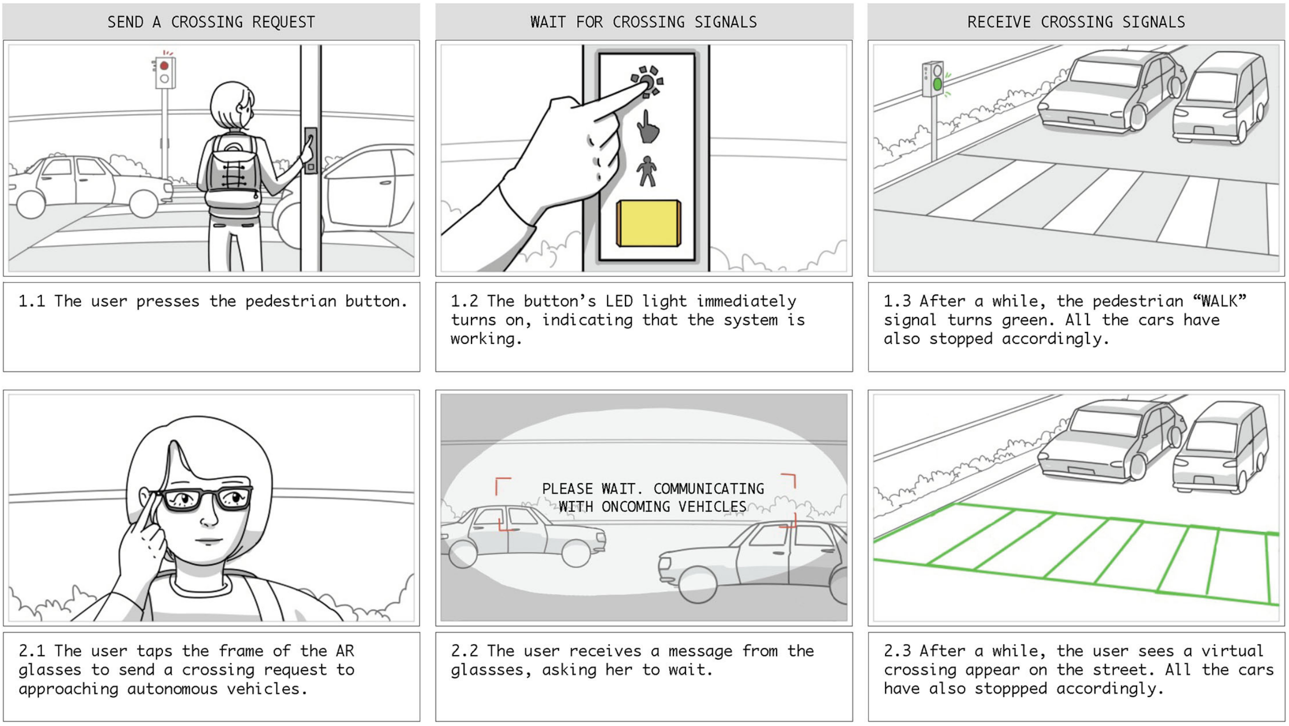

FIGURE 1 | Storyboard illustrating three-stage user interactions of the pedestrian button (top) and AR glasses (bottom). Only visual signals were depicted to keep the storyboard simple.

as well as no mobility impairment. Of our participants, 13 had tried VR a few times, and three had extensive experience with it. Meanwhile, only two participants reported having experienced AR once. Thirteen participants required prescription glasses; the remaining 11 had normal visual acuity, three of which had undergone laser eye surgery, and one was using orthokeratology (i.e., corneal reshaping therapy) to correct their vision. The study was conducted at a shared workspace in Ho Chi Minh City (Vietnam), following the ethical approval granted by the University of Sydney (ID 2020/779). Participants in this study did not receive any compensation.

4.3. VR Prototype

Apparatus. The VR prototype was developed using the Unity[2] game engine and experienced with the Oculus Quest 2 VR system[3]. The head-mounted display (HMD) provides a fully untethered 6DOF experience and hand tracking feature, allowing users to walk around freely and engage in VR naturally with their hands (**Figure 3**). The experiment was conducted in an 8x3-meter open floor space, where participants were able to physically walk two-thirds of the street before being teleported to the other side. The (auto) teleportation was used to overcome HMD tracking space limits and to ensure that participants could observe how the visual cues disappeared and the AVs resumed driving after their crossing.

Virtual environment. The virtual environment was modeled using commercially available off-the-shelf assets. The scene featured an unmarked midblock location on a two-way urban street. Pedestrian crossing facilities, including traffic lights and zebra crossings, were only available under the experimental condition where pedestrians crossed the street using the pedestrian push button. To create a more realistic social atmosphere, we used Mixamo 3D characters[4] to replicate human activities on the sidewalk: some individuals were exercising while others were speaking with one another. Additionally, an urban soundscape with bird chirping sounds and traffic noise was included.

The vehicles used in this experiment were obtained from the Unity Asset Store and comprised a black/orange sports car, a silver sedan, and a white hatchback to create a more natural perception of traffic. Despite their model differences, these vehicles had similar sizes and kinematic characteristics, both of which were found to influence pedestrian experience and behavior Dey et al. (2017). Vehicular traffic was composed of fully automated cars (Level 5) (SAE, 2021) traveling in both lanes. To create the perception of autonomous driving, we did not model people inside and implemented a futuristic Audi e-tron sound[5] for each vehicle. The number of vehicles in each lane varied, but they consistently traveled with impassable gaps to ensure that participants could not cross without the AVs yielding. In

[2]https://unity.com/
[3]https://www.oculus.com/quest-2/
[4]https://www.mixamo.com/
[5]https://www.e-tron-gt.audi/en/e-sound-13626

FIGURE 2 | Simulation environment and interfaces included in the evaluation: **(A)** Pedestrian push button; **(B)** AR crosswalk; **(C)** AR overlay; **(D)** AR-combined.

the simulation, the vehicles were spawned at a location hidden from the participants' view; they started accelerating and driving at approximately 30 km/h before making a right turn. When responding to pedestrians' crossing requests, the vehicles slowed down at a distance of 19 m, following the safe stopping distance recommended in urban zones[6]. They came to a complete stop at 1.5 m from the designated crossing area and only resumed driving once the participants had reached the other side of the road (refer to **Figure 4**).

Evaluated concepts. We commissioned a game artist to create a 3D model of the Prisma TS-903 button[7] used in the city where the study took place. In VR, participants could use their hands to engage with the button in the same way they would in real life (refer to **Figure 2A**). To experience the wearable AR concepts, participants used the VR headset as if it was a pair of AR glasses and were instructed to tap on its side whenever they planned to cross. On Oculus Quest 2, this type of tap gesture was not available; it was prototyped by creating an invisible collision zone around the HMD that detects any contact with the user's fingertips. The tapping immediately triggers sound feedback and displays an HUD text prompt *"Please wait. Communicating with oncoming vehicles"* in users' primary field of vision. After 9 s, all AVs responded to the pedestrian crossing request by decelerating at a distance of 19 m and displaying the car overlays. However, those with a short stopping distance (already approaching the pedestrians when the request was received) continued to drive past to avoid harsh braking. To account for these cars, a 3-s delay was put in place to make sure that the AR zebra crossing only appeared when the crossing area was safe. The design of the zebra crossing was inspired by the Mercedes-Benz F 015 concept[8], with bright neon green lines and flowing animation (refer to **Figure 2B**). The car overlay was made of semi-transparent emissive green texture and appeared to be a separate layer from the car (refer to **Figure 2C**). Both the zebra crossing and the car overlay are conformal AR graphics situated as parts of the real world. In addition to visual cues, we offered audible signals to indicate wait time (slow chirps) and crossing time (rapid tick-tock-tick-tock). These sounds are part of the Australian PB/5 push button signaling system[9], and they were implemented across four experimental conditions.

[6] https://roadsafety.transport.nsw.gov.au/speeding/index.html
[7] https://www.prismatibro.se/en/prisma-ts-903-eng/
[8] https://www.mercedes-benz.com/en/innovation/autonomous/research-vehicle-f-015-luxury-in-motion/
[9] https://www.maas.museum/inside-the-collection/2010/04/16/pedestrian-button-1980s-australian-product-design-pt2/

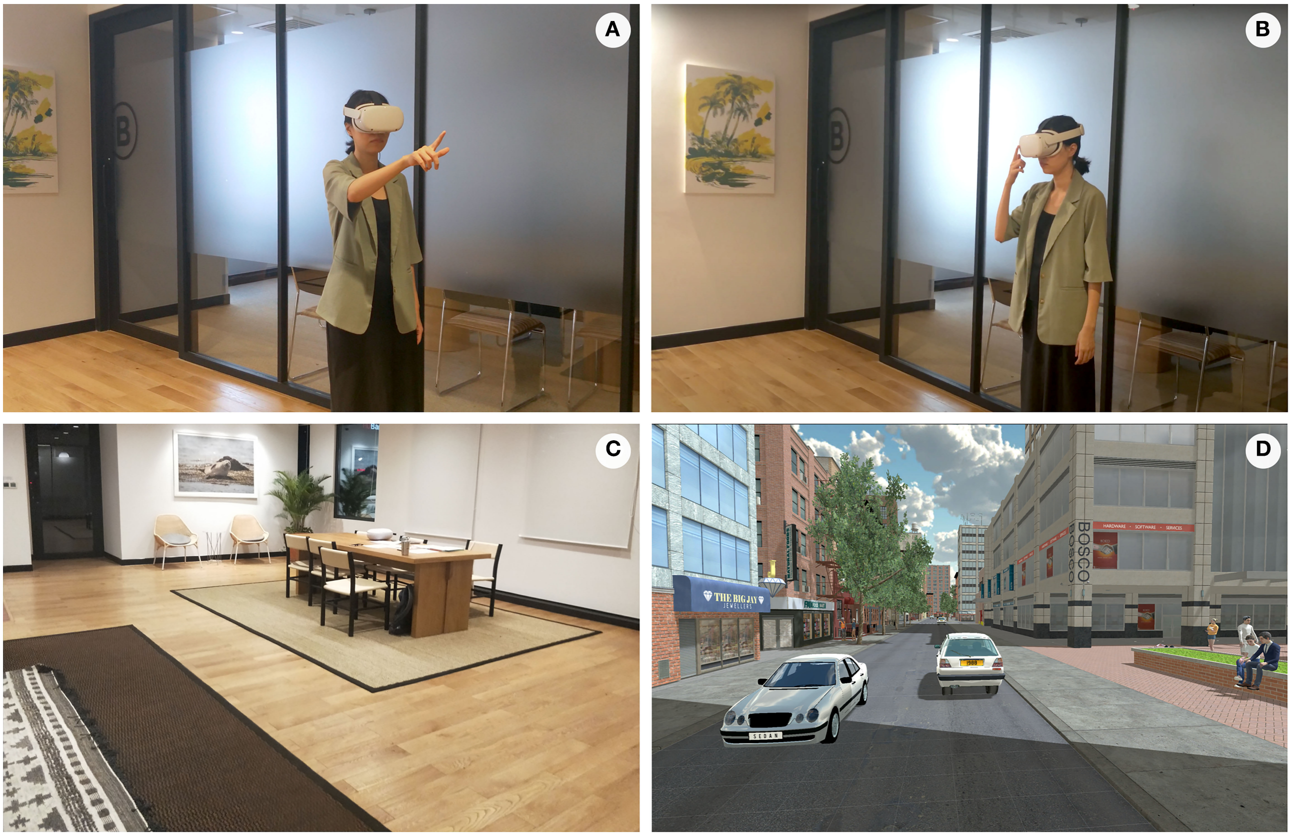

FIGURE 3 | Experimental setup: **(A)** the participant pressing the (virtual) pedestrian button; **(B)** the participant tapping the side of the HMD; **(C)** walking space and interview table; **(D)** virtual environment.

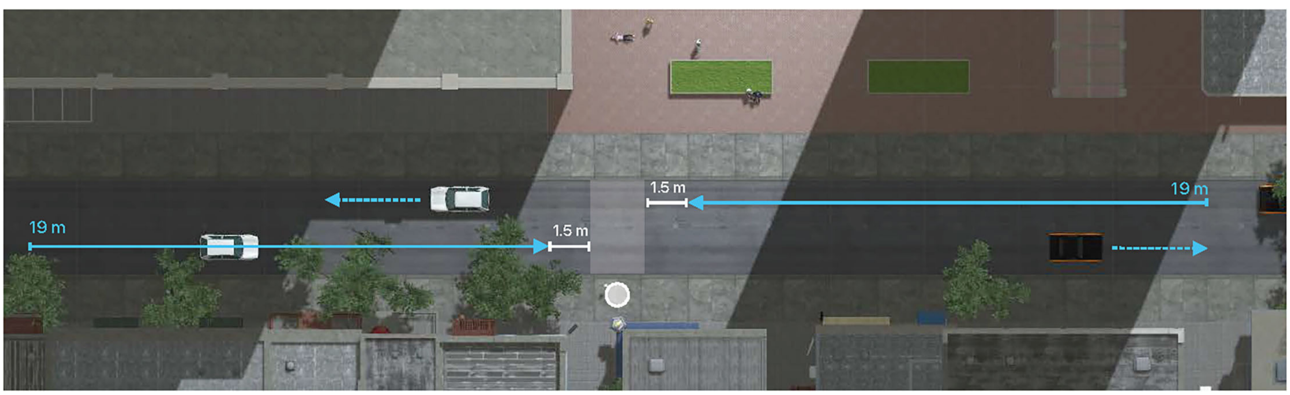

FIGURE 4 | A top-down view of the virtual environment zooms in on the midblock location where participants made the crossing. Dotted blue arrows indicate the travel direction of AVs. Solid blue arrows indicate where the AVs (on each lane) begin to decelerate and where they come to a complete halt. The white circle indicates the pedestrian position at the start of each experimental condition.

4.4. Procedures

After the participants had signed up for the study, a screening questionnaire was used to obtain their demographic information, including age group, gender, English proficiency level, occupation, nationality, length of stay in the current city, walking issues, and eye conditions. On the day of the study, we welcomed the participants and gave them a brief overview of the study and the related tasks. The participants were then asked to read and sign a consent form. Following a quick introduction to the VR system, we asked the participants to put on the HMD and adjust it until they felt comfortable and could see the virtual environment clearly. A glasses spacer was inserted in the HMD such that the participants could wear the headset with their glasses on.

Before beginning the experiment, the participants took part in a familiarization session in which they practiced crossing the street and interacting with virtual objects with their hands. Prior to each experimental condition, we presented the participants with an image of the pedestrian push button or the AR glasses to gauge their familiarity with the technology and inform them about the system with which they would be engaging. However, they were not made aware of the differences between the wearable AR concepts. After each condition, the participants removed their headsets and completed a series of standardized questionnaires at a nearby table. We also ensured that no participant was experiencing motion sickness and that all could continue with the experiment. After all the conditions had been completed, we conducted a semi-structured interview to gain insights into their experiences.

4.5. Data Collection

After each experimental condition, we monitored participants' simulator sickness with the single-item Misery Scale (Bos et al., 2010). If the rating was four or higher, the study would be suspended. We then measured perceived cognitive load with the NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988) on a 20-point scale. The questionnaire has six workload-related dimensions: Mental Demand, Physical Demand, Temporal Demand, Performance, Effort, and Frustration. These dimensions were combined into one general cognitive load scale Cronbach's $\alpha = 0.783$). To assess trust in human-machine systems, we used a 12-item trust scale (Jian et al., 2000). The first five items provided an overall distrust score (Cronbach's $\alpha = 0.896$); the next seven items provided an overall trust score (Cronbach's $\alpha = 0.941$). Finally, the 10-item System Usability Scale (Brooke et al., 1996) was used to measure usability (Cronbach's $\alpha = 0.909$). All the questionnaires were explained to the participants and administered under supervision. We also instructed participants to assess the prototyped systems instead of the VR representation.

After the completion of all experimental conditions, the participants were asked to rank the systems from 1 (most preferred) to 4 (least preferred). Additionally, a semi-structured interview was conducted to gain a better understanding of their overall experience, the reasoning behind their preferences, and their perspectives on various system aspects and the VR simulation.

4.6. Data Analysis

Questionnaires: We first calculated summary statistics and created data plots to investigate the data sets. We assessed the normality of data using Shapiro-Wilk tests and a visual inspection of their Q-Q plots. Because most data have non-normal distribution, we used the non-parametric Friedman test to determine any statistically significant differences in questionnaire outcomes. In case of significant differences, we performed Dunn-Bonferroni procedure for multiple pairwise comparisons as *post-hoc* tests. We considered an effect to be significant if $p < .05$. IPM SPSS version 28 was used for all statistical analyses.

Interviews: Post-study interviews were transcribed by the interviewer with the assistance of an AI-based transcription tool. Two coders performed an inductive thematic analysis (Braun and Clarke, 2006) to identify and interpret patterns (themes) within the data. The first coder (TT) had extensive knowledge of the study, while the second coder (YW) was not involved in its conception and implementation. This approach enabled us to have a more complete and unbiased look at the data.

The analysis began with the first coder selecting a subset of six interviews (25% data units) with good representativeness. The first round of coding was performed independently by both coders, followed by a discussion to agree on the coding frame. In the second round, the first coder applied the coding frame to all interviews. Finally, we examined the themes and patterns that emerged, which composed part of the Results section.

5. RESULTS

5.1. Concept Ranking

Regarding the top preference (first ranking), approximately half of the participants preferred the AR concept incorporating both the animated crosswalk and car overlays, while one-third favored the pedestrian button. The *AR overlay*, followed by the *AR crosswalk*, was the least preferred (refer to **Table 1**).

A Friedman test showed a significant difference in the mean rankings among concepts ($\chi^2(3) = 29.850, p < 0.001$). *Post-hoc* tests revealed that the *AR-combined* (*mdn* = 1.0) was rated significantly higher than the *AR crosswalk* (*mdn* = 3.0) ($z = 1.375, p_{corrected} = 0.001$) and *AR overlay* (*mdn* = 4.0) ($z = 1.875, p_{corrected} = 0.000$) but not the pedestrian button ($p_{corrected} = 0.705$). The pedestrian button (*mdn* = 2.0) was rated significantly higher than the *AR overlay* (*mdn* = 4.0) ($z = -1.292, p_{corrected} = 0.003$).

5.2. SUS

Based on the grade rankings created by Bangor et al. (2009), the System Usability Scale (SUS) scores of the *Button* and the *AR-combined* were considered as "excellent." The *AR crosswalk* and the *AR overlay* had lower scores which were in the "good" range (refer to **Table 2**). A Friedman test indicated a significant main effect of the concepts on the usability scores ($\chi^2(3) = 10.808, p = 0.013$). *Post-hoc* analysis revealed that the usability scores were statistically significantly different between the *Button* (*mdn* = 85) and the *AR overlay* (*mdn* = 77.50), ($z = 1.063, p_{corrected} = 0.026$), as shown in **Figure 5**.

5.3. NASA-TLX

Descriptive data analysis showed that the overall scores were low for all concepts; however, the *AR-combined* elicited the least cognitive load (refer to **Table 2**). A Friedman test showed a significant difference in the overall mean scores ($\chi^2(3) = 11.535, p = 0.009$). *Post-hoc* tests revealed that the *AR crosswalk* received significantly higher cognitive load scores (*mdn* = 18.33) compared to the *AR-combined* (*mdn* = 10.84) ($z = 1.000, p_{corrected} = 0.044$), as shown in **Figure 6**.

TABLE 1 | Ranking results by frequency of nomination.

	Button	AR crosswalk	AR overlay	AR-combined
1st rank	8	2	1	13
2nd rank	8	6	1	9
3rd rank	5	8	9	2
4th rank	3	8	13	0

TABLE 2 | Mean (M) and standard deviation (SD) for NASA-TLX scores, SUS scores, and Trust Scale ratings.

	Button (M / SD)	AR crosswalk (M / SD)	AR overlay (M / SD)	AR-combined (M / SD)
SUS	**85.31** / 12.30	**77.29** / 19.78	**74.48** / 20.61	**85.10** / 13.58
NASA-TLX	**20.94** / 13.87	**20.90** / 14.55	**21.35** / 14.23	**13.99** / 8.53
Trust (subscale)	**5.83** / .96	**5.02** / 1.39	**4.82** / 1.39	**5.52** / 1.17
Distrust (subscale)	**1.85** / 1.10	**2.32** / 1.21	**2.60** / 1.45	**1.99** / .94

Regarding subscales, the Friedman test found a statistically significant effect of the concepts on *temporal demand* ($\chi^2(3) = 12.426, p = 0.006$) and *frustration* ($\chi^2(3) = 8.392, p = 0.039$). The *post-hoc* tests showed no significant differences ($p_{corrected} > .05$). However, the uncorrected p-values indicated that the *AR-combined* received significantly lower scores in *temporal demand* compared to all other concepts.

5.4. Trust Scale

According to descriptive data analysis (refer to **Table 2**), the participant's trust in the three AR concepts was lower than in the *Button*, with the lowest trust in the *AR overlay*. Results from a Friedman test found a significant difference in the mean scores of trust ratings ($\chi^2(3) = 14.724, p = 0.002$). *Post-hoc* tests revealed that the *Button* ($mdn = 6.00$) received significantly higher trust ratings compared to the *AR crosswalk* ($mdn = 5.07$) ($z = 1.021, p_{corrected} = 0.037$) and the *AR overlay* ($mdn = 4.79$) ($z = 1.188, p_{corrected} = 0.009$), as shown in **Figure 7** on the left.

Participants' distrust in the three AR concepts, conversely, was higher than that in the *Button*, with the strongest level of distrust being shown in the *AR overlay* (refer to **Table 2**). A Friedman's test showed a significant difference in the mean ratings ($\chi^2(3) = 15.556, p = 0.001$). *Post-hoc* tests revealed that the *AR overlay* ($mdn = 2.10$) received significantly higher distrust ratings compared to the *Button* ($mdn = 1.50$) ($z = -1.167, p_{corrected} = 0.010$), as shown in **Figure 7** on the right.

5.5. Qualitative Feedback

This section presents the primary themes that emerged from our qualitative data analysis, providing insight into the participants' perceptions of wearable AR concepts and the design features that influenced their experiences.

(1) Wearable AR concepts were unfamiliar yet exciting: The post-study interviews showed that the participant's familiarity with the design solutions appeared to influence their trust in them. The pedestrian push button was perceived as highly familiar by a noticeable ratio of the participants ($n = 10$). This sense of familiarity was often linked to past experiences ($n = 8$) and had frequently resulted in feelings of confidence while crossing ($n = 7$). For example, P23 stated, *"I feel safer because it's something that I'm used to. I have the feeling that it's guaranteed."* Wearable AR applications, on the other hand, were regarded as novel and less familiar than the traditional infrastructure ($n = 6$), which might hinder their uptake, especially in the older generation (P4 and P20). As a result, several participants recommended that providing onboarding tutorials (P7) or a user manual (P2) might benefit their adoption. Furthermore, a number of participants stated that additional exposure to wearable AR applications is necessary to establish their dependability ($n = 7$) - *"I have only experienced it once. Maybe I need to interact and use it a few times. I need to try it more to know if it's reliable"* (P21). P7 added that knowledge of relevant statistics, such as the number of users of the AR system, could also contribute to an increase in trust.

Despite the unfamiliarity, wearable AR solutions were frequently described as exciting and cool (n = 5). As commented by P2, *"It's like I have mind control and being able to stop all the cars."* In contrast, the pedestrian push button was deemed to be a conventional system to support pedestrian crossing ($n = 4$), referred to as *"very old school"* (P16) and *"less technologically advanced"* (P13).

(2) Wearable AR offered both advantages and disadvantages as a personal device: The pedestrian push button baseline enabled a direct comparison of a solution based on personal devices with an infrastructure-based solution, producing a variety of insightful perspectives from the participants on the personal nature of AR eHMIs. The analysis showed that one of the most commonly noted advantages of wearable AR concepts is the increased flexibility of crossing locations ($n = 4$), as opposed to the fixed installation of the pedestrian push buttons. P7 found it particularly useful when *"[she] wants to cross the street in a hurry"* (P7). Furthermore, P5 noted that the precision of requests sent to the vehicles could result in higher efficiency—*"normal vehicles usually focus on the street; maybe they will miss my request to cross the street. If I use the AR glasses, it'd be quicker I think."* Nonetheless, cost ($n = 4$) and data privacy ($n = 4$) were identified as two of the most significant barriers to personal devices being adopted over public infrastructure. Two participants also raised concerns about circumstances where they might forget the personal device at home (P6 and P9) or do not wish to wear the AR glasses at times (P9). Similarly, personal devices were perceived to be inferior to public infrastructure in terms of liability ($n = 3$) and maintenance ($n = 2$). As commented by P8, *"because the button is of the government, if there's something happened, we can find somebody to blame,"* while P4 stated that *"[she] believe[s] there will be someone taking good care of a public system."*

(3) The physical form factor of the AR glasses was found to influence their acceptance: The idea of wearing glasses (or even contact lenses) was not appealing to individuals who had undergone eye corrective surgery. The concern was less about

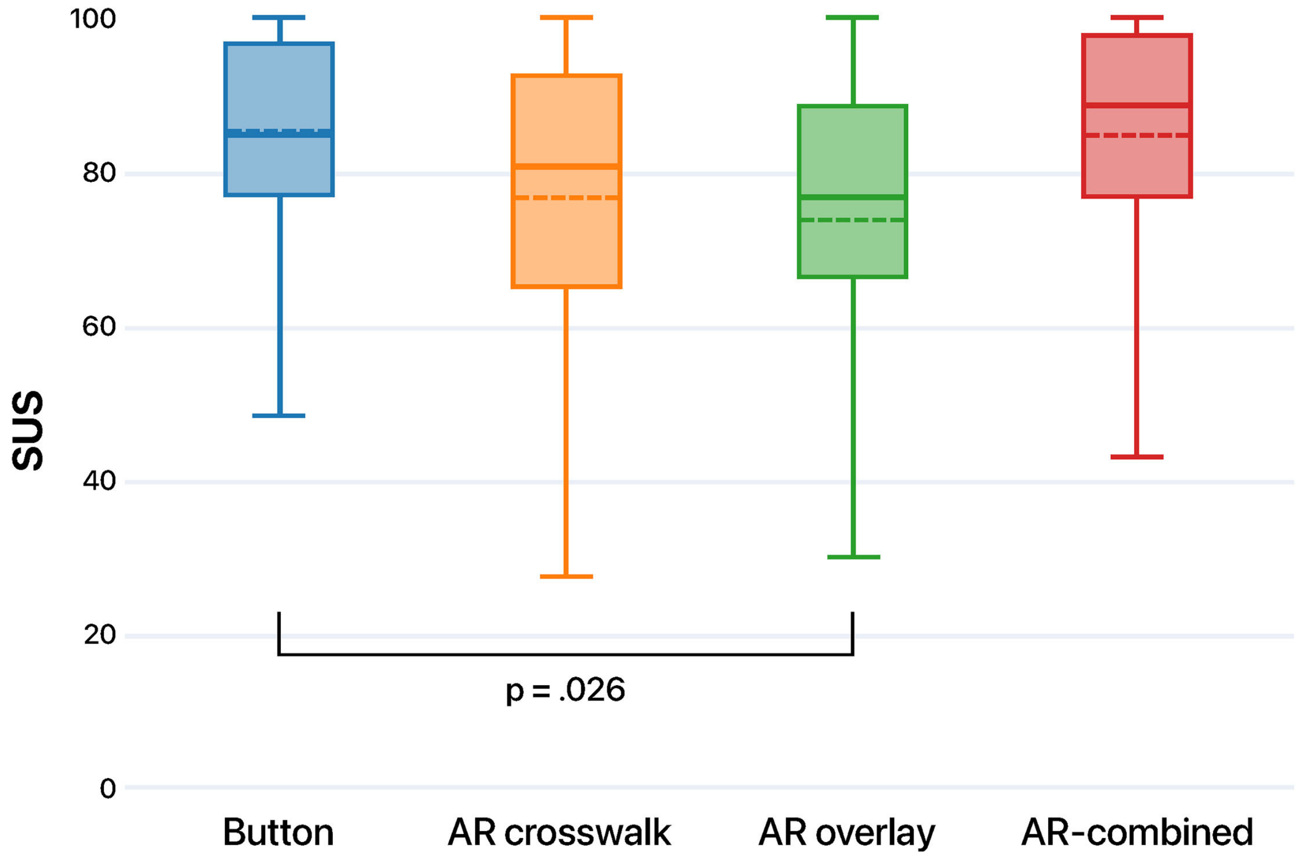

FIGURE 5 | Results of the SUS questionnaire. Median = solid line; mean = dotted line, p-values reported for significant pairwise comparisons.

the aesthetic qualities of the AR glasses but more about the (re)dependence on eyewear on a daily basis (n = 3). Three participants questioned the necessity of using AR glasses to aid in crossing. Furthermore, two people suggested smartphones (P1), smartwatches (P8), and AVs' pedestrian detection feature (P8) as alternative solutions to wearing AR glasses. Nonetheless, three participants identified the potential of using AR glasses for multiple purposes, such as reading the news and watching television (P9), rather than solely assisting in crossing.

(4) User-initiated communication provided a sense of control: When questioned about the preferred mode of interaction, all participants (n = 24) responded that they favored sending a crossing request to AVs rather than waiting for the vehicles to detect their intentions. We found that the participants' reasoning regarding this preference revolved around two aspects. First, some participants were skeptical about the ability of AVs to capture intricate human intentions (n = 13), stating that pedestrians may cross the street "*spontaneously*" (P12), "*change their minds*" quickly, or move in ways that suggest something unintentionally (P16). One participant doubted the reliability of algorithms that learn from "*previously fed data*" (P13). Second, some participants preferred to have some control over the interaction (n = 9); according to them, proactive communication with AVs was deemed critical for ensuring accuracy and hence safety (n = 9). Concerns about the passivity and uncertainty associated with waiting were also mentioned: *"I have no way to know that whether they will stop or not. What if [the cars] just keep moving?"* (P21).

The qualitative analysis further suggested that the participants preferred a digital approach over bodily gestures (e.g., waving hands), owing to the lack of confidence that AVs would all be able to observe their signals (n = 7). For example, P15 stated, *"If I raise my hand, I'm not sure if all cars see it."* Nonetheless, whereas the integration with traffic lights enables the pedestrian buttons to operate effectively in mixed traffic situations, the practicality of wearable AR to communicate with manual vehicles (n = 5) and the extent to which human drivers cooperate (n = 6) were questioned. Furthermore, six participants expressed reservations about potential traffic disruptions in the event of many road users using the AR glasses for street crossing. P14 stated, *"what if there were 10, 20 people wearing glasses, but they do not cross the street at the same time?"*.

(5) Clear communication mechanisms with AVs influenced the perceived safety: We found that the perceived connection between the system used and AVs influenced the participants' feeling of safety. Regarding the AR glasses, the connection was seen as direct and explicit (n = 7). The provision of visual cues

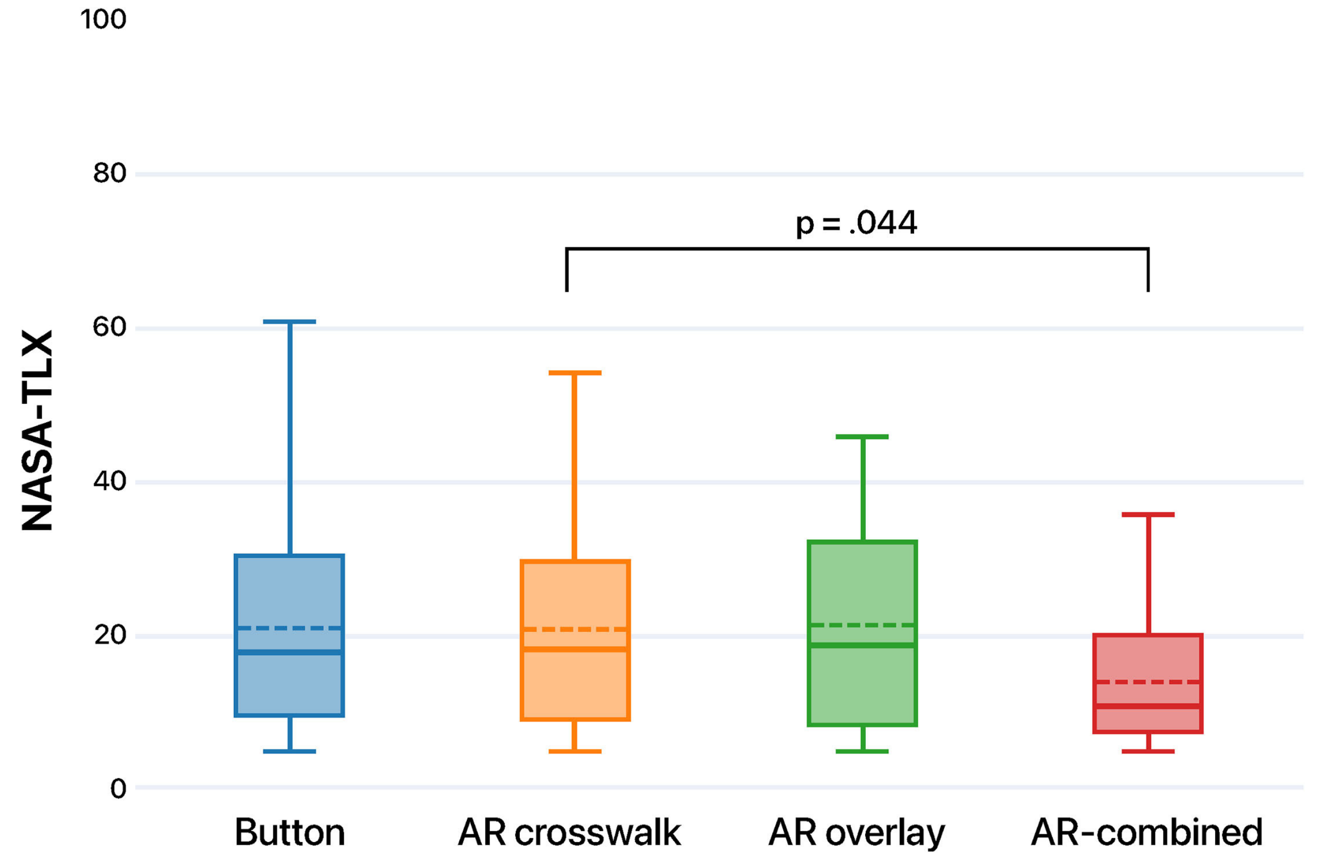

FIGURE 6 | Results of the NASA-TLX questionnaire. Median = solid line; mean = dotted line, *p*-values reported for significant pairwise comparisons.

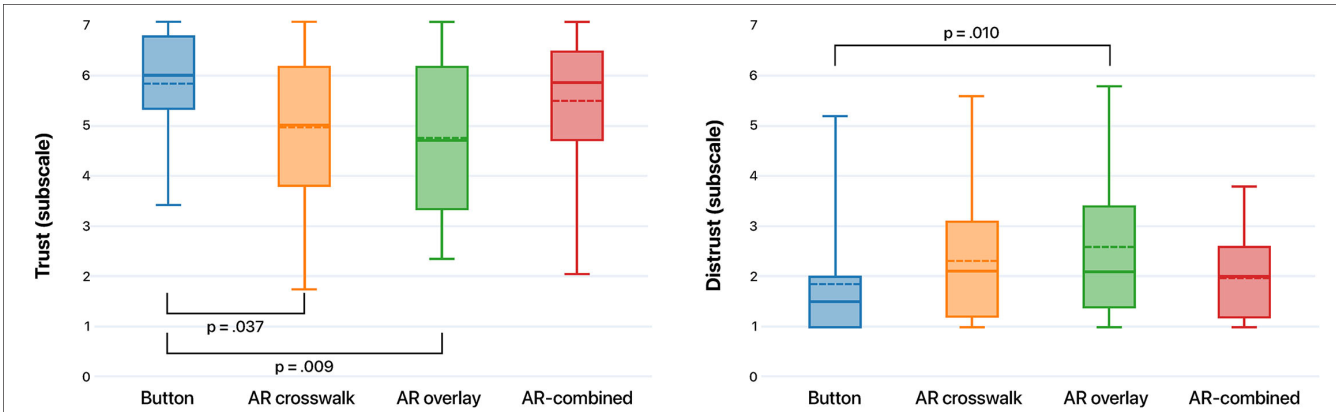

FIGURE 7 | Results of the Trust Scale questionnaire: trust subscale (left) and distrust subscale (right). Median = solid line; mean = dotted line, *p*-values reported for significant pairwise comparisons.

assured the participants that the connection was *"established"* and would continue to be maintained during their crossing, as reported by P1: *"I assumed that the vehicles would be waiting for me to finish the crossing. They will allow me as much as possible time to cross [. . .] because they may be connected to my glasses and aware of my presence."* In the case of the pedestrian button, user feedback revealed divided viewpoints. Eight participants were puzzled as to how the system "talked" to the vehicles. P21 thought that *"the digital context [was] missing*, while P17 viewed the two entities as *'disconnected.'"* Meanwhile, nine participants contended that the AVs came to a halt due to a changing traffic signal. P18 highlighted that the vehicles *"might have a sensor to read the color [sic] of the traffic light."* It was this interpretation and confidence in the ability of the traffic lights to regulate traffic that allowed these participants to feel more at ease in the interaction than the other group.

It is worth noting that several participants paid close attention to the technical aspects of the connection, highlighting possible risks that might occur with wearable AR concepts (n = 10). Five participants voiced concerns about the potential malfunctions of individual entities, which can imperil the operation of the integrated system. P6, e.g., mentioned a scenario where *"one vehicle does not comprehend the signal."* Three participants suggested connection failures, such as internet disconnections (P11) and signal transmission delays (P14). Two participants highlighted that the system might suffer from malicious manipulation (e.g., hacking).

(6) The combined approach provided extra security: Several participants reported that seeing the zebra crossing and car overlays simultaneously boosted their confidence (n = 12). In this regard, they reasoned that the dual cues provided *"extra"* security by exhibiting a strong integration of various entities (i.e., the AR glasses and the vehicles). As P19 explained, *"If there is a misconfiguration or anything that is not synchronized, I may be aware of that and know when the system has an issue."*

Furthermore, we noted several remarks on the perceived usefulness of each visual cue, shedding light on why their presence was instrumental in the pedestrian crossing experience. Approximately half of the participants interpreted the car overlay as a direct response from each vehicle to their crossing request (n = 11). P1, for instance, felt as though *"[the vehicles were] actually listening"* and that the connection worked. In scenarios lacking these individual confirmations, participants reported feeling uncertain about the AV yielding behavior (n = 3). As P21 expressed, *"[...] what if there are three or four lanes of cars? If I don't see this green thing, I feel a little bit worried. Maybe some cars will stop, and some will not stop,"* With respect to the zebra crossing, a sizeable proportion of the participants regarded it as a clear crossing signal due to its high visibility (n = 3) and familiarity (n = 9). The AR marking superimposed on the street also served as a visual cue indicating where the AVs would stop (n = 5).

6. DISCUSSION

In this section, we discuss the findings in relation to our research questions and reflect on the limitations of our study.

6.1. Preference for Wearable AR Concepts (RQ1)

The quantitative results indicated that employing wearable AR to aid AV-pedestrian interaction was a viable approach. This is evident in the case of the *AR-combined* concept, which was ranked higher than the baseline pedestrian button and significantly reduced the street-crossing cognitive load. In addition, even though the concept was rated marginally lower in usability and trust due to its unfamiliar nature, no statistically significant differences could be found. However, not all the wearable AR concepts performed similarly. The *AR overlay* and *AR crosswalk* both significantly induced higher distrust and lower trust compared to the baseline; they also received lower usability scores. The discrepancy in the ratings among the wearable AR concepts leads us to infer that the communication approach employed strongly influenced the pedestrians' subjective experiences. The qualitative feedback confirmed this observation and further suggested that the extent to which pedestrians preferred to use AR glasses to interact with AVs was also influenced by their perception of wearable AR technology.

With respect to wearable AR technology, the semi-structured interviews revealed important factors influencing pedestrians' adoption of AR solutions in interacting with AVs, including costs, data privacy, technical defects, liability risks, maintenance duties, and form factors. Although these problems were not widely discussed among the participants, they reinforce expert opinions that wearable AR should not be the sole means for pedestrians to cross the street or engage with AVs in general (Tabone et al., 2021a). Several participants suggested alternative methods of communication with AVs, such as using smartphones, which indicated that a user-initiated communication concept was appreciated more than the underlying AR technology. This inclination might be explained by smartphones' present ubiquity and their ecosystem of applications. As wearable AR is becoming more pervasive with continuous AR experiences (Grubert et al., 2016)—e.g., a pedestrian may use wearable AR for navigational instructions, communication with AVs when crossing the road, or retrieving information about the next train home—we hypothesize that pedestrian attitudes may shift in the future.

Concerning interactions with AVs in safety-critical settings, the participants unanimously agreed on the need to make their crossing intentions known to AVs. This finding is consistent with a prior study on bidirectional communication between pedestrians and AVs (Colley et al., 2021; Epke et al., 2021), which showed that a combination of hand gestures and receptive eHMIs was the most desired method of communication. However, while hand gestures have been previously observed to have limitations in terms of false-positive (Epke et al., 2021) or false-negative detection (Gruenefeld et al., 2019), a digital approach was viewed as safer and more trustworthy in our study. Additionally, using wearable AR for bidirectional communication not only ensures that AVs accurately interpret pedestrian intentions but might also eliminate potential confusion about AV non-yielding behaviors (Epke et al., 2021). For example, AR may be utilized to increase system transparency by explaining long wait times or a refusal to yield. According to prior study, explanations of AI system behavior can promote trust in and acceptance of autonomous driving (Koo et al., 2015). A substantial body of literature on explainable AI has focused on drivers' perspectives; nevertheless, a survey article has argued that the provision of meaningful explanations from AVs could also benefit other stakeholders (e.g., pedestrians) (Omeiza et al., 2021).

It was anticipated that wearable AR could readily enable targeted and high-resolution communication between AVs and individual pedestrians; a user could be assured that the AVs were addressing them because the device was used individually. In our study, the clarity of recipient was further reinforced when pedestrians were the ones who initiated the communication. However, despite the advantages of wearable AR concepts in delivering unambiguous messages, we found that the aspect of individual perceptions merits further discussion. According to qualitative data, the participants were concerned whether the proposed AR solutions would benefit urban traffic as a whole, as revealed by the raised concerns about frequent crossing requests. In this regard, P17 made a noteworthy comment about a possible shared perception among wearable AR users with regard to visual signals: *"if there are also other people, then I will prefer the crosswalk. People will be crossing the street at the same time and in the same place."* This comment leads us to believe that in certain situations, a shared AR experience (Rekimoto, 1996), where multiple users can see the same virtual elements, may help guide pedestrian traffic more efficiently. As a result, personal and shared (augmented) reality should both be considered when designing AR eHMIs.

6.2. Communication Strategies (RQ2)

The quantitative findings suggested that the *AR-combined* concept performed better than the *AR crosswalk* (aggregated response) and *AR overlay* (distributed response) across all measures, despite a statistically significant difference only being observed in the concept ranking. In terms of cognitive load, the uncorrected p-values indicated that combining visual signals could considerably reduce pedestrians' temporal demand as compared to presenting each cue individually, which might mean that when using the *AR-combined* concept, the participants felt less time-pressured as they crossed the road. This tendency was supported by qualitative findings where the participants reported feeling more confident during their crossings. To further understand the benefits and drawbacks of each communication approach, as well as why they were able to complement one another, we discuss them in further detail as follows.

(1) Aggregated response: As one of the most widely recognized traffic symbols, the marked pedestrian crossing was chosen to show an aggregated response from all incoming vehicles, indicating that they were aware of the pedestrians and would yield to them. We expected that this communication strategy would reduce the amount of time and effort required to read implicit or explicit cues from many vehicles. However, the analysis revealed that while the crosswalk indicated a clear signal to cross and a designated crossing area, the participants remained unsure of the AVs' yielding intention and relied more on vehicle kinematics to make crossing decisions. This finding appears to contradict those of Löcken et al. (2019), in which the participants began crossing as soon as the smart road's crosswalk lights had turned green, without waiting for AV signals. We believe that the difference in traffic scenarios (one vehicle vs. multiple vehicles) and the underlying technologies (smart infrastructure vs. personal devices) between the two studies might have contributed to divergent outcomes.

Notably, user interviews indicated that the participants were not familiar with the notion of connected vehicles; their hesitation persisted even after the leading vehicles had come to a complete stop. The fact that pedestrians do not perceive all AVs as a single system has also been observed during an evaluation of the "omniscient narrator," where one representative vehicle was in charge of aural communications (Colley et al., 2020a). However, it is worth noting that in our study, the crossing signal originated from the AR glasses rather than from one of the AVs. Therefore, it would be useful to further investigate the difference between the two approaches. Moreover, while (Colley et al., 2020a) expressed reservations about the practicality of aggregated communication in mixed traffic scenarios, we believe that the approach may be feasible with the introduction of connected vehicle technologies. Through the use of in-vehicle or aftermarket devices, vehicles of varying levels of automation can exchange data with other vehicles (V2V), roadside infrastructures (V2I), and networks (V2N) (Boban et al., 2018). Such connections may result in a gradual shift of pedestrian trust away from specific entities and toward the traffic system as a whole. For example, when responding to the Trust Scale questionnaire, several participants stated that they viewed AR glasses and AVs as a unified system.

(2) Distributed response: The multi-vehicle traffic situation highlighted the necessity for pedestrians to be guaranteed successful communication with every AV, as evident in the positive user feedback on the car overlay. However, a confounding factor was present in the results when some individuals overlooked the overlay, believing that the cars were *"always green."* We attributed the cause of this issue to the simulation of AR in VR, where the contrast between the augmented graphics and the "real" environment was not as accurate as it should have been. Additionally, we believe that the participants' attention might have been scattered in a scenario involving multiple vehicles. For instance, P21 stated that he had to turn left and right to observe the two-way traffic and, therefore, failed to notice *"the changing colors."* This issue of split attention in complex traffic situations might also present difficulties for distance-dependent eHMIs (Dey et al., 2020a), the encoded states of which change with the distance-to-arrival, as pedestrians may not notice the entire sequence.

Regarding the display of individual car responses in complex mixed traffic situations, the study findings of Mahadevan et al. (2019) have suggested that this approach would enable pedestrians to assess each vehicle's awareness and intent and distinguish AVs from other vehicle types. Nonetheless, even standardized eHMI elements could be problematic since each car manufacturer might opt for slightly different designs. As a result, we believe that wearable AR may present a good opportunity for consistent visual communication across vehicles and serve as a clear indicator of their current operation mode (manual vs. autonomous) as needed.

6.3. Limitations and Future Work

First, the findings of our study drew on the experiences of a small number of university students and young professionals. Although we anticipate comparable outcomes, a larger representative sample would be beneficial, particularly in resolving some borderline quantitative results. Furthermore, past research indicates that cultural differences may cause eHMIs to not have the same favorable effect across countries (Weber et al., 2019). Given that the participants in our study largely came from the same cultural background (92% Vietnamese, 8% Indian) and had similar habitual traffic behaviors, the feasibility of transferring the wearable AR concepts to differing cultures should be further investigated. Nevertheless, we argue that AR could easily offer personalized experiences, as opposed to vehicle-mounted or infrastructure-based eHMIs.

Second, the ecological validity of this study is limited by the use of a VR simulation. The virtual environment could not fully replicate the complex sensory stimuli found in the real world, and the safety associated with VR testing might have influenced individuals to engage in riskier crossing behaviors. Additionally, a few participants expressed anxiety over colliding with physical objects, despite our assurance otherwise. Nonetheless, the majority of the participants responded favorably to the simulation's realism, stating that they behaved similarly to how they would in the real world. They did not experience any particular motion sickness symptoms and were not affected by the short-distance teleportation implemented at two-thirds of their crossing. Existing literature also suggests that while achieving absolute validity and numerical predictions may not be possible, the VR method can effectively identify differences and patterns (Schneider and Bengler, 2020).

Finally, our study employed VR to prototype wearable AR concepts. Although this approach proved useful in overcoming the technical constraints of current AR HMDs, particularly in an outdoor setting, it was challenging for some participants to distinguish superimposed AR graphics from the virtual environment. To some extent, this issue confounded the results of the design concepts with car overlays (the *AR overlay* and the *AR-combined*), possibly causing them to be rated lower than they should have been. However, we believe that it did not invalidate the findings because the order of the four experimental conditions was counterbalanced, and the participants were able to recognize the visual cue in their second encounter. Furthermore, given the possibility of resolving this issue by contrasting display fidelity between AR and VR elements, we recommend that this VR simulation approach be considered in future study. With a large number of proposed AR design concepts in the literature, such as the nine prototypes created by Tabone et al. (2021b), comparison studies may provide intriguing insights into how AR systems best facilitate AV-pedestrian interaction.

7. CONCLUSION

This article has presented novel AR eHMIs designed to assist AV-pedestrian interaction in multi-vehicle traffic scenarios. Through a VR-based experiment, three wearable AR design concepts with differing communication approaches were evaluated against a pedestrian push button baseline. Our results showed that a wearable AR concept highlighting individual AV responses and offering a clear crossing signal is likely to reduce crossing pedestrians' cognitive load. Furthermore, enabling pedestrians to initiate the communication offered them a strong sense of control. This aspect of user control is currently underexplored in AV external communication research, pointing to important future work in this domain. Finally, the adoption of wearable AR solutions depends on various factors, and it is critical to consider how VRUs without AR devices can interact with AVs safely and intuitively.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because The University of Sydney Human Research Ethics Committee (HREC) has not granted the authors permission to publish the study data. Requests to access the datasets should be directed to tram.tran@sydney.edu.au.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The University of Sydney Human Research Ethics Committee (HREC). The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

TT contributed to conceptualization, data collection, data analysis, and writing (original draft, review, and editing). CP and MT contributed to conceptualization, writing (review and editing). YW contributed to data analysis, and writing (original draft, review, and editing). All authors have read and approved the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fcomp.2022.866516/full#supplementary-material

Supplementary Video 1 | Video showcasing wearable AR prototypes and the experimental setting of the study.

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Analysis of Implicit Communication of Motorists and Cyclists in Intersection Using Video and Trajectory Data

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The interaction of automated vehicles with vulnerable road users is one of the greatest challenges in the development of automated driving functions (ADF). In order to improve efficiency and ensure the safety of mixed traffic, ADF need to understand the intention of vulnerable road users, to adapt to their driving behavior, and to show its intention. However, this communication may occur in an implicit way, meaning they may communicate with vulnerable road users by using dynamic information, such as speed, distance, etc. Therefore, investigating patterns of implicit communication of human drivers with vulnerable road users is relevant for developing ADF. The aim of this study is to identify the patterns of implicit communication of human drivers with vulnerable road users. For this purpose, the interaction between right-turning motorists and crossing cyclists was investigated at a traffic light controlled urban intersection. In the scenario, motorists and cyclists had a green signal at the same time, but cyclist had right-of-way. Using the Application Platform for Intelligent Mobility (AIM) Research Intersection, trajectory and video data were recorded at an intersection in Braunschweig, Germany. Data had been recorded for 4 weeks. Based on the criticality metric post-encroachment time (PET) and quality of the recorded trajectory, 206 cases of interaction were selected for further analyses. According to the video annotation, when approaching the intersection, three common communication patterns were identified: (1) no yield, motorists, who should yield to cyclists, crossed the intersection first while forcing right-of-way; (2) active yield, motorists, who were in front of cyclists, gave the right-of-way; (3) passive yield, motorists, who were behind cyclists, had to give the right-of-way. The analysis of the trajectory data revealed different patterns of changes in time advantage in these three categories. Additionally, the communication patterns were evaluated with regard to frequency of occurrence, efficiency, and safety. The findings of this study may provide knowledge for the implementation of a communication strategy for ADF, contributing to traffic efficiency as well as ensuring safety in the interaction with vulnerable road users.

Keywords: vulnerable road users, implicit communication, intersection, right-turn, evaluation

INTRODUCTION

Communication between road users is an essential part of road traffic. In order to improve efficiency and ensure road traffic safety, road users need to understand the intention of other road users, to adapt to their driving behavior, and to show its intention. From the perspective of motorists, this communication can involve a series of explicit information, such as, facial expressions, gestures, eye contact, visual signs, or acoustic signals (Risser, 1985). However, recent studies revealed that pedestrians used vehicles' movement (e.g., speed and acceleration) rather than explicit communication cues to decide whether it is safe to cross (Dey and Terken, 2017; Lee et al., 2020). Moreover, in the self-driving future, automated driving functions (ADF) may be required to communicate its intention by using dynamic information. The interpersonal communication may be eventually replaced by a human-machine interface (HMI) that may mainly depend on the implicit cues. Therefore, to match prior experiences and expectations of the passengers and the surrounding road users (Bengler et al., 2020), it is relevant to investigate the patterns of implicit communication of human road users, particularly in safety-critical situations.

Communicating the intentions with each other is an essential part of a smooth cooperation, even in heavily regulated traffic situations (e.g., controlled by traffic lights, at which the right-of-way between crossing and turning traffic road users is regulated). One of the most common safety-critical scenario in the right-hand traffic is when motorized road users turn right at an intersection, while cyclists approach from the right side of the motorists and cross (Richter and Sachs, 2017). In this particular situation, motorists need to give right-of-way to cyclists. Mostly, motorists focused on the road that they planned to merge into and failed to observe right-of-way or failed to detect the cyclists (Polders et al., 2015). On the other hand, injured cyclists stated that they expected that motorists would give right-of-way, as this corresponded to the regulation (Räsänen and Summala, 1998). The results from the investigations and the crash analyses show that traffic regulation alone does not prevent critical situations between motorists and cyclists. For example, studies showed that motorists do not always give right-of-way to crossing pedestrians and cyclists (referred to as vulnerable road users; VRU) when leaving the roundabout, although the right-of-way of VRU is regulated (Räsänen and Summala, 1998; Silvano et al., 2015). The interpretation is that, in addition to traffic safety, individual time efficiency and comfort are also relevant, suggesting road users compromise between following the rules and individual preferences (Nygårdhs et al., 2020). This may be a challenge for ADF. While it needs to understand the current circumstance, incl. traffic regulations, infrastructure, and surrounding road users, it also needs to consider personal preferences without sacrificing safety.

The kinematic information of other road users or the temporal and spatial relationships between road users are usually considered as implicit communication cues. Fuest et al. (2018) conducted a field study investigating implicit communication in a shared space and suggested that pedestrians decide on whether to cross the road by observing changes in vehicle speed. Usually, deceleration is understood as "give way" (Beggiato et al., 2017; Ackermann et al., 2018). On the other hand, a higher velocity of the vehicle is not perceived as giving right-of-way to other road users (Himanen and Kulmala, 1988; Šucha, 2014; Silvano et al., 2015). Furthermore, time-proximity indicators are also considered as implicit communication cues. For example, post-encroachment time (PET) is an observed time describing the time interval by which two road users missed each other. Time advantage (TAdv) is used to predict the time that two road users would miss each other, if they would continue with the same speed and trajectories. In previous studies, TAdv was applied for risk estimation (Saul et al., 2021) and also used to indicate which road user temporarily dominates: A road user with larger TAdv probably passes first (Laureshyn et al., 2010). Additionally, road users' decision may also rely on the physical distance from the junction. Assuming that TAdv is one second, compared with the road users, who are 10 meters away from the junction, those who are 100 meters away, may have a better chance to adjust their speed and trajectories.

A number of traffic safety studies involved implicit communication between motorists and vulnerable road users in intersections. In previous studies, implicit communication was usually divided into two categories (motorists yielding and motorists not yielding) in the light of which road user crosses first (Sakshaug et al., 2010; De Ceunynck et al., 2013; Silvano et al., 2015). Várhelyi (1998) generalized three categories of vehicle's braking behavior (no braking, provoked braking, and ideal interactions), when approaching a zebra crossing. Furthermore, focusing on the yielding behavior, van Haperen et al. (2018) defined four types of crossing behavior: taking, getting, forcing, and receiving describing the most common implicit communication patterns between motorists and cyclists in intersections. However, the consideration of implicit communication processes as well as the evaluation of implicit communication patterns were rare.

The aim of this study is to reveal the implicit communication patterns by analyzing one of the most common safety-critical situations, right-turning motorist and crossing cyclist. The implicit communication patterns were described by analyzing road users' behavior, particularly, from the perspective of motorists. The following research questions will be answered: What categories of implicit communication can be identified? What is the frequency of the categories of implicit communication? How does implicit communication effect efficiency and safety?

METHODS

Infrastructure

As part of the Intelligent Mobility Application Platform (AIM), an infrastructural detection system was implemented at the intersection of Hagenring/Rebenring in Braunschweig (Knake-Langhorst et al., 2016). Two poles equipped with stereo cameras and infrared lighting were installed at the Western and Southern ford of the intersection enabling the detection of crossing cyclists and right-turning motorists in the Eastern arm when approaching the intersection (approx. 35–40 m) and the point of conflict at the intersection (see **Figure 1**). The output of the system is trajectory data with corresponding videos. The data from the two sensor systems were merged and processed in real time with a sampling rate of 25 Hz. The position of the road user in the Universal Transverse Mercator (UTM) system and the size and category of the road user were detected in the video. The corresponding trajectory data was derived from the video data. In addition, speed, acceleration, and heading of the road user were also derived by using the position of the road user. Road users were assigned to the following categories: cars, trucks, vans, cyclists, pedestrians. The video material of road users and events was anonymized in real time and saved with a low resolution so that neither license plates nor faces were recognized or tracked.

FIGURE 2 | Trajectories of 206 selected cases.

Material

The data had been recorded for 4 weeks: From August 22nd to September, 18th 2016. In order to find the valid interactions of right-turning motorists and crossing cyclists, the PET was used. According to previous studies (Svensson, 1998; Zangenehpour et al., 2016; Johnsson, 2020), interactions with a PET value of less than 1.5 s were considered as dangerous or very dangerous interaction. We chose a higher threshold (i.e., PET < 2.5 s) as we aimed at identifying a wide range of interaction behavior. Altogether, 1,201 interactions of turning motorists and crossing cyclists were initially selected as candidates. Additionally, in order to ensure the quality of the required data for subsequent analysis, we used a package of the density-based spatial clustering of applications with noise (DBSCAN, Hahsler et al., 2019) in the R programming language to cluster the valid paths and exclude cases that contained a high proportion of data outside the valid path. Poor detection may cause road users to appear outside the valid path. Particularly, road users may indeed appear outside the valid path, for instance, when cyclists travel on the sidewalk instead of the bicycle lane. Those cases were also excluded, since they were considered as not representative of normal cycling behavior. Thus, 206 cases of interaction were selected for further analyses (see **Figure 2**).

Scenario

We focused on the scenario, in which motorists turned right from Hans-Sommer-Strasse into Brucknerstrasse, while cyclists crossed the intersection of Hans-Sommer-Strasse (see **Figure 1A**). In the scenario, motorists were on the right turn lane and cyclists on the protected bicycle lane. They had a green signal at the same time, but according to the local traffic regulations, cyclist had right-of-way. The data in the area from when both of

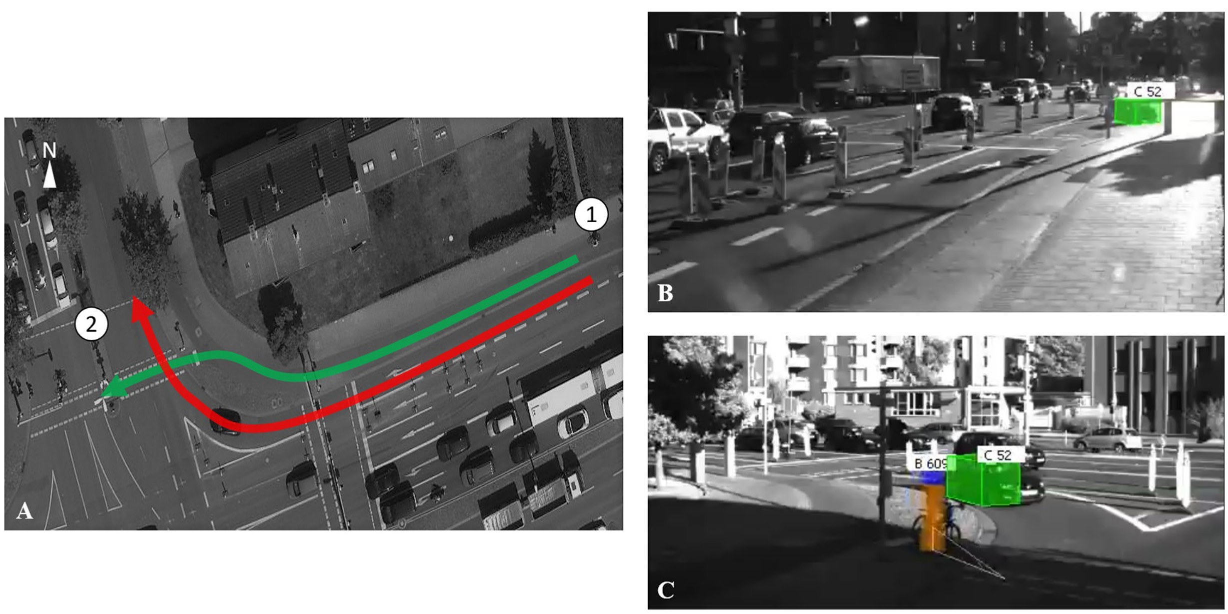

FIGURE 1 | (A) Path of right-turning motorists (red) and crossing cyclists (green) as well as the positions of two poles. **(B)** The view of camera one. **(C)** The view of camera two.

the road users were detectable [about 35–40 meters (m) before the intersection] to when one of the road users exceeded the junction of two paths was considered as the valid data, in which the subsequent annotation and analysis were performed.

In the video annotation, changes in relative position of the right-turning motorist and the crossing cyclist was coded. Therewith, several common interaction patterns between motorists and cyclists were identified when approaching the intersection: For example, motorists were in front of cyclists at all times; motorists were in front, then abreast, and, in the end, behind cyclists; motorists stayed behind cyclists; motorists were behind, then abreast, and, again, behind cyclist.

In order to classify the annotated interaction patterns and give them a semantic meaning, we revised and used the classification of the yielding behavior proposed by van Haperen et al. (2018). According to the previously annotated changes in relative position, the following three categories were defined from the perspective of motorists:

- No yield: The motorist, who should yield to the cyclist, crosses the intersection first while forcing right-of-way (incl. the cases, when motorists were in front of cyclists in the end).
- Active yield: The motorist, who is in front of the cyclist, gives the right-of-way (incl. the cases, motorists were in front of cyclists at first and in the end behind cyclists).
- Passive yield: The motorist, who is behind the cyclist, gives the right-of-way (incl. the cases, motorists were abreast or behind cyclists at first and in the end behind cyclists).

In the original version of yielding behavior classification, a fourth category is proposed describing the situation in which the cyclist gives right-of-way through explicit communication cues (e.g., waving to a driver). Due to the low resolution, we could not identify the waving movement. Thus, receiving was not considered in the following analysis.

Analysis

We investigated the communication categories, no yield, active yield, and passive yield, through the indicators of frequency of occurrence, efficiency, and safety dimension. We used relative frequency to indicate the frequency of occurrence of a communication category. Journey time and standard deviation (SD) of speed was used for efficiency of communication categories. Given that the detection range is consistent and the driving/riding range is limited to the road segment, the journey time is associated with the velocity. With regard to the safety analysis, PET and T2 was used. Additionally, the perspectives of different road users were also considered in the analysis (see details in **Table 1**).

According to the results of Shapiro–Wilk normality tests, journey time, SD of vehicle speed, PET, and T2 were not normally distributed [journey time of both: the statistic of Shapiro–Wilk tests (W) = 0.94, p-value (p) < 0.001; journey time of vehicle: $W = 0.96$, $p < 0.001$; journey time of bicycle: $W = 0.96$, $p < 0.001$; SD of vehicle speed: $W = 0.98$, $p < 0.05$; PET: $W = 0.88$, $p < 0.001$; T2: $W = 0.90$, $p < 0.01$]. Therefore, we used Kruskal–Wallis tests as well as pairwise Wilcoxon-Tests (with Holm method for adjusting p-values) to analyze the effect of communication categories on journey time, PET, and T2, respectively. The results were converted into Z-score. To determine the effect size of Kruskal–Wallis tests, the parameter η^2 recommended by Tomczak and Tomczak (2014) was used. Hereby, the effect size is low when η^2 less than 0.06, medium when η^2 less is than 0.14 and large when η^2 is greater than 0.14. One-way ANOVA was applied to exam the effect of communication categories on SD of bicycle speed. Additionally, we used pairwise t-tests (with Holm method for adjusting p-values) to compare between categories. For significant effects, the Cohen's f was provided, where 0.1, 0.25, and 0.4 represent low, medium, and large effect size, respectively. The significance level of $\alpha = 0.05$ was used for the overall test.

RESULTS

Description of Implicit Communication Patterns

In summary, 206 interactions between right-turning motorists and crossing cyclists were annotated. According to the changes in relative position, they were classified into three categories: no yield, active yield, and passive yield. **Figure 3** shows the different implicit communication processes of these three categories by using averaged TAdv on vehicle's distance to conflict point, meaning that the predicted time, that two road users would miss each other, was averaged within the category at each point.

TABLE 1 | Description of Indicators, which were used in analysis.

Dimension	Indicator	Perspective	Description
Frequency	proportion (%)	Both	The proportion of categories in the defined scenario
Efficiency	Journey time [s]	Both	The time interval from when the one of the road users appears to when both leave the intersection
		Vehicle	The time interval from when the vehicle appears to when it leaves the intersection
		Bicycle	The time interval from when the bicycle appears to when it leaves the intersection
	Standard deviation (SD) of speed (m/s)	Vehicle	Standard deviation of vehicle speed
		Bicycle	Standard deviation of bicycle speed
Safety	PET (s)	Both	Post-encroachment time of the interaction between two road users.
	T2 (s)	Both	The arriving time of the second (later) road user, at the moment when the first road user arrives at the crossing point.

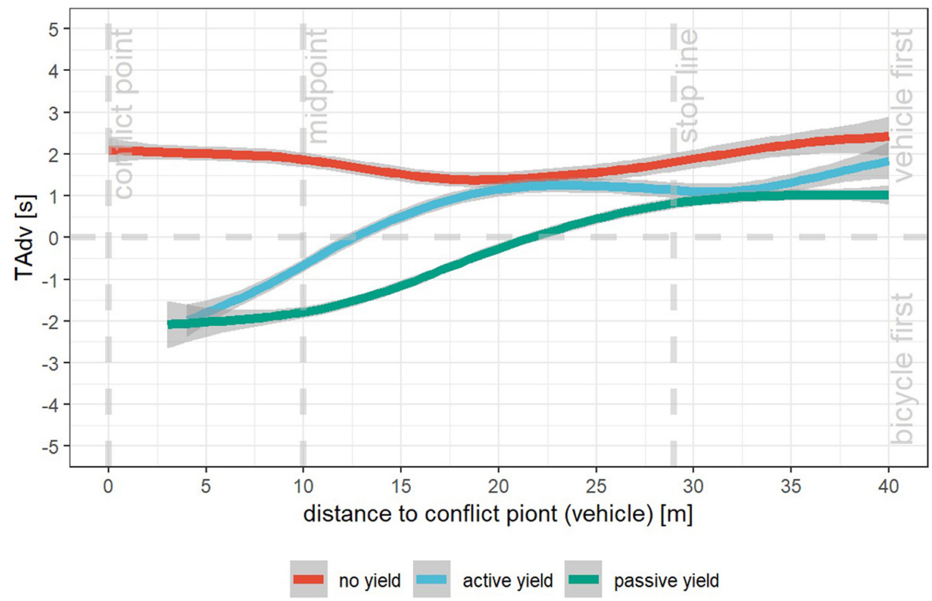

FIGURE 3 | Averaged TAdv in no yield (red), active yield (blue), and passive yield (green) on vehicle's distance to conflict point.

In **Figure 3**, before the stop line, results of TAdv indicate that independent of the corresponding category, vehicles are generally in front of bicycles and are supposed to cross first, if both of the road users maintain their speed and trajectories. At the stop line and at the 20 m before conflict point, motorists in passive yield and in active yield start to lose their advantage. On the contrary, motorists in no yield lead the way and the TAdv is almost always above 1 s. According to the changes in TAdv, the three communication categories present completely different patterns. However, they have one thing in common: the second road user (cyclist in no yield, motorist in active yield and passive yield) always crossed with a time gap of approx. 2 s.

Frequency of Occurrence

In 177 (86%) cases, cyclists crossed the intersection before motorists, while only 29 (14%) motorists crossed the intersection first. Additionally, according to their relative position, the cases were classified into three categories: no yield (29, 14%), active yield (103, 50%), and passive yield (74, 36%).

Efficiency

From the perspective of both road users, the Kruskal–Wallis tests indicated significant differences in journey time across the communication categories no yield, active yield, and passive yield ($Z = 6.25$, $p < 0.001$, $\eta^2 = 0.2$). According to the pairwise comparisons using Wilcoxon tests ($\alpha = 0.05$), the journey time of both road users in active yield [median (Mdn) = 13.56 s, interquartile range (IQR) = 2.82 s] was significantly greater than in no yield (Mdn = 11.4 s, IQR = 2.92 s, $Z = 3.51$, $p < 0.001$) and in passive yield (Mdn = 11.24 s, IQR = 2.12 s, $Z = 5.97$, $p < 0.001$). There was no difference between the journey time of both road users in no yield and passive yield ($Z = 1.71$, $p = 0.96$). From the perspective of the motorists, a significant difference was observed between the categories no yield, active yield, and passive yield ($Z = 10.11$, $p < 0.001$, $\eta^2 = 0.52$). According to the results of the Wilcoxon tests ($\alpha = 0.05$), the journey time of vehicle in active yield (Mdn = 13.48 s, IQR = 3.06 s) was significantly greater than in no yield (Mdn = 10.56 s, IQR = 4.24 s, $Z = 4.61$, $p < 0.001$) and in passive yield (Mdn = 9.16 s, IQR = 1.93 s, $Z = 10.01$, $p < 0.001$). The journey time of vehicle in no yield was greater than in passive yield ($Z = 2.04$, $p < 0.05$). From the perspective of bicycle, a significant difference was observed between the categories no yield, active yield, and passive yield according to the Kruskal–Wallis tests ($Z = 2.91$, $p < 0.001$, $\eta^2 = 0.05$). The journey time of bicycle was greater in passive yield (Mdn = 8.58 s, IQR = 2.26 s) than in active yield (Mdn = 7.84 s, IQR = 1.54 s, $Z = 2.78$, $p < 0.001$). There was no difference between passive yield and no yield (Mdn = 7.96 s, IQR = 1.56 s, $Z = 0.91$, $p = 0.18$) and between active yield and no yield ($Z = 0.02$, $p = 0.51$) (see **Figure 4**).

The Kruskal–Wallis tests indicated a significant difference in SD of vehicle speed between the communication categories ($Z = 5.78$, $p < 0.001$, $\eta^2 = 0.18$). According to the pairwise comparisons using Wilcoxon tests ($\alpha = 0.05$), the SD of vehicle speed in no yield (Mdn = 1.44 m/s, IQR = 0.4 m/s) was significantly less than in active yield (Mdn = 2.21 m/s, IQR = 1.17 m/s, $Z = 5.43$, $p < 0.001$) and in passive yield (Mdn = 2.23 m/s, IQR = 0.8 m/s, $Z = 5.38$, $p < 0.001$). There was no difference between the SD of vehicle speed in active yield and passive yield ($Z = 0.06$, $p = 0.48$) (see **Figure 4**).

The one-way ANOVA indicated no significant difference in SD of bicycle speed between the communication categories [$F(2,203) = 1.29$, $p = 0.28$, $f = 0.11$]. The mean SD of bicycle speed in no yield, active yield, and passive yield were 1.64 m/s (SD = 0.33 m/s), 1.74 m/s (SD = 0.32 m/s), and 1.72 m/s (SD = 0.29 m/s), respectively (see **Figure 4**).

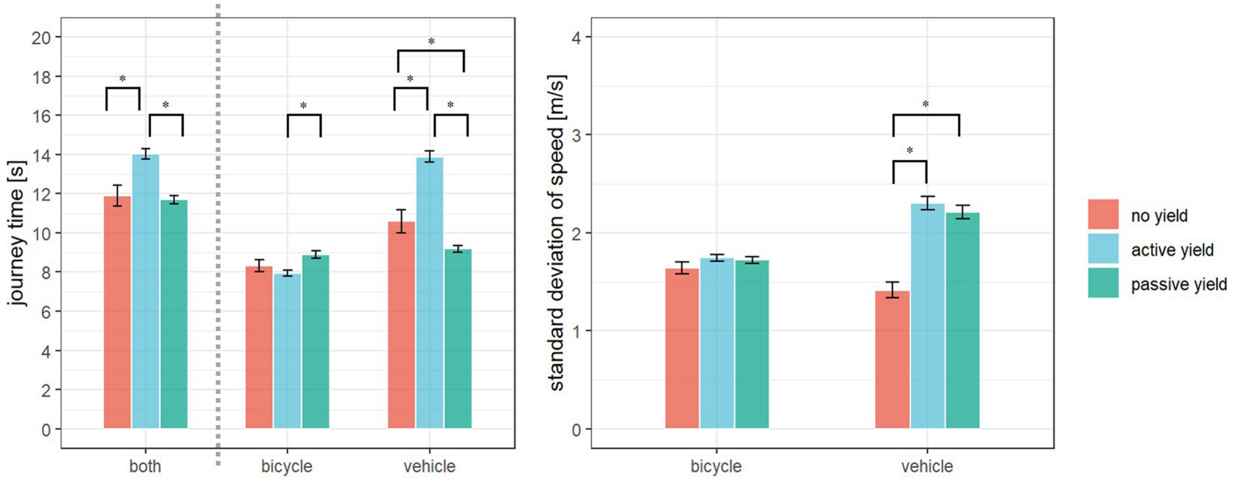

FIGURE 4 | Mean and standard error of journey time from the perspective of both road users, bicycle and vehicle (left) as well as standard deviation of speed of bicycle and vehicle (right) in no yield (red), active yield (blue), and passive yield (green) (*$p < 0.05$).

Safety

The median PET of no yield, active yield, and passive yield were 1.48 s (IQR = 0.64 s), 1.2 s (IQR = 0.8 s), and 1.26 s (IQR = 0.55 s), respectively (see **Figure 5**). The Kruskal–Wallis test indicated a significant difference in PET between the communication categories ($Z = 2.35$, $p < 0.01$, $\eta^2 = 0.03$). According to the pairwise comparisons using Wilcoxon tests ($\alpha = 0.05$), the PET in no yield was significantly greater than in active yield ($Z = 1.98$, $p < 0.05$) and in passive yield ($Z = 1.96$, $p < 0.05$). There was no difference between the PET of active yield and passive yield ($Z = 0.16$, $p = 0.56$).

The Kruskal–Wallis test indicated a significant difference in T2 between the communication categories ($Z = 4.14$, $p < 0.001$, $\eta^2 = 0.09$). According to the pairwise comparisons using Wilcoxon tests ($\alpha = 0.05$), the T2 in active yield (Mdn = 2.77 s, IQR = 1.52 s) was significantly greater than in no yield (Mdn = 1.97 s, IQR = 0.91 s, $Z = 3.35$, $p < 0.001$) and in passive yield (Mdn = 2.25 s, IQR = 0.91 s, $Z = 3.07$, $p < 0.001$). There was no difference between the T2 of no yield and passive yield ($Z = 1.42$, $p = 0.08$) (see **Figure 5**).

DISCUSSION

The aim of this study was to reveal implicit communication patterns between human drivers and VRU. Three implicit communication patterns from the perspective of motorists, no yield, active yield, and passive yield, were identified by analyzing the interaction between right-turning motorists and crossing cyclists. Additionally, frequency of occurrence, efficiency, and safety were analyzed in order to gain knowledge about the performance of the implicit communication patterns. The no yield communication pattern has the lowest probability of occurrence, while active yield occurred more often than passive yield and no yield. Active yield with a higher journey time may suggest more time-consuming interactions. Lower SD of vehicle speed in no yield may be interpreted as less variant and more stable travel through the intersection, which could be considered as more efficient from the perspective of motorists. With regard to the safety analysis, we used PET and T2 to reveal the (prospective) time that two road users missed each other. For both indicators, a lower value may suggest a more critical encounter (Svensson, 1998). Higher PET values in no yield implies a safer interaction, while active yield appears to be safer than passive yield and no yield, because the second road user provided a larger time distance (T2).

According to our analysis, these three implicit communication patterns (i.e., no yield, active yield, and passive yield) represent an interaction strategy when right turning motorists and crossing cyclists approach an intersection. Modeling common interpersonal interactions may help ADF to have a proper interpretation of each other's behaviors (Ezzati Amini et al., 2019). One of the most important aspects is to understand that decisions on driving maneuvers are affected by temporal and spatial characteristics. As mentioned previously, road users who are 10 m away and 100 m away may have different alternatives when facing an encounter with TAdv of one second. In our cases, the directionless changes of TAdv, between 30 and 40 m (in passive yield) 20 and 30 m (in no yield and active yield) away from conflict point, show the hesitation of road users implying the underlying negotiation. On the other hand, the monotone increase in TAdv between 0 and 20 m (in no yield), the monotone decrease in TAdv between 0 and 20 m (in active yield), the and monotone decrease in TAdv between 0 and 30 m (in passive yield) may indicate that road users negotiate in the correspondent section (see **Figure 3**). The results may suggest that the section between 20 and 30 m ahead of the crossing point is relevant for the road users for communication and decision process.

The evaluation of human road users' implicit communication may improve the humanization of ADF. The 86% yield rate provides *a priori* probability for autonomous driving functions when turning right at an intersection. Furthermore, the passive

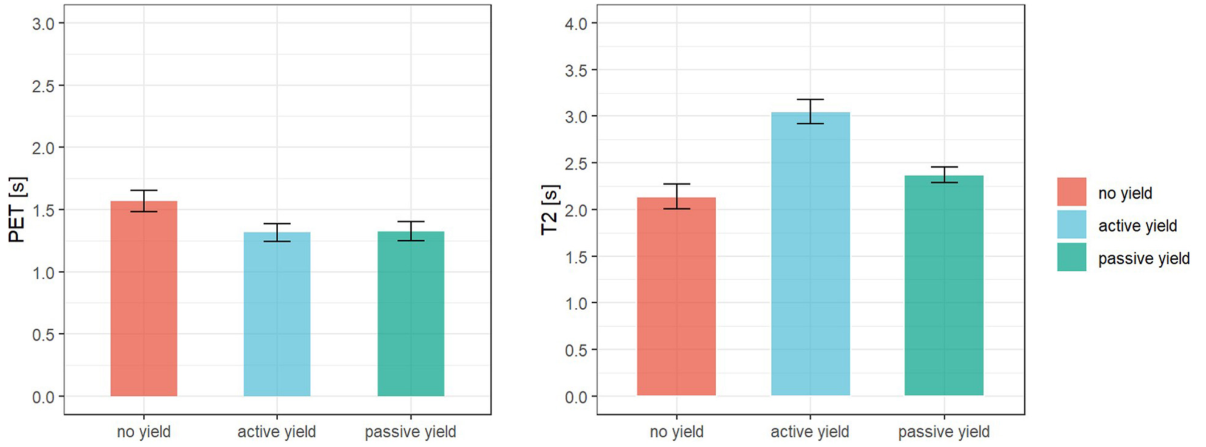

FIGURE 5 | Mean and standard error of PET (left) T2 (right) in no yield (red), active yield (blue), and passive yield (green).

to active yield rate of approx. 7:10 suggests a frequency of common yielding behavior of human driver. This may help ADF to minimize the impact on common interpersonal interactions. According to the German traffic law, motorists need to yield to cyclists when turning right in an intersection. Thus, ADF is supposed to brake on its own initiative in order to yield to cyclists actively. Furthermore, the active yield is considered as the safer interaction, particularly from the perspective of cyclists, which was also proven in previous study (Várhelyi, 1998). But if motorists are well ahead of cyclists and already in the process of turning, they may probably cross before the cyclist. The 29 no yield cases proved the existence of this situation. No yield situations may be interpreted as a trade-off of motorists' individual efficiency and safety, since both, the journey time of motorist (which oppositely indicates efficiency) and the T2 (which indicates safety) in no yield, are lower than the other two patterns. However, the severity of the injuries in a potential collision should not be neglected. The lower journey time of the vehicles resulted in higher speed leading to an increased severity as well as a higher risk. Thus, further research needs to take into account indicators of severity (e.g., Delta-V; Laureshyn et al., 2017) to improve the definition of margins of safety.

The evaluation of human road users' implicit communication may help ADF to understand the intention of VRUs. Compared with passive yield, active yield with a lower cyclists' journey time may suggest less time-consuming interactions. In the result-oriented interpretation, it could be treated as a cooperative behavior, namely, motorists sacrificed their own efficiency to improve the efficiency of cyclists or cyclists sped up to reduce waiting times for motorists. However, it was noted that the difference in efficiency exists only between the cyclists' journey time of active yield and passive yield. The cyclists' journey time and SD of cyclist speed did not appear to be impacted by implicit communication patterns. On the one hand, most cyclists in these cases may not change their crossing behavior, since they may intend to take the regulated right-of-way. On the other hand, the implicit communication patterns (no yield, active yield and passive yield) were classified from the perspective of motorists neglecting the scenarios, where cyclists obviously reacted to motorists. Therefore, fine classification of implicit communication patterns from the both perspective of road users is needed in the further research.

The major limitation of this research is that the influencing factors, such as, traffic flow and the number of conflicts were not considered. According to a recent study (Wu and Xu, 2017), high traffic flow may lead to a sharper deceleration when approaching the intersection. Furthermore, it was inferred that drivers are more likely to yield, when more than two pedestrians are crossing the intersection. The categorization of implicit communication would be more robust if the influencing factors such as traffic flow and the number of crossing VRUs could be controlled. Correspondingly, it also means that a larger sample is required.

A simulator study may be considered alternatively since it provides a controllable experimental environment compared with the naturalistic driving setting. Additionally, it may provide the opportunity to optimize the classification of implicit communication patterns using subjective reports of communication strategies. In our next steps, we will build up the identical setting of the intersection in the virtual environment and ask participants to drive or ride in the connected simulators in order to verify the categorization of implicit communication.

CONCLUSION

This research reveals patterns of implicit communication of motorists with cyclists using video and trajectory data. Furthermore, the communication patterns were evaluated with regard to frequency of occurrence, efficiency, and safety. The results of this research may improve the humanization of ADF.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

MZ, MD, and CS: conceptualization, methodology, and writing – review and editing. MZ: data curation, visualization, and writing – original draft. MZ and MD: investigation. CS: project administration. CS and MD: supervision. All authors contributed to the article and approved the submitted version.

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The Effect of eHMI Malfunctions on Younger and Elderly Pedestrians' Trust and Acceptance of Automated Vehicle Communication Signals

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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

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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.

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.

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.

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.

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.

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)?

MATERIALS AND METHODS

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.

Material

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)].

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

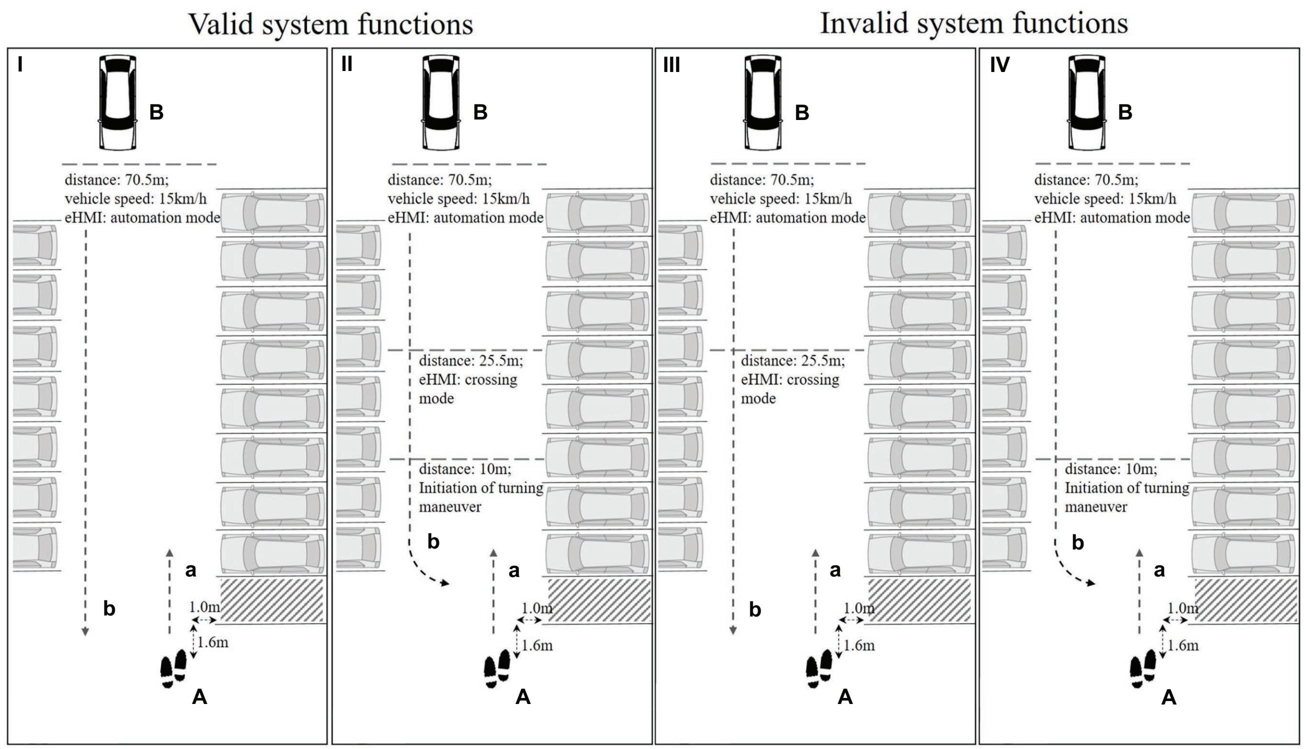

FIGURE 1 | Schematic overview of the investigated scenario in the parking lot (top view). (A) The footprints represent the pedestrians' perspective (i.e., the camera's position), (a) displays the participants' instructed trajectory for crossing the empty parking space (i.e., dashed area). (B) The vehicle 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.

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))

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)].

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 $\alpha = 0.86$). 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 $\alpha = 0.51$, 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

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.

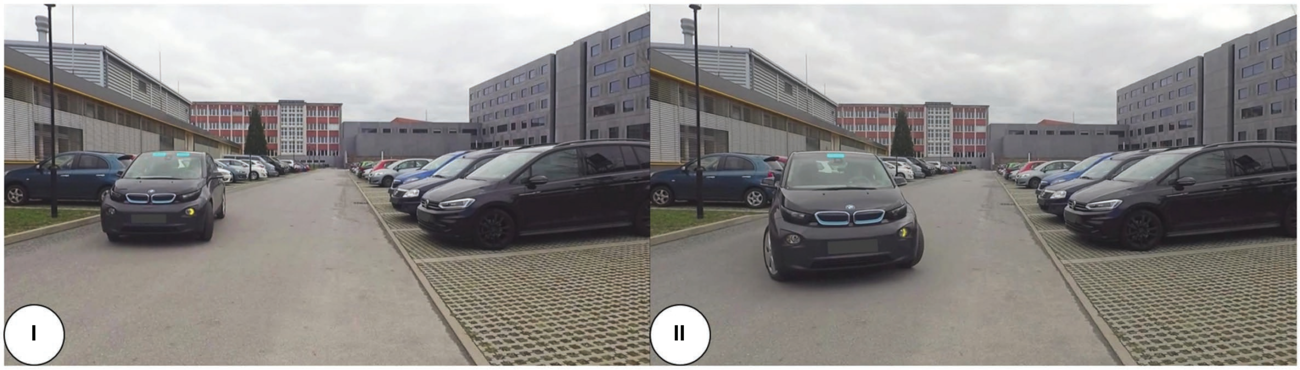

FIGURE 3 | Screenshots of the applied video material displaying the interaction vehicle initiating a left-turn maneuver into the empty parking space in front of the participants with the augmented light-based eHMI (signal: crossing mode) and the activated turn indicator. (I) The interaction vehicle initiated a left-turn maneuver (including deceleration, changes in trajectory, and steering of tires); (II) the interaction vehicle further conducted left-turn maneuver, video stop.

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 $\alpha = 0.86–0.96$). 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 $\alpha = 0.78–0.91$; *satisfaction*: Cronbach's $\alpha = 0.78–0.89$). 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."*

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

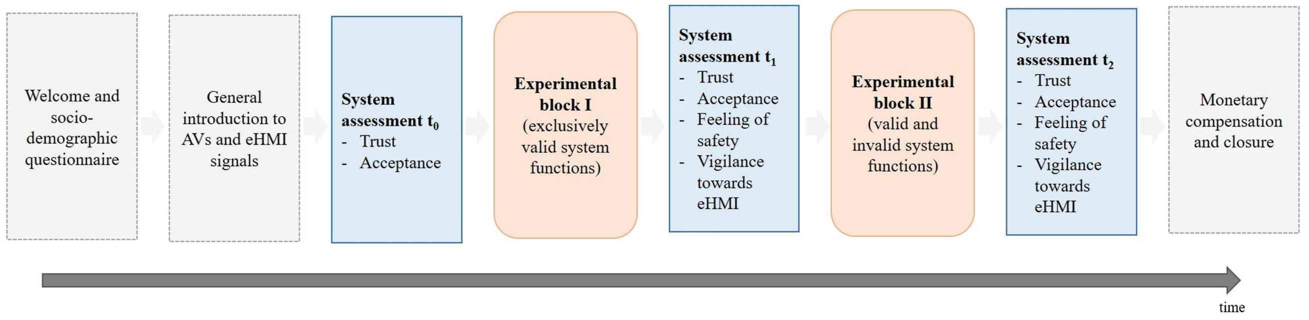

FIGURE 4 | Procedure of the current study.

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.

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

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**	**<0.001**	**0.400**
	Age group	**1, 34**	**10.73**	**0.002**	**0.240**
	Point of measurement x age group[b]	1.69, 57.57	1.71	0.193	0.048
Acceptance: usefulness	**Point of measurement[a]**	**1.43, 50.12**	**11.26**	**<0.001**	**0.243**
	Age group	**1, 34**	**6.33**	**0.017**	**0.157**
	Point of measurement x age group[a]	**1.49, 50.80**	**4.54**	**0.024**	**0.118**
Acceptance: satisfaction	**Point of measurement[b]**	**1.65, 57.60**	**8.69**	**0.001**	**0.199**
	Age group	1, 34	2.95	0.095	0.080
	Point of measurement x age group[b]	**1.77, 60.03**	**3.36**	**0.047**	**0.090**
Feeling of safety	**Point of measurement**	**1, 35**	**49.68**	**<0.001**	**0.587**
	Age group	**1, 34**	**4.43**	**0.043**	**0.115**
	Point of measurement x age group	1, 34	0.43	0.518	0.012
Vigilance toward the eHMI	**Point of measurement**	**1, 33**	**4.89**	**0.034**	**0.129**
	Age group	1, 32	3.86	0.058	0.108
	Point of measurement x age group	1, 32	2.89	0.099	0.083

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.

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**.

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

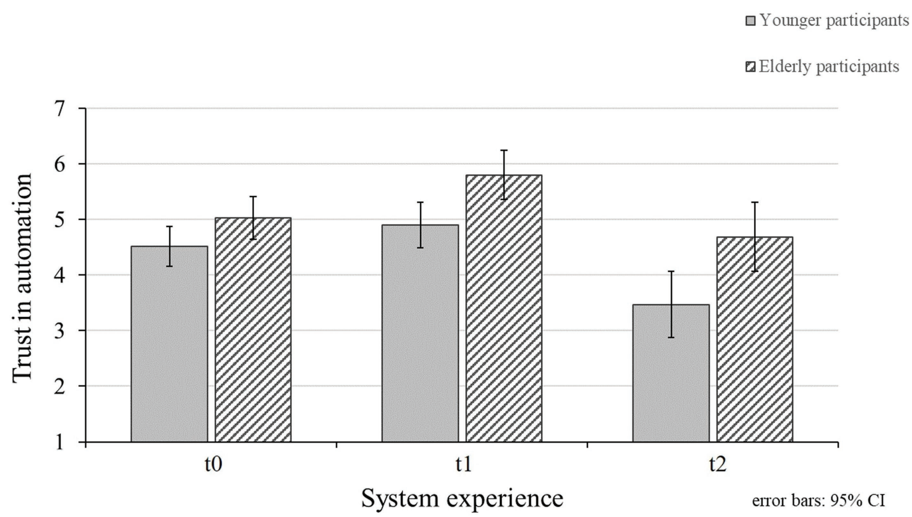

FIGURE 5 | Mean values for younger and elderly participants' trust in the eHMI for the points of measurement (t0 = initial measurement; t1 = valid system functions; and t2 = valid and invalid system functions). Higher values represent higher trust ratings.

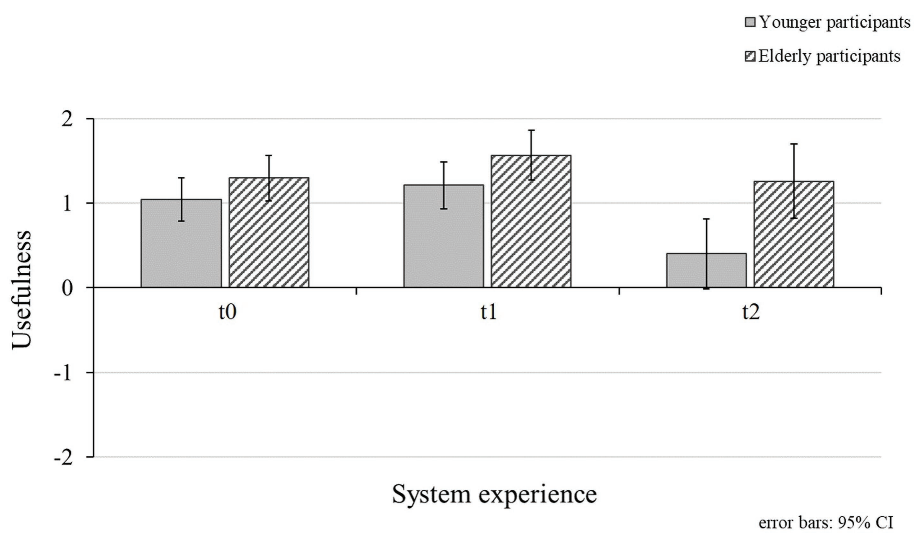

FIGURE 6 | Mean values for younger and elderly participants' usefulness ratings for the different points of measurement (t0 = initial measurement; t1 = valid system functions; and t2 = valid and invalid system functions). Higher values represent higher usefulness ratings.

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**).

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*).

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

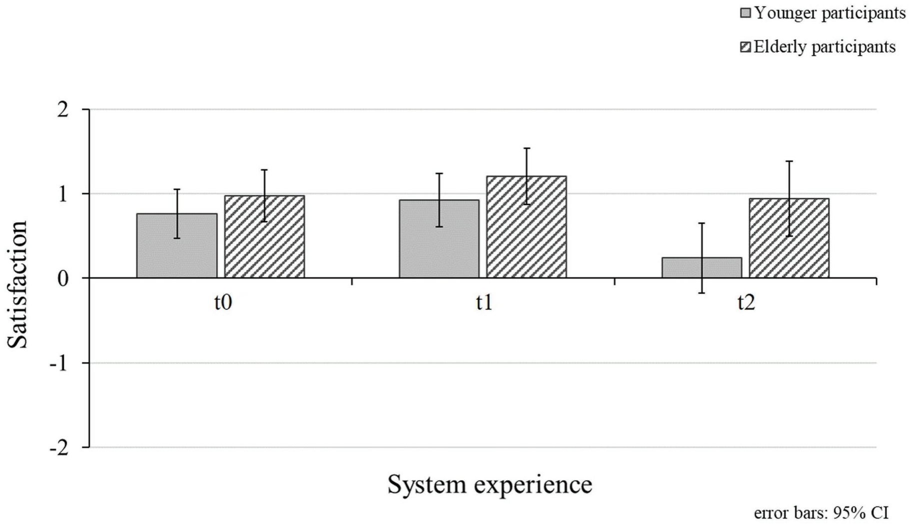

FIGURE 7 | Mean values for younger and elderly participants' satisfaction ratings for the different points of measurement (t0 = initial measurement; t1 = valid system functions; and t2 = valid and invalid system functions). Higher values represent higher satisfaction ratings.

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**).

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**).

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**).

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

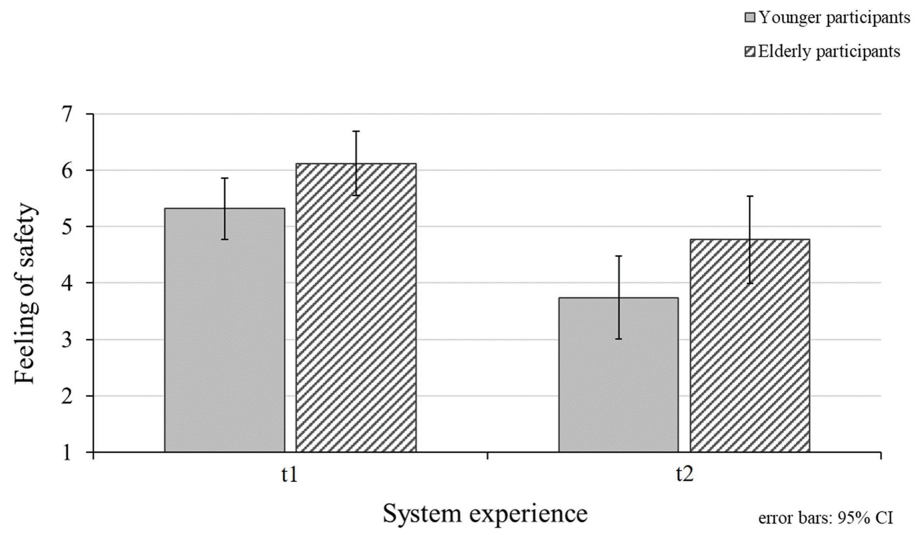

FIGURE 8 | Mean values for younger and elderly participants' feeling of safety ratings during the interaction for the different points of measurement (t1 = valid system functions; t2 = valid and invalid system functions). Higher values represent higher feeling of safety.

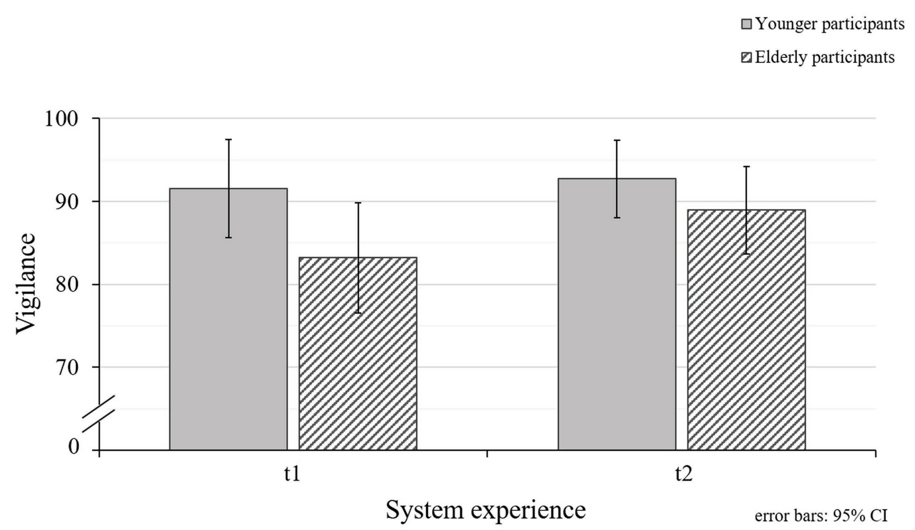

FIGURE 9 | Mean values for younger and elderly participants' vigilance toward the eHMI for the different points of measurement (t1 = valid system functions; t2 = valid and invalid system functions). Higher values represent higher indicated vigilance toward the system.

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**).

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 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).

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.

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Designing Interactions With Shared AVs in Complex Urban Mobility Scenarios

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In this article, we report on the design and evaluation of an external human-machine interface (eHMI) for a real autonomous vehicle (AV), developed to operate as a shared transport pod in a pedestrianized urban space. We present insights about our human-centered design process, which included testing initial concepts through a tangible toolkit and evaluating 360-degree recordings of a staged pick-up scenario in virtual reality. Our results indicate that in complex mobility scenarios, participants filter for critical eHMI messages; further, we found that implicit cues (i.e., pick-up manoeuvre and proximity to the rider) influence participants' experience and trust, while at the same time more explicit interaction modes are desired. This highlights the importance of considering interactions with shared AVs as a service more holistically, in order to develop knowledge about AV-pedestrian interactions in complex mobility scenarios that complements more targeted eHMI evaluations.

Keywords: shared autonomous vehicles, AV-pedestrian interaction, external human-machine interfaces, shared spaces, design process, virtual reality

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1. INTRODUCTION

Fully autonomous vehicles (AVs) have the potential to not only mitigate accidents caused by human errors, but also fundamentally transform the way people commute in cities (Kellett et al., 2019). Recent endeavors from government institutions and industry indicate a trend toward shared autonomous vehicles (SAVs) as a likely future mobility scenario, rather than people owning their personal vehicles (Iclodean et al., 2020; Narayanan et al., 2020). The promise of this approach is that the deployment of SAV services can have a positive impact on the quality of urban life, with less land being devoted to parking and less congestion. Models predict that the required fleet of SAVs to move the same number of people can be met with 70% of the current taxi fleet for New York City and that the demand is equivalent to 30% of the number of today's personal vehicles for Singapore (Pavone, 2015).

The ubiquitous roll-out of AVs and SAVs is closely linked to overcoming technological challenges, such as sensing (Ilas, 2013), in particular during poor lighting conditions (Yoneda et al., 2019), and optimizing routing algorithms (Levin et al., 2017). At the same time, considering the human factors, including those affecting people outside the vehicle, has gained attention from industry and academia (Mora et al., 2020). For example, there is an increasing body of work investigating the use of external human-machine interfaces (eHMIs) to overcome the challenge of how AVs can communicate their internal state to nearby pedestrians. Examples range from projections on the street (Nguyen et al., 2019) to using light strips attached to the vehicle (Dey et al., 2020b; Eisma et al., 2020). A recent literature review by Dey et al. (2020a) found that the majority of concepts only focuses on communicating information related to the vehicle's yielding intent (i.e., whether it is safe for other road users to cross in front of a vehicle); further, concepts which have been evaluated through empirical studies mainly cover simplistic traffic scenarios, for example, one person crossing a roadway in front of an AV (Colley et al., 2020b). This indicates that there remain several unresolved questions when it comes to designing interactions between SAVs and pedestrians that are not addressed by previous eHMI concepts and empirical studies. Many open questions remain, such as whether an eHMI is able to successfully encode information that is broadcast to the general public (e.g., a vehicle's intention and awareness) while at the same time showing information relevant to a particular rider (e.g., to identify which SAV is theirs). Further, with the roll-out of SAVs as a last-mile transport mode between larger hubs, such as train stations, and the passengers' final destination (Yap et al., 2016), it is likely that those vehicles will operate in pedestrianized areas rather than on dedicated roads. A government report published by one of Australia's transport authorities noted that research on pedestrian safety in shared spaces is widely underrepresented (NSW Centre for Road Safety, 2015), which echoes the systematic review by Dey et al. (2020a), finding that eHMI studies mainly focus on intersections and crossings.

In this article, we report on findings from a research project that involved designing a low-resolution lighting-based eHMI for a shared passenger transport pod. Following a toolkit-supported human-centered design process, we developed an eHMI to display the vehicle's status, intent, and awareness, as well as to enable users to identify their vehicle. To evaluate the eHMI, we devised a ride-sharing scenario with multiple vehicles commuting in a shared urban environment where pedestrians, cyclists, and maintenance vehicles share the same road. The scenario was captured with a 360-degree video camera and represented to participants ($N = 14$) in a virtual reality (VR) environment. Through this study setup and feedback collected from participants *via* semi-structured interviews, we investigated the efficacy of eHMI communication in complex urban mobility scenarios. We specifically focused on three aims: The use of eHMIs to convey multiple messages simultaneously, participants' perception of multiple AVs and their eHMIs, and AV-pedestrian interactions for SAVs in a shared space.

The article contributes to the field of automotive user interfaces broadly and to AV-pedestrian interaction specifically in two ways. First, it offers insights about the role of implicit (e.g., vehicle behavior) and explicit (e.g., eHMI) cues and how people perceive those cues in different scenarios (e.g., crossing vs. pick-up). Second, it provides an account of human-centered methods and their value for designing AV-pedestrian interaction in complex scenarios.

2. RELATED WORK

2.1. AV-Pedestrian Interfaces

In recent years, researchers have stressed that autonomous vehicles require additional means to communicate to other road users (Mahadevan et al., 2018; Rasouli and Tsotsos, 2020). Due to the absence of a human driver, interpersonal communication (e.g., eye contact or gestures) and the manual use of signaling devices (e.g., indicators, horn) are not longer available. However, researchers stressed that such communication cues are important, in particular in dense urban areas, where vehicles share spaces with vulnerable road users (e.g., pedestrians) (Holländer et al., 2021) and right-of-way negotiation is necessary. As a consequence of addressing this issue, there exists now a growing body of work on external human-machine interfaces (eHMIs) (Dey et al., 2020a). Concepts range from projection-based eHMIs (Nguyen et al., 2019) to such attached to the vehicle itself, for example light band eHMIs (Dey et al., 2020b). In right-of-way negotiations (de Clercq et al., 2019), most of the eHMI concepts incorporate the vehicle's yielding intent (Dey et al., 2020b). While there has been research suggesting that pedestrians mainly inform their crossing decision based on implicit cues, such as motion (Dey et al., 2017; Risto et al., 2017; Moore et al., 2019), other empirical studies have shown that status+intent eHMIs can significantly reduce the risk of collisions with AVs (Faas et al., 2021) and increase pedestrians' subjective feeling of safety (Holländer et al., 2019). Other research on eHMIs has studied interface placement on the vehicle (Eisma et al., 2020), communication modalities [e.g., light band eHMIs for abstract representations (Dey et al., 2020b), or higher resolution displays for text and symbols (Chang et al., 2017; Holländer et al., 2019)], as well as message perspective (Eisma et al., 2021). Furthermore, researchers began to investigate external communication concepts beyond crossing scenarios: for example, Colley and Rukzio (2020) investigated the specific situation in which automated delivery trucks would block parts of the road and sidewalks and designed and evaluated a visualization concept that guides pedestrians to safely walk past the truck. Others conceptualized autonomous vehicles as public displays that can do more than display information related to the vehicle's operational task and pedestrian safety, such as showing navigation cues and advertisements (Colley et al., 2017, 2018; Asha et al., 2020). However, despite the plethora of eHMI concepts, systematic reviews (Colley et al., 2020a; Dey et al., 2020a) have emphasized that a majority of design concepts are limited to one specific traffic situation, mostly uncontrolled zebra crossings, and only few empirical evaluations take into account urban contexts beyond the road, such as shared spaces (Li et al., 2021).

2.2. Shared Autonomous Vehicles

The global rise of ride-sharing services (e.g., Uber) and the expected uptake of SAVs has led to growing interest from the human-computer interaction (HCI) community (Eden et al., 2017). Researchers began to systematically study aspects that influence passenger's experience and trust toward those services, including trip planning (Svangren et al., 2018), and how to design for in-vehicle experiences (Braun et al., 2018; Khamissi and Pfleging, 2019), for example, informing passengers about their current trip (Flohr et al., 2020) or communicating the vehicle's driving decisions (Sandhaus and Hornecker, 2018). Researchers have also identified potential security concerns of sharing AVs with others (Schuß et al., 2021) and explored the needs of specific user groups, such as the elderly (Gluck et al., 2020) or children (Kim et al., 2019), with the aim to design for more inclusive in-vehicle experiences.

On the other hand, passenger's experience with SAV services in situations outside the vehicle (e.g., while waiting for an approaching vehicle) has received little attention so far. To the best of our knowledge, only Florentine et al. (2016) and Verma et al. (2019b) developed design concepts for eHMIs on SAVs, but those only focused on displaying intent, did not specifically address a passenger-pedestrian perspective, and were evaluated in crossing situations only. Owensby et al. (2018) developed a framework for designing interactions between pedestrians and autonomous vehicles in more complex scenarios. They used a ride-sharing scenario as a foundation for developing and validating the framework. Building on the work from Robertson and Loke (2009) on designing situations, the first proposed step is to break down the scenario into different stages (used synonymously for situations that unfold in an AV-pedestrian interaction scenario). Those stages are then mapped onto three high-level dimensions addressed for each specific situation: how information is being presented, the interactions between user and system, and the user needs being addressed. While the framework is a good starting point (and indeed provided us with the conceptual foundation for our own design process), it has not previously been applied or validated in a larger study. Using the framework as a foundation, in this article, we designed a comprehensive and consistent set of eHMI visualizations for a shared AV and evaluated those in a contextualized study setup [i.e., an immersive VR environment (Flohr et al., 2020)].

3. DESIGN PROCESS

In this section, we report on the iterative process of designing the eHMI for an autonomous transport pod as part of an interdisciplinary research project. The project team involved robotic engineers (referred to as "engineering team" in this section), interaction designers (referred to as "design team") and urban planners. During the 8 months design process (i.e., from initial discussions up to the completion of the VR prototype), we had regular internal planning meetings approximately once every 2 weeks. In the meetings, the larger team provided feedback to the design team on the eHMI light pattern iterations and planned further research activities, such as the design exploration sessions with external experts. The urban planners provided targeted advice on the chosen urban context and scenario. Below we describe the (a) chosen urban context, scenario, and unfolding situations that the eHMI was designed for, (b) the hardware setup, (c) the design of the eHMI concept, which was informed by toolkit-supported collaborative design exploration sessions with external experts, and (d) the VR prototype, which was used to evaluate the scenario and eHMI with potential users.

3.1. Urban Context, Scenario, and Situations

As the study used an existing, fully functional AV, we selected an urban context that suited the operational specifications of the vehicle. The AV was developed as a pod rather than a full-scale car, allowing it to operate in shared spaces. The engineering team had been granted permission to operate the AV on our university's campus, which resembles a shared space, as our campus avenues are frequented by pedestrians, cyclists, and authorized vehicles (e.g., for delivery or maintenance). Thus, we situated our AV-pedestrian interaction scenario on one of our university's main avenues with no road markings and a consistent amount of pedestrian traffic. As a specific scenario, we chose a passenger pick-up scenario given the likely role that SAVs will play in future mobility implementations (Schuß et al., 2021). SAVs have further been implemented on less traveled routes, such as University campuses, already (Iclodean et al., 2020). Choosing this scenario also allowed our study participants to draw on their previous experience with ride-sharing services, such as Uber.

The scenario further allowed us to map out and design how the eHMI would support AV-pedestrian interaction for a number of specific situations. In other words, we broke down the complex urban scenario of interacting with multiple ride-sharing vehicles in a shared space into a set of situations. Specifically, we identified four situations, using the framework by Owensby et al. (2018), which outlines interactions in an autonomous ride-sharing scenario. The situations involved (1) an SAV driving along the shared avenue, (2) the SAV pulling over to pick up a rider, (3) the rider boarding the SAV, and (4) a pedestrian crossing in front of an SAV (in order to illustrate that the vehicle is aware of surrounding people). The chosen situations required us to address the four user requirements previously identified by Owensby et al. (2018) for autonomous ride-sharing scenarios, namely (1) being able to identify the vehicle, (2) knowing the current status of the vehicle, (3) knowing the vehicle's intent, and (4) that the vehicle is aware of the user (the rider and surrounding pedestrians).

3.2. Passenger Transport Pod and eHMI Hardware

We designed the eHMI visualizations for a fully functional AV passenger transport pod, which was also used later for the recording of the immersive 360-degree prototype. The AV hardware was designed by AEV Robotics[1] and was further customized by our engineering team. The platforms have the sensing and computation capacity to eventually operate at SAE level 5[2] and are based on the robot operating system (ROS). The vehicles—being small, efficient and electrically powered—were designed for the purpose to operate safely in low speed road environments (under 40 kph). This makes them suitable to operate in close proximity to pedestrians (Pavone, 2015). One single vehicle is intended to carry up to two passengers.

The engineering team decided early on to use an LED-based low-resolution (low-res) lighting display to implement the final eHMI. This decision was made due to the relatively low power

[1] https://www.instagram.com/aevrobotics/ (accessed January, 2022).

[2] The automation levels are defined by the Society for Automotive Engineers (SAE) for autonomous driving. Level 5 refers to full automation: https://www.sae.org/news/2019/01/sae-updates-j3016-automated-driving-graphic (accessed January 2022).

FIGURE 1 | Passenger transport pod with "U"-shaped low-res lighting display.

consumption of LEDs, thus being able to power the eHMI with the vehicle's on-board battery. Furthermore, LED light strips are a widely available technology which makes it easy to apply this eHMI solution to similar AV platforms (Dey et al., 2020a). Low-res lighting displays have been previously studied in pervasive display research as they allow to communicate information at the periphery of attention (Offenhuber and Seitinger, 2014) and can be perceived from a distance in outdoor environments (Wiethoff and Hoggenmueller, 2017). For this reasons, low-res lighting displays have been also widely used for the implementation of eHMIs in crossing scenarios (e.g., Verma et al., 2019a; Dey et al., 2020b), and previous research has indicated that simple visual cues are easy to understand also in particular for child pedestrians (Charisi et al., 2017).

The engineering team installed off-the-shelf LED strips[3] around the front window of the vehicle in a "U"-shape (see **Figure 1**). The LED strips featured a pitch of 60 pixels per meter, resulting in a total of 145 LEDs. The LEDs were controlled *via* an Arduino board, which was connected to the system of the vehicle. A python ROS node read the information from the vehicle state by subscribing to the relevant information. Light patterns were triggered in real-time based on the sensed information (awareness) and the state of the AV platform (intent). After conducting several tests in the real-world and under different lighting conditions, the designers advised the engineering team to install a diffuser tube of opal white acrylic wrapped around the LEDs. Following design recommendations for low-res lighting displays (Hoggenmueller et al., 2018), this decision was made to improve the viewing angle and to create the illusion of a light bar (rather than a distinct set of point light sources). At this stage of the design process, we also took into account the subsequent production of the virtual reality prototype using a 360-degree camera (see Section 3.4). For this particular purpose, adding the diffuser tubes significantly improved the visibility of the eHMI and eliminated the glaring effect in the recordings that we observed when capturing the LEDs without the diffuser tubes.

3.3. Designing eHMI Light Patterns

Designing the eHMI light patterns for the low-res lighting display, the design team followed an iterative design process, which involved the use of a tangible toolkit for prototyping AV-pedestrian interactions (Hoggenmüller et al., 2020). The toolkit was used to (a) quickly prototype different visualization concepts, (b) present concepts during internal team meetings in a more tangible manner, and (c) to facilitate collaborative design exploration sessions with recruited expert participants to further inform the design of the eHMI light patterns. Below we describe the key features of the prototyping toolkit, the results from seven expert workshops and the final set of eHMI light patterns.

3.3.1. Tangible Multi-Display Toolkit

Building on small-scale scenario prototyping techniques (Pettersson and Ju, 2017) tailored to the context of AV-pedestrian interfaces, a toolkit approach was used to inform the eHMI visualization design (**Figure 2**). The toolkit enables multiple viewing angles and perspectives to be captured simultaneously (e.g., top-view, first-person pedestrian view) through computer-generated simulations orchestrated across multiple displays. Users are able to directly interact with the simulated environment through tangibles, which physically simulate the interface's behavior (in our case through an integrated LED display). Furthermore, a configuration app running on a separate tablet allows to control and adjust the design options in real-time. For the purpose of our project, this allowed users to change between various light patterns and adjust color schemes and animation speed.

3.3.2. Expert Workshops

We conducted seven workshop sessions in total, with each session involving a pair of external expert participants. The aim of the workshops was to receive feedback on light pattern candidates and identify a final set for further implementation on the AV. We recruited 14 participants (seven male, seven female) of various academic and professional backgrounds, covering a range of expertise considered relevant for the design of urban technologies (Malizia et al., 2018; Tomitsch and Hoggenmueller, 2020). Their areas of expertise included architecture and urban planning (n = 5), human-computer interaction (n = 5), psychology (n = 2), software engineering (n = 1), and civil engineering (n = 1). Each workshop session lasted 90 minutes in total and was video-recorded for later analysis. Having participant pairs allowed the experts to have more natural conversations with each other (Nielsen, 1994). This

[3]https://www.pololu.com/category/180/sk6812-ws2812b-based-led-strips (accessed January 2022).

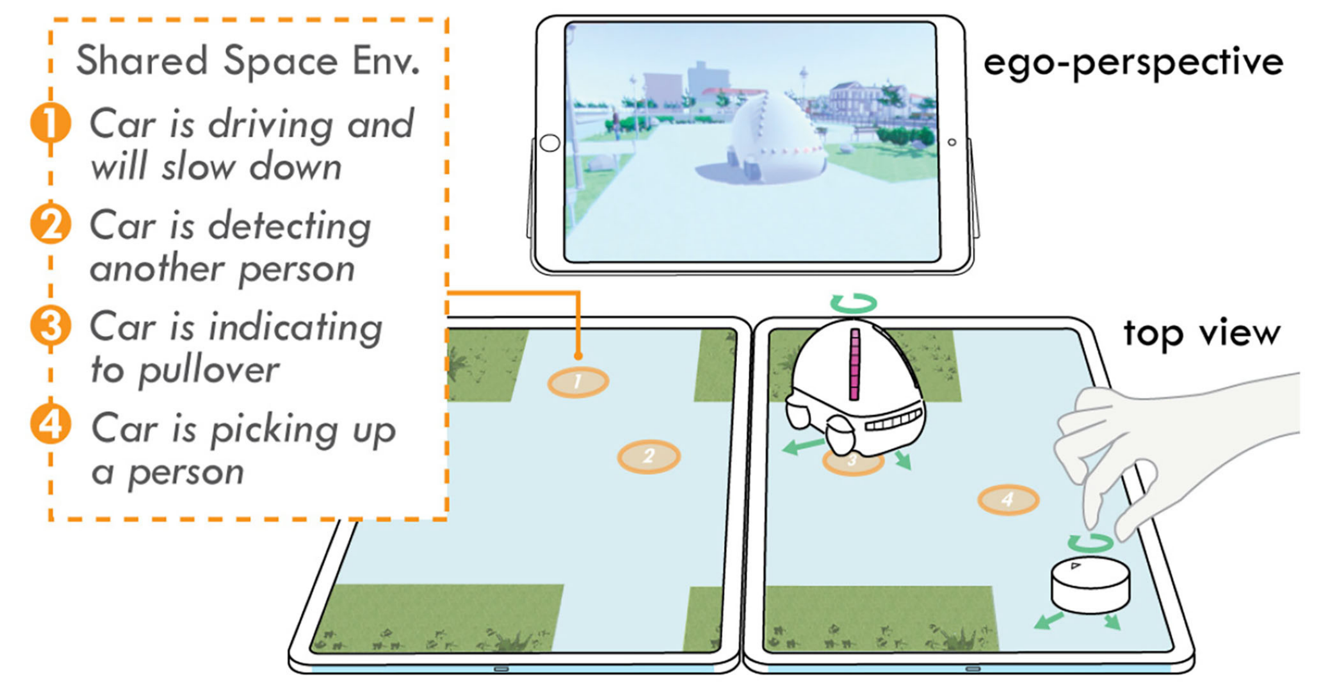

FIGURE 2 | The tangible multi-display toolkit used to inform the eHMI visualization design *via* computer simulations across multiple displays to capture different viewing angles, tangible objects to interact with the simulated environment and to depict the eHMI's behavior through an integrated miniature LED display.

co-participation setup has further been found to be preferred by participants and to detect a higher number of usability issues when evaluating design proposals (Mayhew and Alhadreti, 2018).

In preparation of the workshop we implemented 12 different light patterns for our four AV-pedestrian situations (i.e., three pattern candidates per situation) for a ride-sharing scenario with the toolkit. The design of the light patterns was informed by previous eHMI research (Florentine et al., 2016; Böckle et al., 2017; Dey et al., 2018; Mahadevan et al., 2018; Nguyen et al., 2019) and went through several iterations based on internal discussions within the project team: for example, at the beginning of the design process, we considered re-purposing the SAV's existing front lights to indicate the intent to pull over. However, we rejected this idea later and opted for an eHMI solution that would integrate all messages in the same display space. This decision was made for aesthetic purposes but also in regards to the emerging research question whether a single low-res display would be capable to successfully communicate multiple eHMI messages (Dey et al., 2020a). Considering related literature on ambient light systems (Matviienko et al., 2015), we applied different information encoding parameters (e.g., color, brightness, LED position, or combinations thereof) for the different light pattern candidates. For example, for the situation of the vehicle slowly moving in autonomous mode, we designed a purely color-based pattern to indicate low speed, a pattern encoding slow speed through the size of the light bar (i.e., the numbers of adjacent LEDs lighting up), and a pulsing pattern changing the brightness at a low frequency. Participants were presented with each of the 12 light patterns and asked to interpret their meaning and to provide feedback on the eHMI visualization design. Participants were encouraged to make changes to the color schemes *via* the configuration app as part of their design exploration. At the end of each workshop, we asked participants to select their preferred set of light patterns across all four situations.

3.3.3. Final Set of Light Patterns

Based on the analysis of the participant input collected during the workshops, we derived several insights that guided our subsequent design decisions. These included: avoiding the use of red and green colors, using subtle light patterns by default (in regards to the shared space context in which pedestrians have right of way), using strong signals only when the car is going to do something unexpected or in high-risk situations, using a light pattern that is distinct from a turn signal when pulling over to pick-up a rider, and using a subtle animation for indicating the rider to get on the car (to avoid that the rider feels rushed or distracted during the boarding process). In particular, the use of red and green colors to indicate the vehicle's speed caused confusion or different opinions among our workshop participants. While the majority of participants could establish a connection to the vehicle's speed, some participants interpreted the colors the opposite of our intention to encode low speeds through green colors, reversibly using red at high speeds. Even those participants who interpreted the colors correctly expressed their concerns about the potential ambiguity of this approach. Furthermore, encoding the vehicle's current speed and speed intent (acceleration/deceleration) was deemed as rather not relevant in a consistent low-speed environment. Instead, participants preferred the AV to signal that it is operating in a low-speed autonomous driving mode to express that the vehicle is always aware of its surroundings.

Following the workshops, the design team revised the light patterns and implemented them as a simulation in Adobe After Effects. These simulations were then passed onto the engineering team along with a specification document for each pattern. The engineering team implemented the patterns as eHMI visualizations for the AV, to allow for further testing in a real-world context. The final eHMI visualizations and light patterns are depicted in **Figure 3**. As color was deemed the most intuitive way for a low-res lighting display to represent the identification of the vehicle, we decided to represent the remaining messages (status, intent) through animation patterns only. This design decision was also confirmed through the feedback from workshop participants who mostly considered LED position and animations sufficient to encode those messages and suggested to avoid the use of red and green colors related to the vehicle's status. Thus, the identification of the vehicle through color is laid on top of the other cues. If the vehicle is not intending to pick up a rider, the animation pattern is displayed in a more neutral white. Only for the awareness cue, we decided to use a yellow color in order to add further emphasis on the potential safety hazard through an additional change in color. We decided for yellow as a more neutral color compared to red [i.e., as previously suggested by (Dey et al., 2020b) for eHMIs], and this was also confirmed by some of our workshop participants, who associated red with a potential malfunctioning of the vehicle.

3.4. Virtual Reality Prototype

To safely test the eHMI visualizations in a real context, we opted for creating a 360-degree virtual reality (VR) prototype representation. This kind of prototype, also referred to as hyperreal prototype (Hoggenmueller and Tomitsch, 2019), has been found to result in an increased sense of familiarity in participants (Gerber et al., 2019) compared to other representations, such as computer-generated VR prototypes. VR was chosen over a field study to reduce any potential risk for study participants and as it is a commonly used approach for evaluating AVs and their eHMIs (Deb et al., 2017). Using a pre-recorded video prototype further enabled us to test the situations under the exact same conditions across participants, thus balancing ecological validity and reproducibility of the study findings.

We started with creating storyboards to capture the staged situations and interactions, which involved four actors to represent a pedestrian crossing in front of the SAV, a person boarding an SAV, a person waiting for their SAV to arrive, and a rider inside the SAV. We decided to spread our four situations over three consecutive scenes (**Figure 4**). This decision was made for two reasons: firstly, all staged AV-pedestrian interactions had to occur not too far away from the camera stand for later visibility in VR; secondly, we wanted to give participants the impression that multiple SAVs are commuting through the shared space rather than a single one, however we only had one eHMI-equipped AV available. The scenes (represented from the perspective of the study participant) included: (1) The SAV passing through the shared environment without any staged interactions with pedestrians, (2) the SAV pulling over and picking up another rider (Actor 2 in **Figure 4**), and (3) the SAV indicating to pull over to the camera stand. In the third scene, a pedestrian (Actor 3 in **Figure 4**) crosses in front of the SAV, forcing it to slow down and stop. An additional person was placed directly behind the camera in all three scenes (Actor 1 in **Figure 4**), giving the appearance of another rider waiting for their SAV. This was to constrain participants' movement in the simulation, as 360-degree video does not allow for motion when imported into VR.

We did several tests of the SAV's behavior within the real urban context and to prepare the AV for recording the scenes. At the time, the AV had been programmed to use a combination of algorithms and a cost map that kept the vehicle as close to the middle of the avenue as possible. Upon testing the SAV's behavior when approaching a rider, we found that the SAV would move in a straight line toward the waiting rider, which was in conflict with previous observations that AVs should mirror the behavior of human drivers (Schneemann and Gohl, 2016). Through informal tests with members of the project team, we also found the direct approach to be perceived as threatening from the perspective of the waiting rider. Hence, we programmed the SAV to follow a pathway that was recorded based on a human driver pulling over to the side of the avenue following an S-curve trajectory. On top of the prerecorded trajectory, the vehicle was operating a "virtual bumper" which is a system that detects obstacles in (or adjacent to) the proposed vehicle trajectory and reduces the speed based on a time-to-collision calculation. Due to safety regulations, a licensed operator had to sit in the SAV—in case of having to manually bring the SAV to a halt. However, for the purpose of the recordings, we were able to remove the steering wheel, thus conveying clearly to participants that the vehicle was operating autonomously with the operator playing the role of a rider. The eHMI light patterns were fully implemented and connected with the SAV's operating system and programmed to respond with the appropriate message for each of the staged situations.

We recorded the scenes in the chosen urban context, a pedestrianized area on our university campus which leads to the university's main buildings. We used an Insta360 Pro 2[4] camera (capable of recording 360-degree panorama videos in 8K 3D). For post-processing purposes we used Adobe Premiere and Adobe After Effects. As we recorded the scenes during dusk for better visibility of the low-res lighting display, we had to apply the Neat Video[5] filter to reduce image noise, while still preserving fine details, such as people's faces. We then combined the three scenes, added a short blend transition between them, and exported them into a single 3D over-under video file. To experience the stereoscopic 3D 360-degree video with a VR headset (HTC Vive), we imported the video file into Unity and applied it as a render texture on a skybox material.

[4]https://www.insta360.com/product/insta360-pro (accessed January, 2022).
[5]https://www.neatvideo.com/ (accessed January, 2022).

Situation	eHMI message	Light Pattern	
SAV driving along a shared avenue	Indicating that the SAV is in autonomous driving mode and aware of its surroundings	L1	Lit up pixels at the center of the horizontal bar fade in and out constantly in a 2.5 second cycle
SAV pulling over to pick up a rider	Indicating the SAV's intent to pull over and stop	L2	Lit up pixels move back and forth from the center of the horizontal bar up to the center of the left/right vertical LED strip in a 1.2 second cycle
A rider boarding an SAV	Indicating to the rider that it is safe to board the SAV	L3	All pixels are lit up and periodically fade in and out in a 2 second cycle
Indicating to a pedestrian that it is safe to cross in front of the SAV	Make a pedestrian aware of stepping into the operational area and that it is safe to cross in front of the SAV	L4	Lit up pixels expand from the centre of the horizontal bar to the entire display space and colour fades to yellow (t=0.5sec); after detection pixels fade back (t=2.5sec).

FIGURE 3 | Overview of the encoded eHMI messages and light patterns linked to the previously identified situations. Light pattern L1-L3 are in purple color which we used in the VR study for participants to indicate their vehicle.

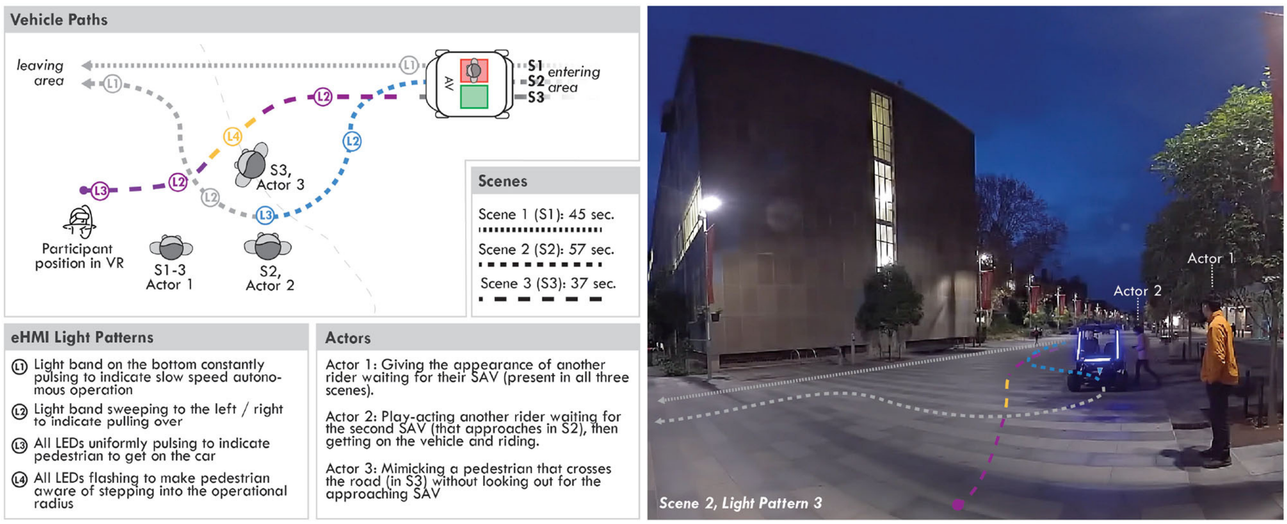

FIGURE 4 | Recording plan of the three scenes, vehicle trajectories and eHMI light patterns **(left)**; screenshot taken from the 360-degree video prototype representing the second scene with an actor entering the SAV **(right)**.

4. EVALUATION STUDY

4.1. Materials and Setup

The study took place in our VR lab space (approx. six by six meters). We used an HTC Vive VR headset for the experiment. To convey the immersive audio recording of the scene soundscape and increase a sense of presence, we used stereo headphones. We further prepared a mock-up interface for a mobile SAV ride-sharing application which showed the following information: (a) a map of the location where the participants were supposed to wait for their vehicle, (b) the vehicle's current position approximately 2 minutes away from the participant, (c) the color which was assigned by the system for the participant to recognize their vehicle (in this case purple), and (d) a mock user profile of the other rider whom they would share the approaching SAV with.

4.2. Participants and Procedure

The study involved 14 participants (seven male, seven female). None of those participants had been involved in the expert workshops. Ages of the participants ranged between 21 and 55 years ($M = 31.42$, $SD = 8.6$). Out of our participants, six were students and eight working professionals; three participants never experienced VR before, eight participants had less than five experiences in VR, and three participants more than five. We recruited participants from our university's mailing lists, flyers, and social networks. Taking part in the study was entirely voluntary and initial contact had to be made by the participants, following the study protocol approved by our university's human research ethics committee.

After arriving in our lab, we first gave a short introduction to each participant about our research and informed them about the study purpose of evaluating interactions between SAVs and surrounding pedestrians (including waiting passengers). Each participant filled out the study consent form and a short questionnaire to collect demographic data. We then quickly briefed participants about the designed scenario of waiting for a requested SAV service. Before commencing with the VR experience, we presented them with the mock-up interface of the SAV ride-sharing application. The duration of the scenario in VR was 2 minutes and 19 seconds. The duration was chosen based on previous tests with members of the wider project team, ensuring that the scenario was long enough for participants to be immersed in the scenario, but at the same time short enough to avoid study fatigue. After experiencing the scenario in VR, each participant partook in a post-scenario semi-structured interview.

Out of the 14 participants, three reported that they had experienced VR more than five times before this study, eight reported that they had experienced VR at least once but less than five times, and three reported that they had no prior VR experience. Interestingly, while the majority of our participants had previous experience in VR, none of them had experienced 360-degree videos in VR before but only computer-generated content. One participant (P10), for example, stated: *"Previously, what I was used to in VR was like a game, so it was not necessarily a realistic situation."* Potentially as a consequence of this, participants commended the high visual realism of the VR experience.

4.3. Data Collection and Analysis

The post-scenario semi-structured interview included questions covering three broader areas: (a) participants' perception and understanding of the eHMI, (b) participants' trust toward the vehicle, and (c) their general experience of the SAV service, all based on the scenario which they experienced in VR. The interview took 8 minutes 39 seconds on average (SD = 3 minutes 36 seconds). The interviews were audio-recorded for later analysis. Additionally, we also took notes about participants' behavior when experiencing the VR prototype (e.g., if participants made comments or gesticulated during the experience).

The interviews were transcribed by a professional transcription service. Two researchers were involved in coding the transcribed interviews, following the thematic analysis approach (Braun and Clarke, 2006). The two coders started the coding process with a different set of interviews. Later on they used a collaborative online whiteboard to look for agreement and disagreement between their codes and to develop the final categories and overarching themes.

4.4. Results

The results are structured following the themes that we conceptualized through the thematic analysis of the interview data. Where relevant we augment the findings with observations recorded during the VR experience.

4.4.1. Interpretation of the eHMI

In our study, participants experienced three scenes accommodating various traffic situations and eHMI messages. In the post-scenario interviews, when being asked about the light patterns, participants most frequently referred back to the eHMI light pattern L4 that would make other pedestrians aware of stepping into the operational radius of the vehicle ($n = 10$), and the color encoding (i.e., purple) that would help participants to identify their approaching vehicle ($n = 10$). Only one participant (P10) mentioned the eHMI light pattern of pulsing white colors (L1) when the vehicle was just commuting through the shared space and signaling its autonomous operation mode. P10 stated: *"To me it was clear that wasn't my car, so I sort of looked at it but I just ignored it."* Also, participants often did not discern between the different sequential eHMI messages (i.e., pulling over, signaling to get on the car) when their vehicle was approaching. Five participants (P4, P7, P9, P12) stated explicitly that they only focused on the color for identifying their SAV. For example, P7 said that *"[she] was just thinking about matching"*, and *"didn't interpret the light patterns as any kind of indication of movement or intent"*. Similarly, P4 stated that *"[she] was just looking at the colours, [...] and wasn't expecting any other meaning from the display"*. In a similar vein, P9 stated that *"[he] was just trying to concentrate on which was [his] vehicle, and [he] didn't look for any additional information"*. Participants who recalled the animation patterns in the interviews expressed mixed opinions. For example, P7 stated that the sweeping animation to indicate pulling over (L2) *"is more intuitive [...] as it conveyed the directionality better than just the on and off [i.e., referring to a conventional blinker]"*. On the other hand, P13 found the sweeping animation *"way too abstract"*, similar to P10 referring to it as *"fancy indicator"* and P8 who stated: *"That's a massive [...] change, if you're now saying a car's indicator is not an indicator anymore, whereas it's been like that for a century"*. Here, a common concern was also that the pulling over animation was functionally and spatially overlaid with the light pattern that helped participants to identify their vehicle. The majority of participants did not make similar comments about the animated light pattern indicating participants to enter the car (L3) or the light pattern indicating alert to pedestrians when stepping into the AV's operational radius (L4).

4.4.2. Color Differentiation and Multiple Vehicles

In our prototype, we deliberately decided for two similar, yet distinguishable color codes for identifying the vehicle, namely blue (hex color code: #46CCFF) for Actor 2 and purple (#876AE8) for the VR participant. While many participants ($n = 10$) recalled on the color code to identify their vehicle, all but one participants also raised that they experienced difficulties in confidently identifying their vehicle based on the assigned color. For example, P8 stated that he *"couldn't distinguish the major difference between those two colours"*. P7 highlighted the limitation of using color to encode important information in terms of the difficulties this would create for colorblind people. Eight participants explicitly brought up the lack of scalability. For example, P8 stated: *"When there are a lot of people around that have ordered something—and in the colour spectrum, there's not heaps of colours that you could actually put on [an eHMI], it would be very hard to distinguish"*. For example, P8 suggested *"another unique identifier"*, such as a *"hologram"*, whereas P13 suggested a combination of *"more expressive light patterns"*, such as *"orange* *and purple [...] gently oscillat[ing] in the windscreen, so you could pick that was your unique ride*". This information should be also constantly available on the rider's personal devices, which P7 also considered as a limitation in the presented VR experience: *"I think if I had the phone in my hand and I could reference the colour, that would have probably been helpful."* While the majority of participants (n = 13) expressed concerns regarding the color differentiation (i.e., blue and purple) for identifying their vehicle, only one participant (P13) expressed concerns about the abrupt yellow light to indicate alert, suggesting that *"it's just all a bit too much*" in reference to the number of different colors and animation patterns.

4.4.3. Pick-Up Manoeuvre and Proximity to Rider

More than half of the participants (n = 8) commented on the vehicle's manoeuvre when picking up the other rider (Actor 2) or themselves and on the proximity of the vehicle toward the rider when coming to a stop. Opinions hereby varied widely; for example, two participants commented that they *"were scared*" (P2) and *"became really wary and alert"* (P10) when the vehicle was approaching them. P2 further commented that *"she was just paying attention at the [vehicle's] sharp movement rather [than] the colour at that point*" and that *"a taxi or a [manual] car would move towards a kerb with a smoother movement*". While these two participants voiced the impression that the vehicle would almost run them over, 5 other participants expressed more positive perceptions. For example, P10 stated that the manoeuvre *"was quite predictable*" and *"you really feel like [the vehicle] is slowing down as it's approaching [and] there is no fear of the car coming at you*". P5 even described a large gap between him and the vehicle once it had stopped: *"[It] was really far away from me when it came to pick me up [...] the purple one. So, then I wasn't sure if it was coming to pick me up or if it was just stopping there for some reason. It seemed like I had to walk a few steps [...] It would have been more clear if it was closer to me at some sort of reasonable distance*". However, he also added that he didn't know *"what a reasonable distance would be*", confirming the varying statements made by participants which suggest that an optimal proximity depends on people's personal preference. In a similar vein, two other participants (P3, P13) emphasized the proximity of the stopped vehicle as the main cue to recognize their vehicle. P9 further added that this implicit cue raises expectations toward the SAV service: *"If you have booked a destination in your [...] iPhone or whatever application it might be, and a vehicle turns up directly opposite you and you get in it, you would expect that vehicle to take you to that location."*

4.4.4. Additional Confirmation and Control

While the vehicle's color encoding and proximity toward the rider were considered important factors to gain confidence in identifying the correct car, participants also stated that they would need additional confirmation for a satisfactory customer experience with the SAV service. These comments were mostly related to the hypothetical boarding process, which was not covered in our scenario. For example, P7 said that while *"the colour is really helpful from afar and getting prepared to get into a vehicle [...] there needs to be something a little bit more specific or unique to confirm"*. P3 who failed to recognize or correctly interpret the pulsing eHMI light pattern (L3) at the end of the last scene asked us: *"How do you know it's safe to get in?"*. P5 suggested a *"more verbal message, such as 'Ready to board*"'. Relating to the safety driver in our scenario, P4 commented on the need for an additional confirmation from inside the car: *"If there wasn't another person in the shuttle, how can you ask if—or how can you confirm that it's the right [vehicle]"*. Two participants related the need for additional cues also to the novelty factor of SAV services. P7 stated: *"There's going to be a while until I have full trust in something autonomous, so I need to have some kind of indication that I am getting into the right place and location"*. Similarly, P9 expressed that his trust toward the SAV service *"would be built up on the number of times it does it correctly"*. While the need for additional unidirectional cues—from the vehicle toward the rider—were repeatedly mentioned, one participant (P7) also explicitly stated the need to gain some control over the vehicle. When asked about her repeated hand waving gesture while experiencing the VR prototype, P7 urged that the aspect of sensing and responding *"is part of this change to autonomous vehicles*' and that *'she would like to know, that she is influencing something*".

4.4.5. Trust and Shared Space

Regarding our scenario of SAVs commuting in shared spaces, the interviews revealed that the majority of participants trusted the vehicle in the sense that they considered the chance of an accident as rather low. Participants' trust was induced by observing the vehicle's interactions with other pedestrians (n = 9), including implicit cues (i.e., vehicle physically slowing down), and explicit cues (i.e., awareness light pattern, L4), as well the low speed of the vehicle (n = 3). Participants P3 and P10 further referred to the slow speed and small size of the vehicle in relation to the *"very light pedestrian flow"*. Given this constraints, P3 even mentioned that *"[he] would be very comfortable if it was driving a lot faster*" in the experienced context.

Interestingly, none of the participants objected the awareness light pattern (L4)—often referred to as *"alert*" signal—in the shared space. Instead participants *"[were] glad to see it turn a different colour"* (P7) in a potentially safety-critical situation and the vehicle being *"really well lit up [...] to say that 'I'm here and I see you*"' (P3). However, several participants urged that additional signage or segregation would be required to *"let pedestrians know they are sharing the space with an autonomous vehicle, [...] because of safety reasons but also efficiency"*. P8 stated, similarly to P9, that *"if you're aware that something will always stop for you [...], you will just consciously not worry and will just do what you want to do"*. P2 further stated that *"there wasn't a marked difference between the roadway and where people were standing*", which made her feel standing in the path of the vehicle. P6 stated similarly that *"because there was no sign [...] for the vehicle to stop, it means it can stop anywhere*", which made her *"feel insecure*". Instead she would expect the vehicle *"to stop at a critical location"* in the shared space, such as a designated pick up area.

5. DISCUSSION

In this study, we investigated the efficacy of eHMI communication in complex urban mobility scenarios exemplified through a ride-sharing service operating in an urban space shared by pedestrians and vehicles. Hereafter, we discuss the results according to the initial aims: the use of eHMIs to convey multiple messages simultaneously, pedestrians' perception of multiple AVs and their eHMIs, and AV-pedestrian interactions for SAVs in a shared space.

5.1. Conveying Multiple Messages

The comprehensive literature review by Dey et al. (2020a) found that there are no recommendations available at this stage regarding an eHMI's optimal information capacity (i.e., number of displays and number of messages), thus leaving it unclear for designers how to avoid potential cognitive overload. Given the ride-sharing scenario, we designed the eHMI to display information that is relevant to an individual rider (i.e., identifying the vehicle) and the general public (i.e., status, intent, and awareness). Furthermore, we deliberately decided to display the information by a single display. This meant that various messages were overlaid, namely the vehicle identifier encoded through color with the vehicle's states and operations encoded through (animated) patterns. Further, given that various traffic situations were covered, distinct messages were displayed successively within a single display space. Participants, who experienced the scenario in VR, reported in the post-scenario interviews that they were mostly focusing on identifying their vehicle based on the color encoding ($n = 10$). Interestingly, however, the same number of participants also noticed and recalled the light pattern to signal awareness to other pedestrians, which they found important given the close proximity of the inattentive pedestrian in the represented situation. This may suggest that people filter for eHMI messages that are relevant to their particular goals or critical in terms of safety. However, it also has to be noted that the sudden and clear change in color (i.e., purple to yellow) and LED position (i.e., from only the bottom to all light bars lit up) was better distinguishable for participants. We therefore conclude that conveying multiple messages through a single low-res lighting display is possible to a certain extent, however, successful interpretation depends on various factors, including the respective situation and visual distinguishability of the different messages. Acknowledging the limitations of our study setup, we argue that more targeted investigations on eHMI's information capacity are needed, including such that compare different number of displays and messages, for different modalities and display types, and across different situations.

5.2. Perception of Multiple eHMI-Equipped SAVs

Addressing the lack of use cases that investigate eHMI concepts beyond interactions with a single AV (Dey et al., 2020a; Tran et al., 2021), we also wanted to test out if multiple SAVs in an urban area would impede comprehension of the eHMI. Specifically to our ride-sharing scenario, findings suggest that identifying a vehicle solely based on color encoding has limitations when multiple SAVs commute through an area. Here, our findings point to the necessity of using a combination of colors or more unique light patterns; further, additional means for identifying a vehicle, e.g., through number plates, dynamic high-resolution displays or personal mobile devices, would improve riders' confidence in identifying their allocated SAV in high-traffic ride-sharing scenarios. However, our findings also show that users appreciate being able to identify their vehicle from a distance, which suggests that SAVs should adopt a combination of highly visible ambient eHMIs and additional cues for interactions in closer proximity. Multimodal interaction concepts, such as Uber's light beacon in combination with their smartphone application (Hawkins, 2016) or the additional use of haptic feedback for AV-pedestrian interaction (Mahadevan et al., 2018), could be further adopted to the context of SAV ride-sharing.

In terms of prototyping and evaluating the efficacy of eHMIs in complex traffic scenarios, our approach of using 360-degree recordings has limitations as we represented multiple vehicles by concatenating various recordings of a single vehicle. This was also emphasized by one participant who stated that *"the lack of cars felt unnatural, [given it] was actually in a city like [anonymised for review]"* (P2). Furthermore, our prototyping setup did not allow participants to interact with the mobile SAV ride-sharing application during the VR experience. Thus, further work is needed to enhance the capabilities of 360-degree VR prototypes (Hoggenmueller and Tomitsch, 2019) for the design and evaluation of interactions with AVs and eHMIs.

5.3. AV-Pedestrian Interactions in Shared Spaces

The majority of eHMI concepts has been designed for and evaluated in crossing situations on roads (Colley et al., 2020a; Dey et al., 2020a), whereas our study focused on interactions in shared spaces that are predominantly occupied by pedestrians. Generally, our participants, who experienced the scenario in VR, did not express any objections against sharing a pedestrianized area with autonomous vehicles; instead, some even stated that the SAV could have moved faster depending on the density of people. In terms of signaling awareness (L4), VR study participants appreciated a strong visual signal. This is interesting, as some of the participants from the expert workshops urged caution about strong alert signals when exploring the shared space scenario within the prototyping toolkit. Our findings also suggest aspects for further considerations, such as how to mitigate pedestrian behavior that would cause an AV in a shared space to constantly come to a halt. Also, despite using eHMIs, additional information integrated into the immediate physical surroundings might still be needed, such as signs and road markings to indicate that an area is populated by AVs and to allocate dedicated stopping points for SAVs within a shared space.

5.4. Additional Implicit and Explicit Communication Cues

The results from our study also confirm the importance of implicit communication cues and, in that regard, extend previous findings (Risto et al., 2017; Moore et al., 2019; Rettenmaier et al., 2021) to the context of ride-sharing scenarios: indeed, more than half of our participants commented on the SAV's approaching manoeuvre and proximity to the rider in relation to trust and user experience. This is an interesting finding as it points out that implicit cues, such as motion and vehicle proximity, are not only relevant in safety-critical situations, such as crossing decisions, but also shape the user's experience with a service and need to be considered in the design. One VR study participant (P9) commented in this regard: *"I think you can't divorce the car displaying technology from that whole package. It has to be looked at holistically."* Considering the eHMI only as one element within human-vehicle interaction design was also supported through some of our other findings. Participants commented that for our ride-sharing scenario additional communication channels, amongst others *via* personal devices and interfaces inside the vehicle, but also direct influence and control over the vehicle *via* sensor input is required. This highlights the need for future work to consider more carefully interaction trajectories and how interactions unfold involving a series of service touch points, as well as considering explicit and implicit human-machine interactions. Instead of only focusing on what information to communicate depending on the vehicle's proximity to a passenger, future frameworks should also consider the relationship of interaction modalities and the rider's spatial distance to the vehicle. We therefore propose to add another overarching dimension "implicit information" to the framework developed by Owensby et al. (2018) in order to cover for the spatio-temporal vehicle movements. This would further emphasize that designing the vehicle's movement should not be left alone to engineers developing algorithms as it needs to be carefully designed to address trust and user experience toward SAV services more holistically.

5.5. Limitations

Due to the exploratory nature of this study, the workshops and the VR evaluation study involved relatively small numbers of participants (14 people each). There was intentionally no overlap between the two groups of participants as having been part of the workshop would have influenced participant's knowledge and expectations in the VR study. However, this may have led to some of the contradictory observations; for example, in regards to preferences about the use of visual light signals. It thus remains unclear whether these observed differences stem from the background and characteristics (including participants' age) or the way participants assessed the scenes in the toolkit vs. VR. Although we had a mix of participants in terms of their experience with VR, our sample was too small to identify whether and how this factor influences participants' perception of the SAV and its eHMI in VR. Furthermore, designing a comprehensive experience of a ride-sharing scenario, including multiple situations and eHMI messages, and following a design process, including several iterations and data collections, made it at times difficult to trace back findings to specific design decisions. These limitations point to questions that could be investigated in future studies and more targeted eHMI evaluations (e.g., re information capacity).

6. CONCLUSION

In this article, we presented insights from our human-centered design process and analyzed participant interview data collected through a VR study involving a ride-sharing scenario recorded as a 360-degree VR prototype. While the light patterns we implemented were not necessarily identified as the ideal solution for the eHMI messages that an SAV should be equipped with, our study pointed out several suggestions for improvements, such as including cues in higher-resolution for close-proximity interaction and avoiding overriding existing norms (e.g., in regards to our pattern for pulling over). Importantly, beyond the specific light pattern design, we were able to uncover insights about the role of implicit (e.g., vehicle behavior) and explicit (e.g., *via* the light pattern) cues. We found that participants filter for explicit cues that are either relevant to their goals or to ensuring the safety of pedestrians. Our study suggests that implicit cues, such as the way a vehicle approaches a waiting passenger, may be equally if not more important to "get right" in order to facilitate clear communication between SAVs and pedestrians.

Our findings also offer insights on the design process and the value of using a staged prototyping approach. To that end, our toolkit catered for context-based eHMI design explorations in complex mobility scenarios at an early stage of the design process. However, design parameters beyond the eHMI (e.g., the AV's motion) were not captured in the toolkit representation. Recording staged scenarios through 360-degree video and evaluating these first-person interactions in VR yielded deeper insights about our eHMI design. We further found that immersive VR prototypes should support participants' use of personal devices in VR, such as smartphones, in order to allow for an evaluation of the holistic experience and the various service touch points of complex scenarios, such as ride-sharing.

As physical driving behaviors seem to play a major role, not only in terms of pedestrian safety, but also passenger's experience with an SAV service, we further urge for more interdisciplinary collaborations between engineering and interaction design. We were in a unique position of having access to a real AV and working as part of a project team that included engineers as well as designers. Having to fully implement the light patterns and the autonomous behavior of the SAV forced us to face technical constraints that may be overlooked in a wizard-of-Oz or computer-generated VR study (Tran et al., 2021). For example, the limitations of the algorithms and cost map for creating more natural, human-like driving trajectories led to further investigations in regard to the vehicle's motion in pick-up scenarios. As a result, the robotic engineering team is implementing modifications to the actual path planning algorithm to imitate an S-curve pattern to cater for more intuitive human-machine interactions.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because we don't have approval from the University's ethics board to publish the raw data publicly. Requests to access the datasets should be directed to marius.hoggenmueller@sydney.edu.au.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The University of Sydney Human Research Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

MH contributed to conceptualization, prototype development, data collection, data analysis, and writing. MT and SW contributed to conceptualization, prototype development, and writing. All authors contributed to the article and approved the submitted version.

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Go Ahead, Please!—Evaluation of External Human—Machine Interfaces in a Real-World Crossing Scenario

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In the future, automated vehicles (AVs) without a human driver will potentially have to manage communication with vulnerable road users, such as pedestrians, in everyday traffic interaction situations. The aim of this work is to investigate pedestrian reactions to external communication concepts in a controlled, but real-world crossing scenario. The focus is to investigate which properties of external human–machine interfaces (eHMIs) promote the comprehensibility of vehicle intention (yielding for the pedestrian) and therefore lead to faster and, at the same time, safer crossing decisions of pedestrians. For this purpose, three different eHMI concepts (*intention-based light-band*, *perception-based light-band*, and the *combination of light-band and signal lamp*) were examined and compared to a baseline (no eHMI). In a Wizard-of-Oz experiment, participants ($n = 30$) encountered a test vehicle equipped with the eHMIs in a real-world crossing scenario. The crossing initiation time in seconds and the participant's intention recognition were measured. Furthermore, the influence of the eHMIs on acceptance and perceived safety was evaluated. It was shown that the presence of the *intention-based light-band*, and the *combination of light-band and signal lamp* led to an earlier crossing decision compared to baseline with no eHMI. In summary, the results indicate that the *intention-based light-band* has a positive effect on the comprehensibility of the vehicle's intention. All concepts were evaluated positively regarding acceptance and perceived safety, and did not differ significantly from each other.

Keywords: external human-machine interfaces, automated driving, human-computer interaction, real-world study, Wizard-of-Oz, vulnerable road user

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INTRODUCTION AND BACKGROUND

Automated driving is currently a ubiquitous and much discussed topic. Automated vehicles (AVs) have the potential to fundamentally change traffic systems by making traffic safer, more efficient, and more comfortable (Fagnant and Kockelman, 2015). With the introduction of AVs, the interaction and communication between pedestrians and AVs in road traffic and their importance have come to the forefront (Rothenbucher et al., 2016; Rasouli et al., 2017; Othersen et al., 2018). This applies in particular as AVs are entering urban environments where vehicle–pedestrians interactions are common. Nowadays, human drivers use a variety of signals to communicate with other road users. In principle, there is a distinction between formal and informal communication in road traffic (Sucha, 2014; Färber, 2015; Lagström and Lundgren, 2015; Rasouli et al., 2017).

Formal communication is also referred to as explicit or standard communication and is regulated by road traffic regulations. It includes visual signals of vehicles, such as indicators, brake lights, hazard warning lights, or blue flashlights of emergency vehicles, as well as acoustic signals, such as horns or sirens (Färber, 2015; Fuest et al., 2018). In contrast, there is informal or implicit communication, which is not represented by any regulated signals. Examples include eye contact, gestures, facial expressions, the reduction of speed, etc. (Färber, 2015; Lagström and Lundgren, 2015; Beggiato et al., 2018). The latter type of communication is especially important in situations where formal rules do not apply (Sucha, 2014; Färber, 2015). This can be necessary to ensure that the driver sees the pedestrian or is aware of his/her intention to cross the road (Song et al., 2018). AVs eliminate the interaction with a driver as a source of information for pedestrians, creating a potential communication deficit. However, communication with other road users, especially vulnerable ones, should always be ensured (Pillai, 2017; Rasouli et al., 2017). This leads to the fact that AVs should have alternative communication strategies that can replace the driver's communication signals to establish comfortable and safe interactions between pedestrians and AVs (Schneemann and Gohl, 2016; Othersen et al., 2018; Ackermann et al., 2019a), as well as to ensure the trust and acceptance of AVs (Weber et al., 2019b).

Previous research has intensively addressed this question. One possible approach is to communicate *via* vehicle movement, for example, braking (Risto et al., 2017; Fuest et al., 2018; Ackermann et al., 2019a). However, most proposed solutions involve explicit communication through external human–machine interfaces (eHMIs) (Lagström and Lundgren, 2015; Clamann et al., 2017). The use of eHMIs is recommended by many researchers because they have the potential to improve interactions with pedestrians and facilitate a better understanding of intentions in road traffic (Deb et al., 2017; Merat et al., 2018; Ackermann et al., 2019b). Furthermore, eHMIs can increase the efficiency of the vehicle–pedestrian interaction and the perceived safety of pedestrians (e.g., Matthews et al., 2017; Habibovic et al., 2018; Clercq et al., 2019). Systematic taxonomies of the different HMIs of AVs and their interaction are given by Bengler et al. (2020) and Dey et al. (2020). However, considerable diligence is required to ensure an appropriate eHMI design (Rasouli et al., 2017; Deb et al., 2018).

The international research project interACT, funded under the European Union's Horizon 2020 initiative (interACT Project, n.d.), has addressed this issue by developing a communication concept based on traffic observations and simulation studies with eHMIs for future AVs. This concept was prototypically applied to a BMW i3s and has been evaluated in simulator, virtual reality (VR), and test track studies (Lee et al., 2019; Weber et al., 2019a; Dietrich et al., 2020). These environments account for high controllability of events on one hand, they lack complexity and realism on the other hand (Lee et al., 2019; Faas and Baumann, 2020). To ensure that eHMIs are also useful in real environments in which they are supposed to be used, research should seek ways to conduct studies in environments that are more similar to public road traffic. An evaluation of the eHMI concepts developed by the interACT project in such environments is lacking. Therefore, the present work aims to investigate pedestrian reactions to these eHMI concepts in a real crossing scenario. Before introducing the methodology in detail, Section 2 reviews previous research.

RELATED WORK

Numerous studies have already addressed the question of how communication between AVs and pedestrians might look in the future when there is no longer a human driver. A study by Matthews et al. (2017), for example, examined participants' interactions with a vehicle equipped with an external communication system. The results showed that participants who interacted with a vehicle without the external system were more hesitant to act than when the external communication system was present. The results of questionnaires showed that participants felt higher confidence and felt safer when the external communication system was present than when none was present. Similarly, Mahadevan et al. (2018) examined the utility of interfaces that explicitly communicate AV behavior and intention to pedestrians. Participants were asked to decide whether to cross the street or not. The results suggested that participants preferred to receive explicit information about the vehicle behavior and intention *via* interfaces, rather than just information about vehicle movement. However, a clear and unified design concept of eHMIs is not yet available. To investigate an understanding of the eHMI design, which consisted of a light on top of the windshield, Habibovic et al. (2018) conducted a series of experiments using the Wizard-of-Oz method. This meant that the vehicle control remained obscured from participants during the experiment. They indicated that they felt significantly less safe when they encountered the AV without the interface compared to a conventional vehicle or an AV with the interface. Thus, Habibovic et al. (2018) were able to show that pedestrians felt safer when they received information *via* eHMIs in addition to implicit communication about the vehicle intention. Both Faas and Baumann (2020) and Hensch et al. (2020) used the Wizard-of-Oz technique to investigate different eHMIs. In the study by Faas and Baumann (2020), three different light signals (steady light, flashing light vs. sweeping light) were evaluated. A steady or flashing light was found to be more suitable for a self-driving car to indicate its intention to yield the right-of-way to pedestrians than a sweeping light. They reflected a good to excellent user experience, higher user learning and likability. In the study by Hensch et al. (2020), the eHMI consisted of various light signals and was displayed as a light bar on the roof of the vehicle. A steady light indicated that the vehicle was driving autonomously, flashing lights that the vehicle was approaching, and sweeping lights indicated that the pedestrian in front of the vehicle could cross the street. The study was conducted in a parking garage on the campus of the University of Chemnitz, and random pedestrians passing by the vehicle were surveyed. In contrast to the study by Faas and Baumann (2020), the light signals used were found to be only partially trustworthy and poorly understood. However, the general use of light signals in the context of automated driving is generally perceived as useful (Hensch et al., 2020).

Altogether, previous research showed that eHMIs had the potential to improve perceived safety and were generally perceived as useful. Furthermore, the studies presented revealed that explicit communication through eHMI was preferable to solely implicit communication through vehicle movement. The design of eHMIs seems to play an important role in the perception and understanding of AVs. The results are conflicting whether steady, flashing or sweeping lights are the safest and most intuitive design. Previous studies can provide important insights into the effects and design of eHMIs and pedestrian interaction with AVs. Based on previous findings and different evaluation criteria for eHMIs (Weber et al., 2019a), the interACT research project (interACT Project, n.d.) has developed different eHMI concepts. The concepts consist of two main components: a LED light-band and a directional signal lamp (Kaup et al., 2019; Weber et al., 2019a). The light-band is mounted around the test vehicle and is visible from any angle. Thus, it allows 360-degree communication with pedestrians. Different pulsating frequencies and amplitudes aim to communicate current or future vehicle maneuvers of the AV and can therefore be classified as "*intention-based*" (Weber et al., 2019a). A calm, slow pulsating of the light-band aims to communicate "I am giving way." In addition, it is possible to illuminate only segments of the light-band around a vehicle to specifically illuminate pedestrians, a so-called *perception-based light-band* (Weber et al., 2019a). This concept is mainly characterized by giving explicit information to other traffic participants that they have been detected by the AV. This is meant to replace information that is normally exchanged by interpreting eye contact or head rotation in human–human communication (Weber et al., 2019a). The two interaction concepts utilizing the LED light-band (*intention-* and *perception-based*) are described in detail by Sorokin et al. (2019). In contrast, the second main component of the developed eHMI concepts is a signal lamp only visible to relevant pedestrians. A specifically directed light beam lets her/him know that she/he has been detected and that the vehicle is aware of them (Kaup et al., 2019). In the interACT projects, the signal lamp was combined with the *intention-based light-band* to explicitly communicate that the pedestrian was detected, along with communicating the intentions of the AV (Weber et al., 2019a). Cyan was chosen as the color for the eHMI concepts because it emerges as the color of choice for novel AV lighting functions (Kaup et al., 2019).

Final concepts developed by the interACT project were assessed in several VR and test track experiments among others regarding the acceptance, usability, traffic efficiency, and perceived safety of other road users and passengers (Dietrich et al., 2020). Dietrich et al. (2020) summarizes the studies already conducted by the interACT project. The Institute for Transport Studies (ITS) in Leeds, for example, conducted a pedestrian simulator study to investigate the effect of one of the eHMI concepts developed in the interACT project on pedestrian crossing behavior. The authors compared the slow pulsating light-band to conventional flashing headlights and no eHMI by assessing among others the crossing initiation time. The results revealed a significantly shorter crossing initiation time for the flashing headlights than for the slow pulsating light-band. The authors suggested that signal familiarity played a role. Generally, crossing initiation time was significantly shorter when the eHMI was turned on compared to no eHMI. Furthermore, a study was conducted in BMW's pedestrian simulator to assess the influence of the three eHMIs developed by the interACT project on pedestrian crossing behavior. The results revealed no differences between the eHMIs on crossing initiation times without previous exposure or explanations to eHMIs. However, improved crossing times for the *intention-based light-band* were noted when participants were educated about the functionality of eHMIs. Perceived safety was at a high level in all groups, including the control group, which did not encounter an eHMI during the experiment. Different eHMI concepts were examined on pedestrian crossing behavior, intention recognition, subjective perception, and rating of the eHMIs in a Wizard-of-Oz study conducted by the Technical University of Munich on a test track. The results showed no significant differences between the eHMI concepts on pedestrians crossing initiation or intention recognition times. However, the *intention-based light-band* was ranked highest regarding their preference, with the *perception-based light-band* being a close second. The signal lamp was only perceived by a few participants. In general, most participants preferred to have an eHMI present on AVs. The purpose of another test track study at the Centro Ricerche Fiat (CRF) facilities in Torino was to evaluate the impact of the *intention-* and *perception-based light-band* on pedestrians' behaviors and perceptions. The results suggest that the different eHMIs may not impact road users crossing decisions but the *perception-based light-band*, in particular, may lead to greater confidence and comfort in the AV behavior compared to no eHMI (Dietrich et al., 2020).

Generally, these eHMIs have proven to be beneficial, in the interACT studies regarding the subjective perception of vehicle intention and AVs themselves. Most interACT studies revealed that these eHMIs lead to quicker interactions compared to encounters without eHMI. However, the different eHMI concepts did not result in different objective results among themselves. The results showed that participants almost unanimously preferred to have AVs equipped with one of the presented eHMIs. To clarify the previous findings that are partially contradictory, further research is needed. In addition, an examination of eHMI concepts in real-world road traffic scenarios is missing. This is the aim of the present work described as follows.

AIM AND RESEARCH QUESTIONS

The aim of this work is to investigate pedestrian reactions to the external communication concepts developed in the interACT research project (interACT Project, n.d.) in a real-world crossing scenario using a study design which we called *instructed walking*. The eHMIs were tested under the conditions that are less controlled but more realistic than test track environments. The focus of this work is to ascertain whether pedestrians can understand the intention of the vehicle ("I saw you" and "I'm letting you go ahead") through the different eHMI concepts on the outside of the vehicle. It is also examined which eHMI leads to better intelligibility and an earlier crossing decision. In

FIGURE 1 | The participants encountered the test vehicle with external human–machine interface (eHMI) at one of the two predefined interaction points.

addition, how these eHMIs affect acceptance and perceived safety is assessed. The specific research questions are as follows:

RQ1: How does the use of the eHMI concepts affect the comprehensibility of vehicle intention compared to no eHMI?

RQ2: How do the different eHMI concepts differ from each other regarding comprehensibility, acceptance, and perceived safety?

METHOD

Participants

In total, 30 participants (14 men, 16 women) with a mean age of 24.53 years [standard deviation (SD) = 2.37, min = 19, max = 30] participated in the experiment. Most of the participants were students. Apart from one participant with color vision deficiency, no participants had other uncorrected visual impairments. This participant had a red/green color vision deficiency. In the authors' opinion, this did not affect the interaction with the vehicle or the comprehensibility of the eHMIs, and thus the results of the study. Therefore, this person was not removed from the data set.

Study Design

The study employed a single-factor within-subject design. Three different eHMI concepts were tested (see section independent variable: eHMI concepts for a detailed description of the concepts) and compared to a baseline in which no eHMI was displayed. A Wizard-of-Oz approach (i.e., the driver hidden by a seat cover) was used to simulate an AV. In a real-vehicle study conducted at the private premises of the Technical University of Munich with other road users, participants encountered a test vehicle with eHMI in a specified road section at two predefined interaction points (see **Figure 1**). An attempt was made to conceal the actual purpose of the study with a cover story. The goal of this procedure was to reduce the possible bias in the expectations that participants had before entering the study to be able to investigate more natural interactions between the vehicle and participants. Participants were guided so that the interaction occurred at the appropriate time. We refer to this technique as *instructed walking*. With three encounters for each of the eHMI concepts and the baseline, each participant experienced 12 runs in total. The order of the eHMI concepts was randomized to counteract potential sequential effects.

Independent Variable: EHMI Concepts

The following three eHMI concepts were developed as part of the research project interACT (interACT Project, n.d.), and varied during this experiment: *intention-based light-band*, *perception-based light-band*, and *a combination of light-band and signal lamp*. Cyan was used as the color for the light of the signal lamp and of the light-band. The technical setup enabling the eHMIs comprised two components: First, a signal lamp placed in the top part of the windshield. The signal lamp could be partly occluded through an aperture to be visible only at a certain angle (only for a certain person, while others cannot see the light). In this experiment, the lamp's aperture was fully opened for maximum visibility, as there was only one participant. The second component was a light-band that run underneath the windshield, alongside the hood, and along the side of the test vehicle at the edge of the roof. The light-band could glow and pulsate as a whole. Furthermore, several lights could be activated at a certain location while the rest of the light-band was turned off. The co-driver adjusted both components in real time using

FIGURE 2 | eHMI concept *intention-based light-band* communicating "I'm letting you go ahead".

an experimenter interface on a tablet within the test vehicle. This was used to trigger the different eHMIs during the experiment.

The first eHMI concept *intention-based light-band* (see **Figure 2**) used the light-band that was pulsating slowly to indicate vehicle intention to stop in front of the participant and yield the right-of-way to the participant (Weber et al., 2019a).

The *perception-based light-band* (see **Figure 3**) was intended to signal to participants that they have been detected by the vehicle. For this purpose, a narrow section of the light-band was illuminated to indicate the position of the detected road user. If the participant moved, the illuminated section of the light-band also moved.

The third concept *combination of light-band and signal lamp* (see **Figure 4**) consisted of the pulsating light-band concept and the signal lamp that shone directly on the pedestrian by changing its direction depending on the participant's position relative to the vehicle. The signal lamp was visible only to relevant participants, communicating "I saw you." The combination of these two components should indicate that the participant was detected, along with communicating "I'm letting you go ahead" (Weber et al., 2019a).

In this study, the signal lamp was not investigated in combination with the *perception-based concept* because these two concepts aim to communicate the same message that the pedestrian is detected by the AV.

Dependent Variables

To gain insights into the crossing behavior, the reaction time in seconds, also called crossing initiation time, was assessed. Crossing initiation time is defined as the time at which the participant enters the road with the intention to cross. For this purpose, the video recording of vehicle-participant encounters was analyzed. Crossing initiation time represented the difference between the two points in time "step into the walking flow" and "reference point vehicle." The moment "step into walking flow" was defined as the moment when the leg, used to start the step into the fluent crossing of the road, was visibly angled in the video. The "reference point vehicle" is the moment when the right front wheel touches a virtual red line added to the footage. This moment was chosen because it was the point at which the eHMIs were switched on. To ensure comparability with the runs without eHMIs, we decided on a reference point for all runs. This reference point also represents the starting point of braking, which was 7 m away from the participant. At this point, the vehicle was already visible to the participant.

Furthermore, intention recognition was defined as a dependent variable, whereby a verbal statement from participants was used to record whether they understood what intention the vehicle was pursuing and what meaning the eHMI had. For this purpose, a structured interview was conducted at the end of this study to determine whether participants understood the intention of the eHMI concepts. First, participants were asked whether they noticed the different eHMI concepts during the study. This question served to ascertain which concepts were seen at all. After explaining the different concepts, participants were questioned which of the three concepts they found most understandable and which they found least understandable. An explanation of their assessment was also requested. Using this question, a comparison between the different eHMIs could be made. To examine whether participants generally prefer the use

FIGURE 3 | eHMI concept *perception-based light-band* that communicates “I saw you” following the participant.

of eHMIs, they were asked if this approach to communicate between the vehicle and the pedestrian is generally good. A further question was whether participants felt that they were adequately informed at all times about what the vehicle was going to do next (e.g., whether it was going to stop, etc.).

In addition, acceptance and perceived safety were assessed. The acceptance questionnaire of van der Laan et al. (1997) was used. The perceived safety questionnaire included one question about each eHMI concept and asked participants to rate on a 5-point Likert scale how confident they felt when interacting with each eHMI concept (i.e., “I felt very confident interacting with the *intention-based concept/perception-based concept/combination of light-band and signal lamp*”).

Materials and Equipment

The study test vehicle was a BMW i3s with no driver automation and was therefore driven manually. However, an automated driving condition was simulated by using seat covers, under which the driver and co-driver were hidden from the participants’ view to make the vehicle appear driverless (see **Figure 5**).

Furthermore, to examine the participants’ behavior (i.e., crossing initiation time), wide-angle cameras were installed at fixed locations where participants walked across the street. A GoPro Hero 3 Silver Edition and APEMAN A79 action camera with a resolution of 1,920 × 1,080 pixels were used for this purpose.

Procedure

The study duration was ∼60 min per participant. Before starting the experiment, participants completed an online demographic questionnaire. Participants gave written informed consent and were instructed by the investigator before entering the study. The protocol was approved by the ethics committee of the Technical University of Munich under grant number 24/20 S. With the help of a cover story, participants were supposed to believe that they

FIGURE 4 | eHMI concept *combination of light-band and signal lamp* communicating “I saw you” and “I’m letting you go ahead”.

were taking part in a GPS tracking experiment. According to the cover story, movement profiles of several users were to be recorded in a precisely measured street section *via* GPS using a smartphone. Participants were also told that their location would be monitored live, and that the accuracy of the location data would be checked regularly. The participants’ instruction was to walk a predefined round course and stop at predefined points (see **Figure 6**). These points were necessary to control the timing of the participant–vehicle encounters. The vehicle drove in the opposite direction of participants and came from the right at each interaction point.

A trial run was conducted in which participants did not encounter the test vehicle. This served to show participants the defined route and all relevant markings on the ground. Participants were tasked to stop at certain markings until the experimenter told them to move on to the next marking. The experimenter was in constant communication with the driver via a walkie-talkie, coordinating the encounter between the participant and the vehicle.

The test vehicle approached the participant at a constant speed of 20 km/h, stopped in front of the participant on each of the runs, and waited until the participant had crossed the road before continuing. This was for participants’ safety. The start of braking and switching on the eHMI took place simultaneously at fixed positions to keep these factors constant across all runs. This position was reached when the test vehicle was at a distance of 7 m from the participant, bringing it to a stop at a distance of 4 m from the participant. To ensure that deceleration was as constant as possible during braking, the recuperation function of the BMW i3s was used to stop in front of participants. Switching on the eHMI was manually controlled by the co-driver using a tablet.

After completion of the runs, a semi-structured interview was conducted. Participants were informed of the purpose of the study, and that the vehicle was not driving automatically at any time. Participants were then asked to complete the two questionnaires.

Statistical Procedure and Data Analysis

Statistical tests were conducted using the statistical software IBM SPSS Statistics (IBM Corp., 2017). It was determined whether there was a significant difference between the three eHMI concepts, including the difference to show no eHMI. Therefore, a one-way repeated measures analysis of variance (ANOVA) with eHMI as the within-subject factor and subsequent *post hoc* pairwise comparisons (Bonferroni-adjusted t-tests) were calculated for the crossing initiation time. The alpha error level was set to $\alpha = 0.05$.

The participant and the test vehicle encountered each other at two predefined interaction points. However, the evaluation showed that the comparability of these two interaction points is not guaranteed. During the execution of the experiment, an enormous data failure occurred at one interaction point due to the lack of a smooth interaction and crossing scenario, and thus these data could not be used. This leads to the fact that, in the following, only one interaction point is analyzed in more detail.

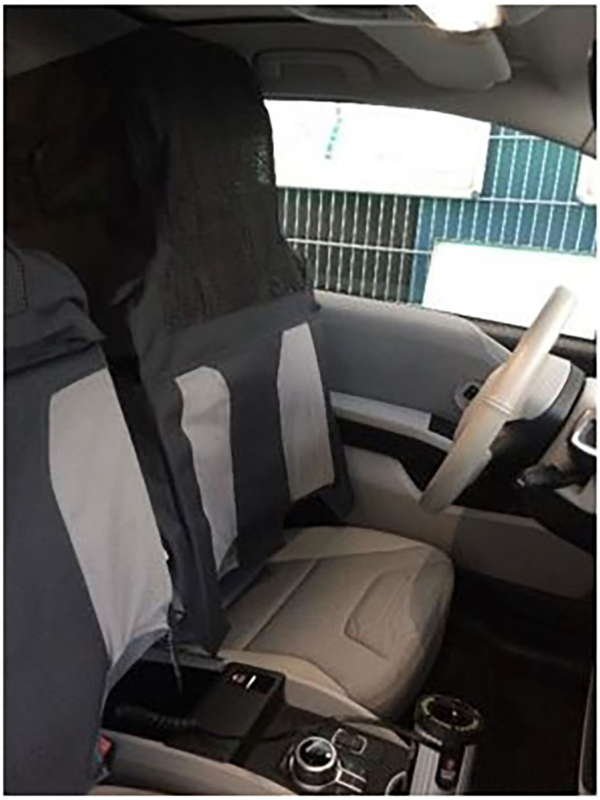

FIGURE 5 | The seat cover of a test vehicle to hide the driver and to simulate automated driving.

During the evaluation, one participant had to be completely excluded from the analysis because the participant did not show any natural interaction with the vehicle. Despite being told that it was a public road, this person did not pay any attention to the traffic. Therefore, it was assumed that this person did not normally exhibit such behavior in a crossing scenario. Therefore, it was decided to exclude this individual from further analyses because no natural crossing situation occurred.

The acceptance questionnaire was prepared according to the evaluation instructions of van der Laan et al. (1997) and analyzed. A coding system from +2 to −2 was used, with +2 being the most positive score. For the reversed items, the coding was adjusted accordingly. The questionnaire on perceived safety was scored from 1 (completely disagree) to 5 (completely agree). During the evaluation of the semi-structured interview, the statements of participants were collected and then clustered into categories. For each category, the number of mentions was recorded as absolute frequency so that frequently made statements could be identified. This categorization was based on inductive, thematic free coding according to Mayring (2015). The average inter-rater reliability was Cohen's $\kappa = 0.83$, reflecting a almost perfect agreement according to Landis and Koch (1977).

RESULTS

Crossing Initiation Time

Figure 7 shows the descriptive analysis of the data. The *intention-based light-band* was associated with the lowest average crossing initiation time ($M = 1.41$, $SD = 0.82$) and no eHMI with the highest ($M = 2.3$, $SD = 1.13$). The crossing initiation time of the *perception-based light-band* ($M = 1.71$, $SD = 1.17$) and of the *combination of light-band and signal lamp* ($M = 1.54$, $SD = 0.95$) lay between the *intention-based light-band* and no eHMI.

A repeated measures ANOVA showed a significant difference between the eHMI concepts [$F_{(3,66)} = 6.45$, $p < 0.001$, $\eta_p{}^2 = 0.23$]. The effect size can be classified as large according to Cohen (1988). *Post hoc* pairwise comparisons revealed a significant difference between the *intention-based light-band* and no eHMI ($p = 0.002$), as well as between the *combination of light-band and signal lamp* and no eHMI ($p = 0.031$). Hence, a significantly faster crossing initiation time was observed for the *intention-based light-band* and the *combination of light-band and signal lamp*, compared to no eHMI. No significance was found for the other comparisons.

Acceptance Questionnaire

The items were rated on a scale of −2 to +2, with +2 being the highest acceptance score. **Figure 8** displays the participants' scores on the two subscales. The examination of the descriptive analysis suggests that, on average, the *perception-based light-band* was rated best regarding usefulness ($M = 1.28$, $SD = 0.63$). The *intention-based light-band* was rated as slightly less useful ($M = 1.23$, $SD = 0.71$). The *combination of light-band and signal lamp* received the lowest rating ($M = 0.92$, $SD = 0.73$). Concerning ratings on user satisfaction with eHMIs, the *intention-based light-band* ($M = 1.16$, $SD = 0.72$) and the *perception-based light-band* received similarly high ratings ($M = 1.04$, $SD = 0.74$). The *combination of light-band and signal lamp* received the lowest rating ($M = 0.78$, $SD = 0.92$).

The two subscales of the acceptance questionnaire (i.e., usefulness and satisfying) were further evaluated with a repeated measures ANOVA. The statistical analysis revealed no significant effect on either usefulness [$F_{(2,56)} = 2.52$, $p = 0.09$, $\eta_p{}^2 = 0.08$] or satisfying [$F_{(1.53,42.95)} = 2.29$, $p = 0.13$, $\eta_p{}^2 = 0.08$].

Perceived Safety Questionnaire

Descriptive statistical analysis revealed that all three variants of the eHMI received high ratings. The *intention-based light-band* ($M = 4.24$, $SD = 0.87$) and the *perception-based light-band* ($M = 4.28$, $SD = 1.00$) received similar ratings. *The combination of light-band and signal lamp* received a slightly lower rating ($M = 3.90$, $SD = 1.08$). A repeated measures ANOVA showed no significant difference between the eHMI concepts [$F_{(2.55,38.78)} = 1.84$, $p = 0.17$].

Semi-Structured Interview

Participants were asked to name the different concepts they noticed during the study. Almost all participants named them as the *intention-based* ($n = 27$) and the *perception-based light-band*

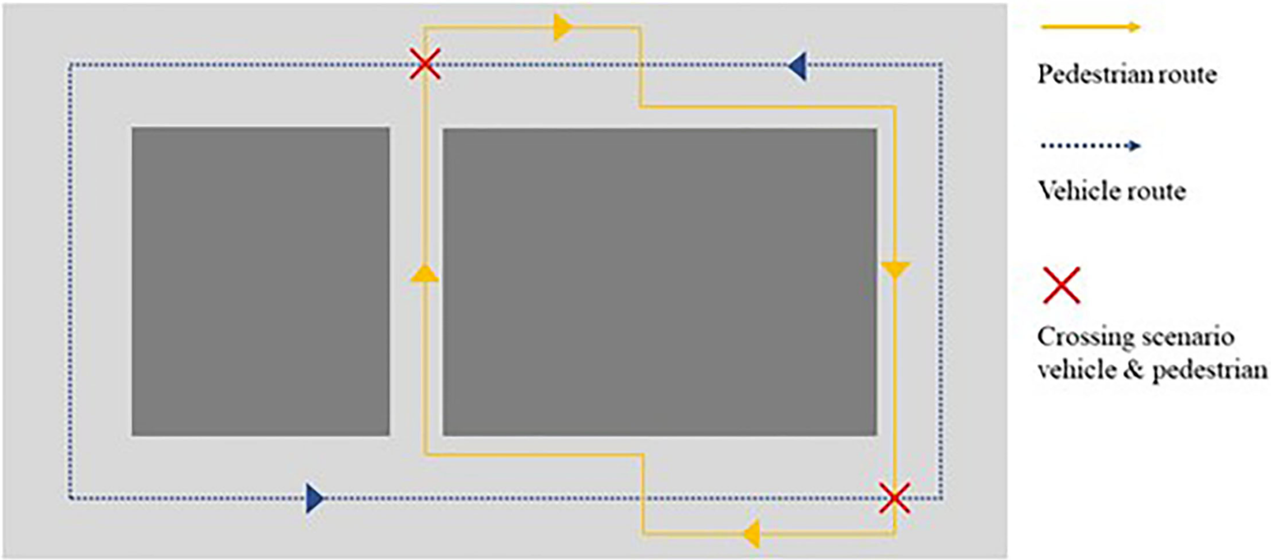

FIGURE 6 | Visualization of the test procedure with the predefined interaction points (red *x*).

($n = 27$). The signal lamp as part of the concept *combination of light-band and signal lamp* was mentioned only 13 times. After the three eHMI concepts were presented in terms of videos and explained, participants were asked which concept they found most or least understandable. Most participants named the *intention-based light-band* ($n = 13$) or the *perception-based light-band* ($n = 13$) as most understandable. The *combination of light-band and signal lamp* was rarely rated as the most understandable ($n = 3$). As a reason for the comprehensibility of the *intention-based light-band*, five participants mentioned the strong saliency of the concept, as the area in which the vehicle lights up green is large and thus easily perceivable. Regarding the *perception-based light-band*, eight participants noted as positive that the vehicle detects the participant's position and feeds back its detection. In total 11 participants described the *combination of light-band and signal lamp,* and ten the *perception-based light-band* as the least comprehensible. The *intention-based light-band*, on the other hand, was rather rarely described as incomprehensible ($n = 6$). Two participants rated none of the eHMIs as non-understandable. The main reasons given for a negative evaluation of the *perception-based light-band* were ambiguity of the concept ($n = 4$) and the lack of saliency ($n = 6$). The signal lamp was also criticized for its unobtrusiveness ($n = 5$), and four saw no added value or need for it. Five participants also noted that the signal lamp could be quickly misinterpreted. For example, three participants mistook the point-shaped light for that of a camera.

In general, almost all participants ($n = 25$) rated the approach of using eHMIs to communicate between vehicles and pedestrians as good. Eight participants commented that this was a very useful and intuitive communication option, which was especially good as a replacement for driver–pedestrian communication. The comprehensibility ($n = 6$), feedback ($n = 6$), and the feeling of safety ($n = 7$) that the external concept can provide were also mentioned. In total, 21 of the 29 participants said they felt adequately informed about what the vehicle was going to do next at any point in the study. One of the reasons cited was eHMI ($n = 11$), but another very common reason was the vehicle's implicit communication in the form of braking ($n = 16$).

DISCUSSION

Three different eHMI concepts were investigated in a real-world crossing scenario regarding their comprehensibility and their influence on the timing of the crossing decision. They were compared to a baseline without eHMI. For this reason, two research questions were posed (see section method), which are answered as follows:

RQ1: How does the use of the eHMI concepts affect the comprehensibility of vehicle intention compared to no eHMI?

The results showed a significant effect on the crossing initiation time between the *intention-based light-band* and no eHMI. This could be due to the good perceptibility and comprehensibility of this concept. Furthermore, there was a significant effect between the *combination of light-band and signal lamp* and no eHMI. This concept includes the concept of *intention-based light-band*, which can be an explanation for this significance, despite the poor subjective evaluation of the *combination of light-band and signal lamp* in the interview. Because only 13 participants noticed the signal lamp during the experiment, it is presumed that the other participants based their crossing decisions on the pulsating light-band and the signal lamp did not negatively influence it. In general, participants crossed the road earlier when the vehicle was communicating with the *intention-based light-band* or the *combination of light-band and signal lamp*. This is in line with the results of Matthews et al. (2017), Othersen et al. (2018), and Clercq et al. (2019)

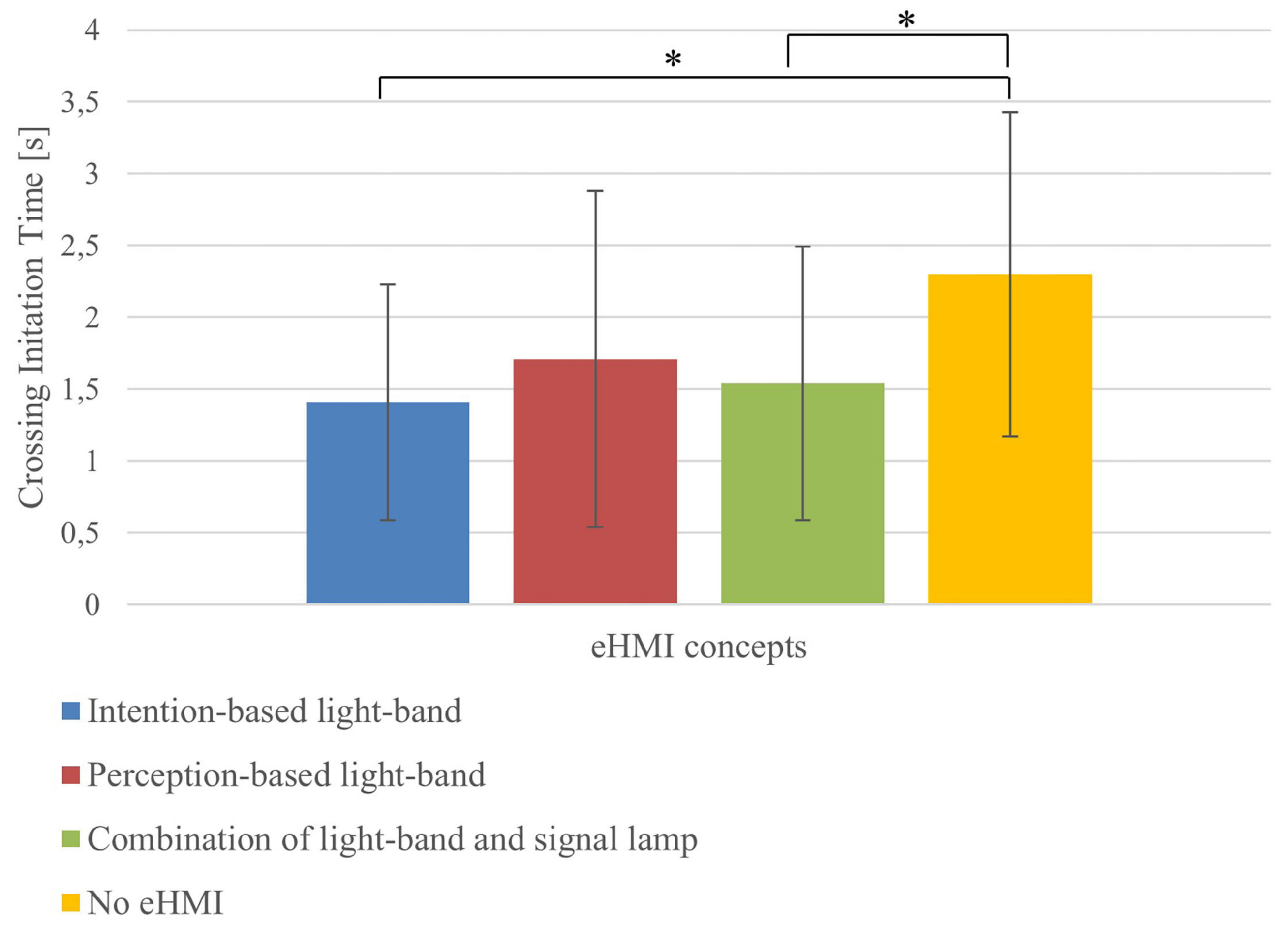

FIGURE 7 | Mean crossing initiation time in seconds across the different eHMI concepts. Error bars reflect ± 1 *SD*. *Reflects $p < 0.05$.

who were able to demonstrate in their studies that the presence of an eHMI led to an earlier crossing decision. This was also confirmed by ITS in Leeds as part of the interACT project (Dietrich et al., 2020). No significant difference was found between the *perception-based light-band* and the baseline. One reason for this could be the perceptibility and the partial lack of comprehensibility of this concept, which was criticized by participants. Another reason could be that participants needed time to infer from the eHMI statement, "I saw you," to the intention of the vehicle. However, there was no significant difference between the concepts *per se*. This can be due to the fact that the concepts are similar in their implementation and thus do not differ strongly enough from each other. This is in line with a test track study conducted by the TUM as part of the interACT project (Dietrich et al., 2020).

Another important factor to consider is vehicle movement. A finding of the interview was that participants also cited implicit communication through braking as a reason to infer the vehicle's intention. This is also consistent with the results of other studies. Clamann et al. (2017), for example, found that the use of external displays for communication with pedestrians influenced the crossing decision of only 12% of participants, while most pedestrians mainly used other information, such as vehicle speed and distance, for their crossing decision. This was also evident in the interview analysis, where several participants mentioned implicit communication as an additional reason for the comprehensibility of the vehicle's intention. The results of Rothenbucher et al., 2016 study also suggested that pedestrians' crossing decision depended solely on vehicle movement, but at the same time, pedestrians wished for clear signals to show them that they had been detected and could safely cross the street. This is in accordance with Mahadevan et al. (2018) who recommended to use explicit communication of vehicle intention rather than just implicit communication. Thus, it can be concluded that the use of eHMIs is not a substitute for implicit communication, but can be supportive and helpful to pedestrians in making crossing decisions. Therefore, an interplay of both means of communication should be aimed for, whereby the eHMI communication must in no case contradict the behavior of the vehicle.

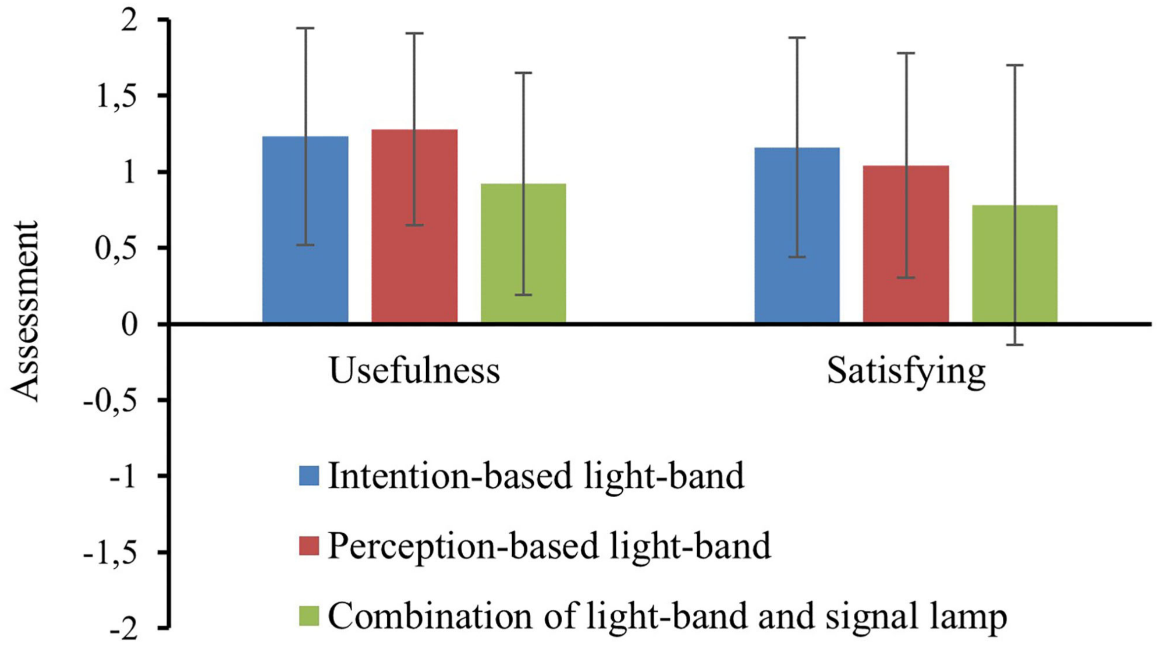

FIGURE 8 | Mean acceptance rating across the eHMI concepts. Error bars reflect ± 1 *SD*.

In summary, the present results provide evidence that the evaluated eHMI concepts have a positive effect on the comprehensibility of the vehicle's intention. The subjective evaluation of participants reveals that explicit communication using these eHMIs is helpful. This is also reflected in the objective data, showing that participants crossed the road earlier when either the *intention-based light-band* or the *combination of light-band and signal lamp* was present. However, there were no significant differences in crossing initiation times between the absence of eHMI and the *perception-based light-band*. Also, implicit vehicle communication probably contributes to the comprehensibility of the concepts.

RQ2: How do the different eHMI concepts differ from each other regarding comprehensibility, acceptance, and perceived safety?

The interview showed that the *intention-based light-band* was perceived by almost all participants and could therefore be noted as the most salient concept. This might be due to the large area of the light along the entire vehicle contour and should be emphasized as positive. For this reason, it can be assumed that this concept is easily recognizable by participants. High perceptibility could be a prerequisite for good comprehensibility because this concept was often evaluated as positive in this respect. Overall, the *intention-based light-band* can be rated as comprehensible.

In the evaluation of the *perception-based light-band*, the interview did not reveal any clear tendency among participants. This concept was perceived by some participants as the most comprehensible one. The continuous display of the detected participant position was mentioned positively. However, the *perception-based light-band* was also rated as the least understandable by some participants. This could be an indication that not all participants understood the running light-band as an indication of their own position or did not perceive it as soon as they crossed the street and turned their gaze forward. The designation of the concept by some participants as a "small green bar" also suggested that the salience of this concept was not sufficient for several participants. This finding is consistent with the results of a study conducted by Faas and Baumann (2020). They stated that a steady or flashing light was better suited to indicate the intention of an AV, or to give pedestrians the right of way, than a "sweeping light." Thus, the comprehensibility of the *perception-based light-band* has to be questioned.

The interview showed that the *signal lamp* was only perceived by 13 participants and could therefore be noted as the least salient component of the eHMIs concepts. The *combination of light-band and signal lamp* was often described as the least understandable concept after explanation. The interview showed that the signal lamp was misunderstood and had a negative impact on the comprehensibility of the concept. It was not clear to all participants what message the signal lamp communicated. Therefore, this eHMI scored the worst in the evaluation regarding its comprehensibility. However, it can be assumed that this poor rating is due to the signal lamp and not to the entire concept, including the *intention-based light-band* concept.

The evaluation of the acceptance questionnaire showed that all three eHMIs scored high ratings. No significant differences were found between the concepts in the evaluation of usefulness and satisfaction. Therefore, it can be assumed that they do not differ greatly from one another in terms of subjective acceptance. The evaluation of perceived safety did not indicate any major differences between the three eHMI variants, with only the *combination of light-band and signal lamp* being rated slightly lower. Although participants might not see or understand the signal lamp, they would still rate this concept quite high regarding acceptance and perceived safety. This could be explained by the fact that the well-understood and well-rated pulsating light-band was additionally present, which positively influenced the evaluation of this concept. Because this rating was high on average for all eHMI variants, it could be assumed that the presence of eHMIs conveyed a sense of safety to participants, regardless of the concept. This is also in line with the results of Habibovic et al. (2018), who were able to demonstrate that participants feel safer when information is communicated *via* eHMIs in addition to implicit communication. Thus, it can be assumed that all concepts can contribute to a higher subjective perception of safety.

Limitations and Future Research

Firstly, no pilot study was conducted beforehand. Prior to the experiment, preliminary studies were performed with several participants; however, not all limitations were discovered during these studies. The limitations of the study are reported below. The location of the experiment proved to be problematic. Spontaneous events along the test route, although favoring the impression of a real traffic situation, led to problems during the experiment. Other vehicles, e.g., trucks, parked on the sidewalk or car entering and exiting, interfered with the smooth test procedure. Pedestrians crossing participants' path also forced the repetition of the corresponding passes. Furthermore, this study can reflect the natural crossing behavior of a participant only to a certain extent. The planned and repetitive encounter between the vehicle and the participant led to a rather artificial flow of the experiment.

A central limitation of this study was that the two interaction points at which participants encountered the test vehicle were not identical. For this reason, the interaction points could not be compared and the results could not be merged. This resulted in a loss of data. A further study with more data is recommended.

Moreover, it could be assumed that the learning effect considering the behavior of the vehicle during the study was high. Because participants encountered the vehicle several times and the vehicle stopped for them each time, participants could have decided to cross the road completely independent of the display of an eHMI, but solely based on their previous experiences and lessons learned. Furthermore, it should be mentioned that the switching on of the eHMIs was done manually by the co-driver on a tablet. An automated solution would have been useful at this point to ensure standardized timing.

An additional limitation of this study is the composition of the present sample. This consisted mainly of students under 30 years of age, which corresponds to a very young and homogeneous group. Rasouli et al. (2017) noted that culture also plays a role in determining pedestrian behavior. In the future, communication with AVs must be intuitive, understandable, and easily learnable by all road users, regardless of culture, language, or age. Therefore, it would be important to replicate the results of this study by resurveying with a more heterogeneous sample. To rule out possible cultural influences on the intelligibility of eHMIs, the study should be repeated in other countries. The results presented must be considered with the reservation of low power. It cannot be ruled out that possible differences between the concepts cannot be detected due to the small sample size. Future experiments should take this aspect into account and be conducted with a larger sample size.

The results of this study indicate the potential for improvement and further development of eHMI concepts. Further research questions can be posed, which need to be examined in further studies. For example, it must be ensured that eHMI concepts are sufficiently perceptible and understandable for people with color vision impairment. Similarly, it should not be possible to confuse the display of an eHMI with the lighting system of emergency vehicles. Differently rated comprehensibility of eHMIs reinforces the call for cross-manufacturer communication concepts. Manufacturer-specific eHMIs could lead to ambiguity, lack of comprehensibility, and confusion when making crossing decisions. This could counteract the goal of increasing traffic safety through AVs. In a standardized solution approach, attention should be paid to an intuitive and easy-to-learn design. The need for a detailed explanation should be avoided. In addition, future studies should consider crossing situations where pedestrians have to interact with more than one AV, which might lead to conflicting yield/pass messages.

CONCLUSION

The introduction of AVs could lead to a lack of communication between drivers and pedestrians. New and intuitive communication concepts for achieving safe interactions between AVs and vulnerable road users, such as pedestrians, are needed. The present work aimed to investigate participants' reactions to external communication concepts in a real-world crossing scenario. Three different eHMI concepts developed in the interACT project (*intention-based light-band, perception-based light-band, and combination of light-band and signal lamp*) were varied and compared to a baseline without eHMI. The study investigated whether the use of eHMIs affects the comprehensibility of vehicle intention and leads to earlier road crossing. For this purpose, crossing initiation time in seconds was measured and the intention recognition was queried.

It was shown that participants crossed the road significantly earlier with the concepts of *intention-based light-band* and the *combination of light-band and signal lamp* compared to no eHMI. Moreover, all eHMIs were rated with high acceptance and perceived safety. The *intention-based light-band* was evaluated as well understandable and had high saliency. It communicated the vehicle intention "I'm letting you go ahead," which was explicit for most participants. This is preferable to the *perception-based light-band* that communicated "I saw you." The constant communication of the participant's position through the *perception-based light-band* was noted positively, but the lack of perceptibility and comprehensibility of the concept was evaluated negatively. This results in an ambiguous picture, which calls for a revision of this concept, especially regarding its saliency. The *combination of light-band and signal lamp* was subject to most criticism because the signal lamp was not salient enough and could be easily misinterpreted. Therefore, the signal lamp investigated in this study is neither suitable and nor recommended for communication between AVs and pedestrians.

Conclusively, the *intention-based light-band* investigated in this study can be rated as the best and most comprehensible concept and is therefore recommended for further application. This work makes an important contribution to clarify how communication between pedestrians and AVs can be designed and investigated in a safe and intuitive way. In addition, the present study design provides a novel approach for assessing eHMIs in a realistic traffic situation. However, future work is needed to enhance this approach.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethic commission of the Technical University of Munich; Grant No. 24/20 S. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

AL wrote the first draft of the manuscript. JG, LH, AG, AB, and AD contributed to conception and design of the study. AL and JG performed the statistical analysis. All authors contributed to manuscript revision, read, and approved the submitted version.

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Deviant Behavior of Pedestrians: A Risk Gamble or Just Against Automated Vehicles? How About Social Control?

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Recent evidence suggests that the assumed conflict-avoidant programming of autonomous vehicles will incentivize pedestrians to bully them. However, this frequent argument disregards the embedded nature of social interaction. Rule violations are socially sanctioned by different forms of social control, which could moderate the rational incentive to abuse risk-avoidant vehicles. Drawing on a gamified virtual reality (VR) experiment (n = 36) of urban traffic scenarios, we tested how vehicle type, different forms of social control, and monetary benefit of rule violations affect pedestrians' decision to jaywalk. In a second step, we also tested whether differences in those effects exist when controlling for the risk of crashes in conventional vehicles. We find that individuals do indeed jaywalk more frequently when faced with an automated vehicle (AV), and this effect largely depends on the associated risk and not their automated nature. We further show that social control, especially in the form of formal traffic rules and norm enforcement, can reduce jaywalking behavior for any vehicle. Our study sheds light on the interaction dynamics between humans and AVs and how this is influenced by different forms of social control. It also contributes to the small gamification literature in this human–computer interaction.

Keywords: automated vehicles, self-driving cars, social control, deviant behavior, bullying, virtual reality, pedestrian, vulnerable road users

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1 INTRODUCTION

In the near future, we can expect mixed traffic mobility in which vehicles with no, partial, or full automation (SAE, 2016) will coexist and cooperate with human traffic participants, including vulnerable road users (VRUs) such as pedestrians and cyclists (Holländer et al., 2021) (see **Figure 1A**). At first sight, road traffic appears to be a highly regulated system in which agents act according to traffic code rather than their normative beliefs and values. Many interactions in urban traffic, however, are not only weakly regulated and observed; they also rely on established social norms and practices. Moreover, there might be many other factors in traffic that can shape the behavior of individuals. There are many traffic situations in which cooperative behavior is exercised, such as letting a pedestrian pass in slow-flowing traffic on an urban street even though there is no traffic light or pedestrian crossing. In such situations, the car and its driver use little signs of vehicle behavior such as "indicative" braking or hand gestures that help all parties in a decision-making situation (Moore et al., 2019), for example, to cross the street in front of a car. With the disappearance of a driver in a fully automated vehicle, signs by the driver no longer exist. At the same time, there is a

FIGURE 1 | Human–AV interaction in everyday traffic and in pedestrian simulators. **(A)** In the future, pedestrians will interact with AVs with higher levels of automation daily. **(B)** VR enabled us to utilize our meeting room with a long corridor for a safe testing environment for our pedestrian simulator.

clear understanding of the pedestrians that automated vehicles are highly regulated and have safety measures in place in case a pedestrian crosses their way (Millard-Ball, 2018; Holländer et al., 2019). Therefore, the question is, in which situations pedestrians would indeed exploit the latter when crossing a street by relying on the safety features of automated vehicles (AVs) and by enforcing the vehicle(s) to stop and to claim the right to cross the street. Hence, understanding how individuals will interact with AVs in urban traffic is still a key challenge on the path to autonomous driving (Tabone et al., 2021) before AVs can independently navigate our streets.

As an additional constraint, social challenges play a key part before they can travel the streets without continuous interference. Various news articles report incidents where vulnerable road users disturb AVs, ranging from simple negative gestures to pointing a gun (Condliffe, 2016; Randazzo, 2018; Brown, 2019; Keck, 2019). Those instances even led some companies to conduct their trials with unmarked AVs to prevent potential bullying by other road users (Connor, 2016). As these instances paint a rather grim picture of human-AV interaction, traffic interaction is not a one-shot game and does not occur in a social vacuum. Instead, it is embedded in a set of formal and informal (social) norms (Björklund and Å berg, 2005). Exploiting an AV, for example, by jaywalking in front of it, is, therefore, a specific form of human behavior often referred to as deviant behavior. Deviance refers to acts that break the social rules of those kinds of behaviors that are deemed acceptable by society. Deviant (rule-breaking) behavior is frequently sanctioned by society through social control (Brauer and Chaurand, 2010), a set of sanctioning and reward mechanisms that incentivize individuals to conform to societal expectations. These range from formal forms of sanctioning (e.g., laws and punishment) to social feedback in the form of, for example, positive reinforcement, shame, or ridicule. Social control could thus potentially moderate the rational incentive to exploit AVs. However, the moderating effect of social norms (*via* social control) on deviant behavior has received limited attention in the literature so far.

This study investigates how different forms of social control moderate pedestrians' decision to jaywalk in front of AVs and human-driven vehicles (HDVs). Utilizing jaywalking behavior of pedestrians to study deviant behavior in the context of AVs has several benefits: 1) pedestrians benefit the most from a conflict-avoidant AV, drastically reducing their vulnerability in accident-prone situations, thereby increasing their utility to exploit them; 2) deviant behavior of pedestrians is commonplace in urban traffic situations, making it the most probable cause of interference for AVs; and 3) compared to other road users, the behavioral movement of pedestrians is significantly less predefined by the physical traffic environment, offering more frequent opportunities to act in line with self-interest.

1.1 Background

Road traffic is highly regulated in unclear traffic situations; drivers and VRUs use several forms of implicit and explicit communication ranging from deceleration up to hand gestures to let someone pass (Dey and Terken, 2017; Moore et al., 2019). Implicit or vehicle-centric (Dey et al., 2020a) communication cues can be summarized by vehicle movement patterns such as acceleration, deceleration, and vehicle distance (Varhelyi, 1998; Te Velde et al., 2005; Schmidt and Faerber, 2009; Risto et al., 2017). Explicit or driver-centric communication cues are managed *via* eye contact (Guéguen et al., 2015; Ren et al., 2016; Schneemann and Gohl, 2016; Nathanael et al., 2018) and gestures (Guéguen et al., 2015; Färber, 2016; Sucha et al., 2017) of the traffic participants.

With a disappearing driver in the automated vehicle, in unclear communication situations, the pedestrian would only have to rely on the vehicle-centric signals of the driverless vehicle alone. Research on pedestrian–AV interaction largely addressed this issue by exploring External Human–Machine Interfaces (eHMIs), which could assist communication between drivers and other traffic participants and could increase the acceptance of AVs (Carlsson and Nilsson, 2016; Chang et al., 2017; Dey et al., 2020b; Colley et al., 2022). Moreover, some other studies explored trust and overtrust of VRUs in AVs (Holländer et al., 2019; Jayaraman et al., 2019; Faas et al., 2020a; Holthausen et al., 2020).

Alongside acceptance and trust, one of the favorable measures for understanding interaction dynamics between AVs and pedestrians is the crossing decisions of participants. Faas et al. (2020b) emphasized the realistic walking behavior in related crossing paradigms rather than using a button or a safety slider for a better matching experience to realism. As a feasible solution, virtual reality (VR) has been widely used in pedestrian–AV interaction research because it allows for reproducible and controllable environments in immersive settings (De Clercq et al., 2019; Holländer et al., 2019; Jayaraman et al., 2019; Löcken et al., 2019; Mahadevan et al., 2019; Kalatian and Farooq, 2021). VR has also been effectively used in experimental paradigms where time pressure was tested in crossing tasks (Morrongiello et al., 2015; Schneider et al., 2019). Moreover, Bhagavathula et al. (2018) reported that pedestrian behavior was similar in VR compared to reality in terms of perceived safety and risk.

In order to reveal pedestrian crossing decisions in detail, Kalatian and Farooq (2021) conducted a large (N = 180) VR study. Their deep learning model emphasized the effect of AVs alongside street width, traffic density, and limited sight on elongated waiting times of pedestrians before crossing. In the VR cave study of Dommès et al. (2021), the authors tested the crossing behavior of pedestrians in front of conflict-avoidant AVs and conventional vehicles in a mixed traffic environment. They reported that participants were more hesitant to cross in front of AVs in some conditions. However, they also argued that participants mainly relied on locomotion cues of vehicles independent of their automation status. Jayaraman et al. (2019) conducted a gamified virtual reality study to investigate pedestrian trust in AVs in situations where AVs' locomotion cues signalized aggressive, normal, and defensive behavior. Moreover, they controlled the traffic environment by testing pedestrian trust in unsignalized and signalized crossings with a traffic light. Their results indicated an increase in trust when AVs exhibited defensive behavior and when pedestrians were on signalized crossings. The work of Jayaraman et al. explored the aspects that can establish more pedestrian trust in AVs to encourage pedestrians to cross in front of AVs without hesitance. However, the long-term effects of trustworthy and defensive AV behaviors on individuals' interaction with them are yet to be explored (Dommès et al., 2021).

Undeniably, human trust and the safety of AVs are essential before AVs are released on the streets. Nonetheless, some studies highlight the possible drawback of the conflict-avoidant behavior of AVs in their interaction with humans (Camara et al., 2018; Fox et al., 2018; Camara et al., 2020; Dommès et al., 2021). For instance, Moore et al. (2020) reported that human road users disturb driverless cars in a Wizard-of-Oz study with obstructive behavior types, ranging from playful curiosity to aggression to purposely stepping in front of them, which was also observed by Madigan et al. (2019). Similar behavioral patterns were also observed toward service robots by Salvini et al. (2010). Drawing on game theory, Fox et al. (2018) and Millard-Ball (2018) argued that if AVs are programmed with a zero-probability for collision, situations as these were to be expected: the shared argument is that a collision-avoidant AV will reduce other traffic participants' risk of a crash or injury when interacting with them, thereby increasing the rational utility to exploit their passive stance for individual benefit, hence leading to a "freezing robot problem" in the mixed traffic of the future (Trautman and Krause, 2010). As a countermeasure, Camara and Fox (2020) introduced a pedestrian–AV interaction model where they suggested replacing conflict-avoidant AVs with a milder space invading AVs without introducing severe crash risks, inspired by findings regarding social factors in traffic among individuals.

One overlooked factor in AV–VRU research is social norms and social factors (Colley et al., 2019), alongside scalability problems (Colley et al., 2020; Dey et al., 2021). Pedestrians were more likely to cross the road if other pedestrians around them had started crossing (Faria et al., 2010). In a very recent study, Colley et al. (2022) tested the effects of pedestrian group behavior and a single pedestrian behavior on their participants' crossing decisions in front of AVs, and they found similar results to Faria et al. (2010). However, there is still a large gap in exploring the social norms in AV–pedestrian research and carrying one-to-one interaction paradigms a step further.

1.2 Own Approach

In our study, we build on rational-choice theory, which assumes that individuals use their self-interests to make choices and model deviance as a function of an individuals' cost-benefit calculation (Becker, 1968). In this context, deviant behavior occurs if the anticipated net gains from the specific action outweigh the anticipated losses associated with that action. This means exploiting the conflict-avoidant nature of AVs might only serve the self-interest of individuals, as it outweighs the costs of breaking social rules. Specifically, we focus on three different types of social control: 1) the "broken-window thesis" of a negative bystander effect, which should incentivize deviant behavior, 2) social conformity, moderating deviant behavior by conforming with societal expectations when in the presence of others, and 3) formal norm enforcement and sanctioning by authority.

Methodologically, we designed a 2 × 2 × 4 full-factorial VR experiment (vehicle type, task urgency, and social control), where individuals were asked to deliver pizza in a simulated urban traffic environment. We carried out the analysis in two parts: first, we tested for the effect of the experimental treatments under unknown probabilities that the human-driven car would stop, and then, we gave participants the possibility to signal the driver to stop, which succeeded 50% of the time. This way, we could likewise test whether the treatment effects depend on the lower crash risk when confronted with AV or whether potential effects might be caused by the autonomous nature of AV. Conducting this experiment in VR not only enabled us to obtain a closer approximation of the natural behavior of participants in a virtual environment (Deb et al., 2017a) but also offered time- and cost-effective testing setups where traffic situations could be built securely and flexibly. In our study, participants were faced with the choice to cross a busy road by jaywalking through a gap in traffic or wait until the traffic flow allowed for a safe and norm-compliant crossing. The first vehicle at the end of this gap was randomized to be either human-driven or an AV. Different social control conditions varied randomly by the presence of different road users with different characteristics and behaviors presented. Moreover, we manipulated the task urgency for the individual task as a third factor to test whether the moderating effect of social norms depends on the individual payoff for deviant behavior. Individuals were incentivized to cross the street by a small monetary reward.

The experiment employed a within-subjects design (n = 36), where every participant received all experimental treatment conditions. As repetitive crossing scenarios might potentially decrease motivation and increase task fatigue for participants Schneider et al. (2019), we employed gamification, a technique where participants are incentivized with various game elements such as badges or scores (Sailer et al., 2017).

Our research questions are formulated as follows:

- Are there differences between the crossing behavior of individuals when they encounter automated or conventional vehicles right after a traffic gap?
- Do positive, negative, and legal representations of social control cues affect the crossing behavior of individuals?
- Do different levels of task urgency-related time pressure affect the crossing behavior of individuals?

1.3 Contribution to the Field

Our study is timely concerned with newly emerging considerations in pedestrian–AV research. Firstly, we introduced a mixed traffic environment where both AVs and HDVs existed in the experimental scene. Secondly, we went out of the widely studied one-to-one interaction paradigms between AVs and pedestrians and contributed to limited scalability research in this area. Third, we explored potential social control mechanisms that can reduce or enhance the deviant behavior of pedestrians from three different dimensions: legal, positive, and negative norm cues. To our knowledge, such social control mechanisms were not a major focus in existing research, except for a negative example of a crossing pedestrian or idle pedestrian groups. Moreover, we tested legal norm cues under a study where the legal sanctioning was ambiguous, as opposed to studies that utilized definitive traffic lights or traffic signs. Forth, we further tested the effect of vehicle type and social control on deviant behavior when controlling for the risk of accidents for conventional vehicles. This allowed us to test whether significant differences between human-driven and autonomous vehicles existed, resulting from the autonomous nature of AVs and not their conflict-avoidant stance. Last but not least, our research contributes to the small sample of gamification literature in pedestrian–AV interactions, which supports a better-blinded method for repetitive within-subject designs.

		Pedestrian	
		Wait	***Walk***
Autonomous Vehicle	*Yield*	(–1, –1)	(–1, 1)
	Drive	(1, –1)	(–100, –1,000)

2 THEORETICAL FRAMEWORK

2.1 Exploiting Automated Vehicles as a Rational Decision

Recent studies on AV–pedestrian interaction draw on the game theory to argue that AV's inability to adapt their behavior from a passive, conflict-avoiding stance would make incentive pedestrians step in front of them (Fox et al., 2018; Rahmati and Talebpour, 2018). Testing a sequential game of chicken, Fox et al. (2018), for example, suggested that assuming a zero-probability of collision between an AV and an HDV, based on the assumed conflict-avoidant programming, the expected cost of collision for the human driver likewise is nearly zero, which would result in the rational incentive to abuse AV for human drivers. Applying this model to the AV–pedestrian interaction and assuming the payoff structure to consist of the trade-off between time-savings and risk of personal injury while keeping the probability of crash at 0, we would receive the same result, even if the expected cost of a crash would be significantly higher for the pedestrian. Formally, this can be expressed by the expected utility theorem, which assumes that an individuals' rational decision, given a set of possible alternative choices, is a function of the expected utility of the different choice options based on the probability distribution of the decisions' outcomes. The decision to abuse an AV thus occurs if the expected utility of this choice is larger than or equal to the expected utility of alternative actions:

$$ExpectedUtility_{humanabuses} = Utility_{abuse} * Probability_{AVstops} > ExpectedUtility_{alternativeactions}.$$

To illustrate this, we use the following hypothetical payoff matrix for the interaction between an AV and a pedestrian. We assume that, for each player, the utility to yield possesses a utility of −1 (lost time), whereas walking/driving possesses the utility of 1 (gained time). When both players choose to walk/drive, the result is a crash, which is significantly more costly to both players than the other choice outcomes.

We can then calculate the expected utility for a pedestrian to either walk or wait:

$$EU_{Walk} = U_{Walk/AV\,yield} * p_{AV\,yield} + U_{Walk/AV\,drive} * (1 - p_{AV\,drive})$$

$$EU_{Wait} = U_{Wait/AV\,yield} * p_{AV\,yield} + U_{Wait/AV\,drive} * (1 - p_{AV\,drive}).$$

Because $U_{Wait/AVyield} = U_{Wait/AVdrive}$, which holds true for all possible payoffs as the cost to wait is independent of the choice of the vehicle:

$$EU_{Wait} = U_{Wait/AV\,yield} = U_{Wait/AV\,drive} = -1,$$

Given that $U_{Wait/AVyield} = U_{Wait/AVdrive}$, the decision to cross then depends on the probability that the car will yield, which is a function of the utilities for the car yielding or driving when the pedestrian crosses. In this example,

$$EU_{Walk} > EU_{Wait} \text{ if } EU_{Walk} > U_{Wait/AV\,yield} = U_{Wait/AV\,drive} = -1,$$

which is true if $p_{AVyield} > 99, 8\%$.

Given this minimalist payoff structure, the introduction of conflict-avoidant AVs would create a rational incentive for bullying AVs, as highlighted in previous studies (e.g., Fox et al., 2018; Millard-Ball, 2018). However, the utilities of traffic interaction in real life do not solely consist of the trade-off between time savings and risk of personal injury, which makes this model too narrow to reflect real-life behavior. For instance, traffic interaction (in most instances) is regulated by formal and informal rules.

2.2 The Cost of Norm Violation

Formally, traffic is regulated by traffic code, and to step in front of an AV would, in many instances, be considered a traffic violation, subject to fines and penalties. Similarly, even the AV/HDV interaction at an unmarked intersection used in the previous example would, in most jurisdictions, fall under the "priority to the right" rule. Informally, traffic is further regulated by social norms (including compliance with formal norms). Social norms generate a sense of predictability under uncertainty. In other words, social norms can be understood as equilibria of strategies to solve repetitive games, reducing the cost of uncertainty by believing that others will act in accordance with the norm. Frequent norm violations thus carry the risk of norm erosion, meaning that an established norm ceases to exist if individuals too frequently deviate from the said norm. The resulting norm erosion, in return, increases interaction costs by creating uncertainty with regard to the behavioral choices of other individuals in future interactions, which is not limited to the individual committing the norm violation but to society. Drawing on the previous example, if HDVs frequently violate the "priority to the right-" rule in the context of AVs, future interactions at unmarked intersections would be more time-consuming, as they would require individual negotiation between traffic participants because trust in norm compliance would be low, as the norm of "priority to the right" eroded.

Abusing or bullying a self-driving car, here in the form of jaywalking in front of it, is thus a form of human behavior commonly referred to as deviant behavior. Deviance describes actions or types of behavior that violate formal (i.e., laws and traffic code) or informal (i.e., social norms) rules (Goode and Ben-Yehuda, 2010). In other words, deviance refers to behavior that goes against what is deemed acceptable by society. Building on a rational-choice approach to deviance (Becker, 1968), we understand the associated norm violation as a function of an individual's cost-benefit calculation and, following the expected utility theorem, expect deviant behavior to occur if the anticipated net gain from breaking the (formal or informal) rules outweighs the anticipated net gain from alternative actions. To be more specific, we build on the argument by Keuschnigg and Wolbring (2015) that a rule is rationally anticipated to be broken if the expected benefit of breaking this rule minus the cost of punishment (multiplied by the probability the rule-breaking will be sanctioned), is larger than the expected utility of alternative actions. The cost of norm violation then results from the incentive of other individuals to sanction norm violations (to prevent norm-erosion) and the cost of punishment, a mechanism often referred to as social control. While from the other perspective, norm compliance might also positively increase the utility of alternative actions (e.g., by intrinsic rewards). Adding the effect of social control to the utility function of jaywalking behavior, a person would then jaywalk if $EU_J > EU$ and, thus, if

$$[U_{JS}*p_S + U_{JD}*(1 - p_S)]U_{punishment}*p_{sanctioning} > [U_{WS}*p_S + U_{WD}*(1 - p_S)] + U_{reward}*p_{reward}.$$

Note: J = jaywalking, S = vehicle stops, W = pedestrian waits, D = vehicle drives.

The decision to jaywalk would thus be influenced by three different components:

1) The individual gross utilities for the different choice options.
2) The probabilities for the individual choice outcomes to occur.
3) The cost of punishment and the probability of sanctioning.

Given that the moderating effect of norm compliance influences the net gains of the behavioral choice, all else being equal, its effect should be stronger in situations where the net gains are lower; that is, the expected utilities between the different choice options are more similar, compared to a more limited effect when the utility trade-offs between the choice options are higher. Hence, we would expect that an increase in utility for the deviant choice of jaywalking would increase the expected utility to jaywalk and therefore increase deviant behavior. We, therefore, expect the following:

H1. All else being equal, a higher utility payoff for the deviant behavioral choice will increase deviant behavior.

Because the expected utility of the deviant behavioral choice is dependent on the probability of occurrence of the different choice outcomes, we likewise expect that passively programmed AVs should increase deviant behavior, given that the probability the car will yield is programmed to be 100%.

H2. All else being equal, individuals will jaywalk more frequently when interacting with an AV.

The second hypothesis already implies that we do not expect social control (the cost of norm violation) to fundamentally alter the utility differences between interactions with AV and HDV, that is, social control to formally interact with vehicle type. This would be the case if the effect of social control would be substantially different for the individual vehicle types or specific social norms would exist that only apply to a specific type of vehicle. However, we are not aware of empirical evidence demonstrating that the cost of norm compliance significantly differs between HDV and AV or specific social norms that only apply to one type of vehicle. On the contrary, our main argument in this study is that social control applies to both HDV and AV and reduces the overall occurrence of deviant behavior, disregarding the vehicle type. In order to understand the extent of this moderating effect, it is important to differentiate between different forms of social control.

2.3 Social Control as a Moderator of Deviant Behavior

The influence of others on deviant behavior was formalized by Hirschi (1969) in the theory of social control. Hirschi viewed social sanctioning, which he explicitly differentiated from formal sanctioning, as an even higher deterrent of deviant behavior than formal rules (Hirschi and Gottfredson, 1994). Norm compliance, in return, results from individuals' motivation to conform to social norms. More generally, social control refers to the rewards and sanctions that result from conforming to or deviating from social norms (formal or informal) (Ross, 1896). In line with this theory, research on red-light violations of pedestrians (Rosenbloom, 2009; Fraboni et al., 2018; Raoniar and Maurya, 2022) revealed that individuals cross with a higher frequency if they are alone, compared to situations where multiple individuals are waiting for the green light. Recent evidence suggests that this effect is further moderated by social proximity; it increases when individuals are surrounded by people they feel closer to or who belong to their social group.

H3a. (Norm conformity) The presence of other pedestrians will decrease deviant behavior.

However, the presence of others can also have the opposite effect on deviant behavior. The observation of deviant behavior by other individuals incentivizes norm violations (Keizer et al., 2008). Formally, other individuals violating norms might serve as a cue that norms are not enforced in this area, or norm erosion occurs, which decreases the marginal cost for non-compliance. This effect exists even if the behavior of others has not been observed directly. However, the inference of low levels of norm compliance is made by social cues, such as littering, graffiti, or broken windows ("broken-windows thesis") (Wilson and Kelling, 1982).

H3b. (Negative bystander/broken windows) Cues signaling norm violations by others will increase deviant behavior.

Hirschi argues that social sanctioning serves as a higher deterrent to deviant behavior than formal norms, so evidence on traffic violations suggests that cues signaling the enforcement of formal norms have a strong negative effect on deviant behavior. Given the moderating effect of social proximity on norm-compliance, this might be explained by the larger social distance between individuals on public roads, which limits the effect of social sanctioning (e.g., a nasty look by a bystander is less costly than reproach by family members). In contrast, cues of formal norm enforcement and sanctioning make the cost of norm violation more salient for individuals.

H3c. (Formal norm enforcement) Cues signaling sanctioning of formal norms will have a negative effect on deviant behavior.

3 MATERIALS AND METHODS

3.1 Virtual Reality Environment

To conduct this experiment, we designed a virtual street environment in Unity 3D (version 2020.3.0f1). VR served as a flexible and safe test bed for running our study (see **Figure 1B**). The environment was limited by tunnels on both sides of the road and surrounded by hills. Urban buildings were placed on both sides of the street. Because we used game elements in our experiment, we did not focus on making the virtual environment realistic and utilized low polygon mesh elements (see **Figures 2–4**). The placement of traffic signs, pedestrian crossings, and traffic lights intentionally abstained so that participants could only use the information of vehicle movements and communication cues on their crossing decisions. The size of the street, including pavement, was 12 m. Participants emerged a few steps away from the sidewalk while traffic was flowing on the road. The unidirectional traffic coming from the left side of the participant consisted of fully automated and conventional vehicles. Vehicles had a 50 km/h start speed and exponential deceleration behavior with starting value of 1.98 km/h. Vehicles stopped at a sufficient distance to provide a traffic gap for participants to cross. Virtual human characters emerged on the left side of the participant when they accompanied the scene. This allowed both oncoming vehicles and virtual road users to be in the participants' field of view (see **Figure 2**).

The task of the participants was to score points by delivering pizza to a virtual character waiting on the opposite side of the road (see **Figure 4A**). If participants failed to deliver pizza for reasons such as getting caught by the police, they did not receive any points. Otherwise, they either received 1 base point for delivering the pizza or 2 points for delivering the pizza within the bonus timer. The traffic pattern consisted of two waves of vehicles passing the scene from left to right. Between the first and second waves of vehicles, a gap of around 3 s opened up. Participants were then faced with the choice to either jaywalk in this situation or wait until the second wave of cars passed.

FIGURE 2 | Virtual reality "street-crossing game" (participant perspective). Note: the participant is given the task of delivering pizza to a non-player character across the road. On the left side of the participant, a non-player character attempts to cross the road. A yielding AV can be spotted with blue deceleration light cues. The timer in the middle indicates 5 s left to earn the extra tip from pizza delivery.

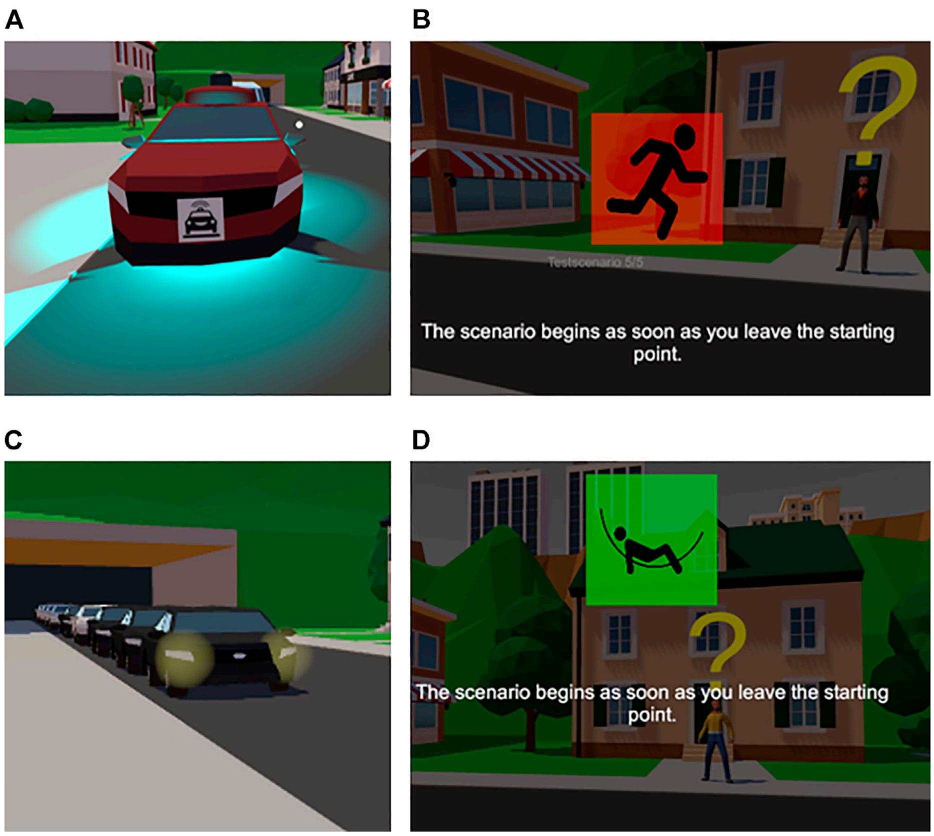

FIGURE 3 | Vehicle type and task urgency factor levels in the experiment. **(A)** Decelerating AV casts blue light cues. **(B)** Urgent task indicator with a running man on a red background. **(C)** Decelerating HDV flashes headlights. **(D)** Non-urgent task indicator with a resting man on a green background.

3.2 Experimental Design

Our experiment consisted of three factors (vehicle type, task urgency, and social control) with different factor levels, resulting in a 2 × 2 × 4 full-factorial design, where all experimental conditions varied randomly within subjects. This design provided control for individual differences; it allowed us to examine the effect of multiple independent variables and their interactions at a time, and it was more efficient because smaller

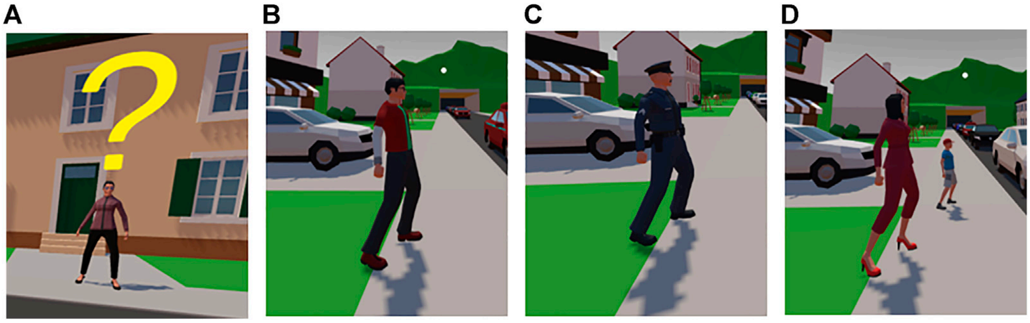

FIGURE 4 | Non-player characters. **(A)** Target customer waiting for pizza delivery. **(B)** A walking person who crosses the road represents negative social control. **(C)** Police officer representing legal control. **(D)** Mother and child representing positive social control of abiding by the rules.

sample sizes could be sufficient for statistical power. The experimental treatments consisted of the combinations of the different factorial levels that we operationalized by manipulating specific elements of the individual scenes.

3.2.1 Vehicle Type

To understand the differences in crossing behavior between self-driving and conventional vehicles, we manipulated the first vehicle of the second wave of cars to be either an AV or an HDV. To increase the realism of the situation and understand whether the crossing decisions are dependent on a lack of communication between the pedestrian and vehicle, we operationalized the HDV condition in two ways: equal amounts of conditions with a successful communication between the driver and the pedestrian when participants tried to negotiate for the right of way and conditions with conventional vehicles that did not respond to negotiation request.

AVs always yielded to participants as soon as participants stepped onto the road, so we could simulate their defensive design principles. For sending feedback to participants, AVs switched on a light-blue light when they started decelerating (Werner, 2018) (see **Figure 3A**). Conventional vehicles stopped for the participant if the participant performed a hand gesture coupled with a button press and the vehicle was a part of the successful communication subset. This gesture represented the explicit communication between the vulnerable road users and drivers. For sending deceleration feedback, HDVs flashed their headlights to participants (see **Figure 3C**). In the failed-communication subset, HDVs neither stopped nor indicated other forms of cues to participants. Participants were unaware of the types of conventional vehicles, and they were only informed that human drivers may or may not respond to them.

3.2.2 Social Control

To understand the effect of different forms of social control on crossing behavior, next to the baseline condition of no social control, we tested for the effect of social conformity, cues indicating formal norm enforcement, and the effect of a negative bystander. To represent different social controls, we placed virtual human characters on the left side of the participant (see **Figures 4B–D**). For representing a positive norm of social conformity, a mother and a child waited before crossing until all vehicles passed. A mother and her child were chosen for this condition, as the social norm of rule compliance should be stronger when acting as a possible role model for the child. The negative bystander/broken-windows condition was operationalized by a walking person who stopped the oncoming vehicle wave after the small traffic gap was used. Formal norm enforcement and possible sanctioning were operationalized by the presence of a police officer. Participants were informed that police may or may not see them. If police saw them attempting to cross by obstructing the traffic flow, participants were stopped; hence, they received 0 points from that trial. This game mechanism represented a subtle cost of legal punishment. Because crossing the road in our scenario was not illegal, we avoided any direct punishment implications. In order to reduce the bias of police behavior, we sat up equal amounts of catching and non-catching police conditions in the design.

3.2.3 Task Urgency

To understand the effect of different payoffs on jaywalking behavior, we tested for the effect of different task urgency and different payouts for jaywalking. This factor consisted of two levels: urgent and non-urgent. Urgency levels were cued with symbols before each trial started (see **Figures 3B,D**). In the scenario, participants received 1 base point for successful pizza delivery. However, they could double their earnings when completing the task in the set time frame. Therefore, scenarios were presented with a timer indicating the remaining time for earning a bonus point (see **Figure 2**). In non-urgent trials, the bonus timer started counting back from 23 s, which was enough for waiting until all vehicles passed, and it was safe to cross. In this condition, individuals received 2 points (base + bonus), disregarding their crossing decision. In urgent trials, the bonus timer started counting back from 13 s, meaning that participants had to jaywalk in front of a vehicle to complete the task with 2 points.

3.3 Collected Measures

As dependent variables, we collected both the crossing decision of individuals and the associated crossing onsets. Crossing onsets captured the time passed from the moment a trial started until a participant stepped on the road (in seconds). The crossing decision was observed by the researchers and was cross-checked with the collected crossing onsets, which were filtered by a series of criteria. First, participants crossed if the crossing onsets were smaller than the time needed for the last car of the second wave of cars to pass an invisible line. Second, if the last car could not reach the invisible line before the participant, either the participant successfully reached the other side or because a crash occurred (See **Supplementary Material**).

Because we implemented a second choice task for HDVs, to test for the effect of vehicle type and social control under equal risk of collision between human-driven and automated vehicles, we then split the dependent variable of crossing onsets into two. For the general differences, we only used those observations where the crossing decision was made within 1 s after the first wave of cars passed (7.75 s), which equals around 1 s before the second wave's arrival. This point is likewise below the reaction time of the risk-controlled, yielding signaling its intention to stop. For those observations, we could logically assume that the crossing decisions for scenarios with an HDV were made, disregarding the behavior of the other vehicle and under unknown probabilities of a collision. To compare the crossing decision under equal risk for a crash, we used all observations where the participant crossed later than the initial time frame, crossed or did not cross when interacting with an AV, or elected to not cross when faced with an HDV where successful negotiation could have been possible (which was unknown to the participant, but signalized that no attempt to stop the car was made). As independent variables, we used the experimental treatment conditions and coded them into three factors (vehicle type, task urgency, and social control).

After finishing the VR experiment, participants filled out an online survey in LimeSurvey (version 3.27.26) Schmitz (2012) consisting of the IGroup Presence Questionnaire (IPQ) (Schubert et al., 2001), a demographics form (Deb et al., 2017b), the Pedestrian Receptivity Questionnaire for Fully Autonomous Vehicles (PRQF) (Deb et al., 2017b), the Pedestrian Behavior Questionnaire (PBQ—Short Version) (Deb et al., 2017b), and the Social Value Orientation (SVO) (Murphy et al., 2011) scale. Within the scope of this study, we have only used these measures to draw a clearer participant profile, and we did not evaluate them further in statistical analysis. Lastly, we presented five open questions regarding the effects of manipulated factors in the experiment (see **Appendix**).

3.4 Participants

Thirty-six participants (21 females, age: $M = 25.22$, $\pm SD = 5.15$) were recruited *via* the online notice board of the university and printed "Pizza Delivery Game" advertisements on bus stops. Participants were informed they would be reimbursed with 8–10 euros, depending on the final game score. However, all participants eventually received a compensation of 10 euros for their participation, which was revealed at the end of the experiment. The Ethics Committee of the University of Oldenburg gave ethical approval for the experiment according to the Declaration of Helsinki.

Most participants reside in big cities with an overall population density of at least 193 people per square km. Most of them were high school graduates ($n = 14$) or graduate students ($n = 10$). Thirty-two participants would fall in the prosocial category on the Social Value Orientation angle ($M = 32.69$, $\pm SD = 8.77$) (Murphy et al., 2011). Their (PRQF) (Deb et al., 2017b) grand scores had a mean more on the positive side of the scale ($M = 66.63$, $\pm SD = 10.88$), indicative of greater receptivity for AVs. The average PBQ-Short Version (Deb et al., 2017b) grand score of the participants was 43.08, on the negative side of the scale, indicating safer pedestrian behavior ($\pm SD = 6.80$). Inspection of the IGroup Presence Questionnaire (IPQ) (Schubert et al., 2001) revealed high general presence ($M = 4.52$, $\pm$ SD = 1.20), high spatial presence ($M = 4.29$, $\pm$SD = 0.97) and above-average involvement $M = 3.77$, $\pm$SD = 1.12) in our VR experiment. However, experienced realism was rated on the negative side of the scale ($M = 2.60$, $\pm$SD = 0.74) (see **Figure 5**).

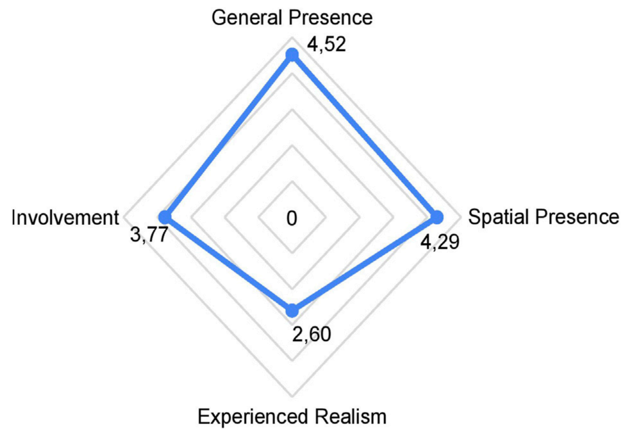

FIGURE 5 | iGroup Presence Questionnaire Evaluation. Note: iGroup Presence Questionnaire Evaluation with means of the subscales involvement, experienced realism, spatial presence, and general presence.

3.5 Experimental Procedure

Participants were invited to a large meeting room. This provided enough space for walking a street-long distance of 12 m (see **Figure 1B**). First, participants gave their written consent and received specific information about the study and the associated task. Secondly, they were introduced to the Oculus Quest 2 VR headset and controllers (Facebook Technologies, LLC.). Then, they were instructed about the virtual guardian walls that indicate safe zones in the real environment. The virtual environment was re-positioned in a way that participants could walk straight to the virtual customer within the safe zone.

Before the experiment started, each participant conducted five test trials to familiarize themself with the environment, as in Jayaraman et al. (2019) and Kalatian and Farooq (2021). In the first trial, participants experienced crashing and dying, where they received the information about dying with a text on black background. They were also falsely informed that if they died in the experiment, the experiment would be over without earning the extra incentive. We gave this information to increase the cost of dying in the game. In the second trial, participants tried to stop the conventional cars by communicating with a gesture combined with a button press on the controller. The third trial showed them that conventional vehicles do not always consider their requests, and they keep on driving. In this trial, they also saw a very large traffic gap where the road was free of vehicles. They were reminded that this gap existed in each trial. The last two test trials were dedicated to police conditions where a policeman is either aware or unaware of the participant. In these last two trials, participants also practiced crossing in front of an AV. After making sure participants had no questions, 30 pseudo-randomized experimental trials began. Lastly, participants filled out online survey questions at the end. The virtual reality experiment took, on average, 30 min, in line with Kalatian and Farooq (2021) due to the increase in fatigue after 30 min, and the survey took 30–40 min to complete.

3.6 Analytical Approach

Before conducting the analysis, we ran a series of validity checks and excluded observations that were either implausible or instances where participants did not start crossing due to rare bugs. These include instances where respondents were free-falling from the environment or the trial time was elapsed. Unusual crossing onsets smaller than 1 s and bigger than 20 s (4/864) were ignored, resulting in a final sample size of N = 36 with 860 observations.

To understand the effect of the experimental treatments on the crossing behavior, we calculated a generalized linear mixed-effects model (GLMM) (Nelder and Wedderburn, 1972), including the experimental factors as fixed effects and treating within-subject variance as random effects. The crossing behavior of individuals served as a binomial dependent variable in the analysis, which we regressed on dummy variables for the experimental factors. We tested for both the main effects of the three experimental factors and interaction effects between vehicle type and both social control and task urgency. The statistical analysis was performed in RStudio (version 1.4.1106) (R Studio Team, 2020), using the glmer function of the Lme4 package (version 1.1-27.1) (Bates et al., 2015). The distribution of residuals in our models was cross-checked with the check_distribution function of the R performance package (version 0.8.0) (Lüdecke et al., 2021). Model fittings were tested *via* the base ANOVA function of R with Chi-squared tests and compare_performance function in the performance package. We also report the predicted marginal effects of each condition with crossing probabilities, which were calculated using the ggeffects package (version 1.1.1.1) (Lüdecke, 2018). They are reported in percentages after the multiplication of 100. Marginal effects indicate the average treatment effect of our experimental factors (or interaction of factors), holding the other factors constant in their proportions.

4 RESULTS

In this part, we report the results of the experiment, both for the baseline experiment under unknown risk of a crash with an HDV (see **Section 4.1**) and a second analysis using a subset of risk-controlled crossing decisions, where participants were able to stop the HDV (see **Section 4.2**). **Section 4.1** includes crossing attempts in front of HDVs where participants did not try to negotiate with the driver. **Section 4.2** excludes these trials and demonstrates the results of participants when they negotiated with HDVs and when they tried to stop the vehicles by communicating with the drivers with a gesture. We have made this two-level analysis to observe the overall effect of vehicle types on our study and the pure effect of vehicle automation on crossing behavior when the risk of crashing is eliminated for HDVs.

For reporting the main effects, we elected to present the average marginal effect of the experimental factors, which is the effect of the factor levels of interest in reference to the baseline level, while holding the other factors constant at their proportions and the marginal means, which is the average crossing probability of participants when holding the other factors constant at their proportions. As the average marginal effect helps illustrate the causal effect in reference to the reference level, the marginal means illustrate the overall descriptive means for the different treatment conditions. We chose to report marginal effects because they are more intuitively understandable than odds ratios, reporting changes in or the overall means of crossing decisions for the different treatment conditions in percentages.

Overall, participants chose to cross deviantly in 62.1% of the trials, whereas in 37.9% of the cases, they decided to wait. The crossing decisions were most common when confronted with an AV, where they chose to cross in 71.4% of the trials, whereas when confronted with an HDV, only 57.4% elected to cross. When faced with an HDV, the crossing decision was equally distributed between observations where participants did not know about the probability that the car would stop (27.7%) and trials where participants successfully signaled the car to stop (29.7%).

4.1 General Crossing Predictions

The results of the Generalized Linear Mixed Effects Model to model individuals' general crossing decisions are provided in **Table 1**, and the predicted marginal effects and marginal means for the different treatments are illustrated in **Figure 6**. We used distinctive models to calculate the marginal effects. While models 1, 2, and 3 show the results for the main effects of vehicle type, task urgency, and social control, respectively, models 4 and 5 indicate the interaction between vehicle type × task urgency and vehicle type × social control.

With all else being equal and keeping the effect of the other factors constant at their proportions, we find the presence of AV to significantly increase the crossing probability by 43% in comparison to HDV (β = 2.03, z (860) = 12.01, Pr ($>|z|$) $<$ 0.001) (see **Figure 6** top left). Overall, this meant for our participants that the average probability of crossing increased from 26% when interacting with an HDV to around 73% when interacting with an AV (see **Figure 6** top right). Similarly, in reference to non-urgent scenarios, urgent scenarios significantly increased average probability of crossing by 13% (β = 0.56, z (860) = 3.95, Pr ($>|z|$) $<$ 0.001) (see **Figure 6** middle left). The average

TABLE 1 | General results for the effect of vehicle type, task urgency, and social control on crossing decisions.

Predictors	M1 odds ratios	M2 odds ratios	M3 odds ratios	M4 odds ratios	M5 odds ratios
(Intercept)	0.36***	0.55***	0.62*	0.25***	0.23***
Autonomous vehicle	7.61***			7.94***	14.68***
Urgent		1.76***		2.01***	
Walking person			4.58***		6.85***
Police presence			0.33***		0.31**
Mother and child			1.04		1.06
Autonomous vehicle * urgent				1.04	
Autonomous vehicle * walking person					2,233,228.92
Autonomous vehicle * police presence					0.56
Autonomous vehicle * mother and child					1.02
Random effects					
σ^2	3.29	3.29	3.29	3.29	3.29
τ_{00}	0.57	0.35	0.54	0.61	1.08
ICC	0.15	0.10	0.14	0.16	0.25
N	36	36	36	36	36
Observations	860	860	860	860	860
Marginal r^2/conditional r^2	0.192/0.312	0.022/0.117	0.187/0.301	0.220/0.342	0.865/0.898

***p < 0.001, **p < 0.01, *p < 0.05.
Note: results of generalized mixed-effect regression models. Odds ratios and random effects are reported for models 1–5. M1: vehicle type, M2: task urgency, M3: social control, M4: vehicle type × task urgency, M5: vehicle type × social control.

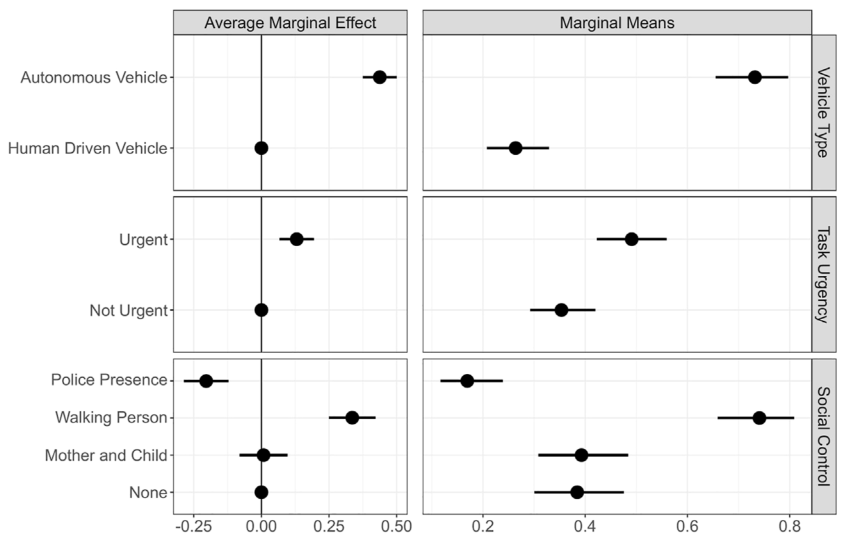

FIGURE 6 | Average marginal effects and marginal means for general crossing. Note: left plot shows the average marginal effects (AME) of our three experimental factors in reference to their baseline factor levels. The vertical line represents the effect of the reference level. The right column reports the marginal means (MM) for the different factor levels on crossing probabilities, holding the other factors constant at their proportions. Points indicate AME/MM, horizontal lines the 95% CIs. Effects based on results of GLMM.

probability of crossing in urgent scenarios was 49%, whereas it was 35% in non-urgent scenarios (see **Figure 6**, middle right). Lastly, when contrasted to the baseline social control condition of being alone, the presence of a police significantly reduced the crossing probability by 20% ($\beta = -1.11$, z (860) = -4.77, Pr (>|z|) < 0.001); the presence of a walking person significantly increased crossing probability by 33% ($\beta = 1.52$, z (860) = 7.06, Pr (>|z|) < 0.001); and the bystanders mother and child did not change the probability of crossing ($\beta = 0.03$, z (860) = 0.17, Pr (>|z|) = 0.86) (see **Figure 6** bottom left). Our participants' crossing probability was predicted as 16% in the presence of police. Moreover, an increase of 74% was observed when accompanied by a walking person who attempted to cross the road. With mother and child condition, the crossing probability was at 39%. Finally, when the participants were alone in the scene, their crossing probability was 38% (see **Figure 6**, bottom right).

4.2 Risk Controlled Crossing Predictions

Since participants were unaware of the probability that an HDV would stop for the initial crossing decision, the strong effect of AV

TABLE 2 | Risk-controlled results for the effect of vehicle type, task urgency, and social control on crossing decisions.

Predictors	M1 odds ratios	M2 odds ratios	M3 odds ratios	M4 odds ratios	M5 odds ratios
(Intercept)	2.65***	2.03***	4.50***	2.25***	8.13***
Autonomous vehicle	0.97			0.82	0.38*
Urgent		1.75**		1.47	
Walking person			79,112,259.30		44,516,415.95
Police presence			0.13***		0.07***
Mother and child			0.62		0.28*
Autonomous vehicle * urgent				1.38	
Autonomous vehicle * walking person					2.64
Autonomous vehicle * police presence					2.57
Autonomous vehicle * mother and child					3.81*
Random effects					
σ^2	3.29	3.29	3.29	3.29	3.29
τ_{00}	0.28	0.29	0.79	0.30	0.83
ICC	0.08	0.08	0.19	0.08	0.20
N	36	36	36	36	36
Observations	524	524	524	524	524
Marginal r^2/conditional r^2	0.000/0.079	0.021/0.102	0.944/0.955	0.023/0.105	0.944/0.955

***p < 0.001, **p < 0.01, *p < 0.05.
Note: odds ratios and random effects are reported for models 1–5. M1: vehicle type, M2: task urgency, M3: social control, M4: vehicle type × task urgency, M5: vehicle type × social control.

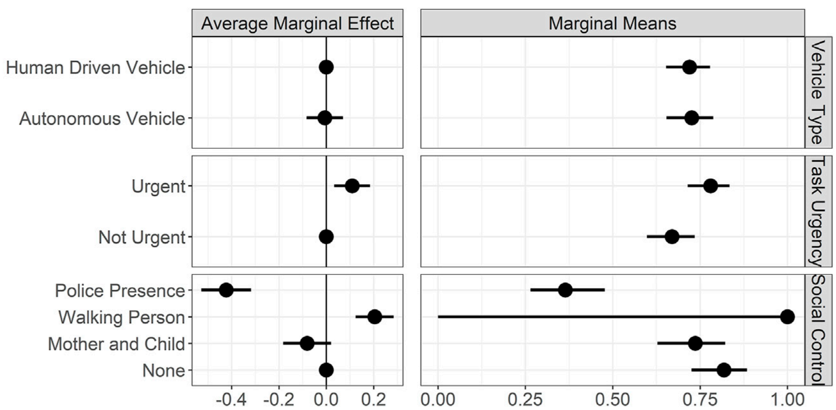

FIGURE 7 | Average marginal effects and marginal means for risk-controlled crossings. Note: left plot shows the average marginal effects (AME) of our three experimental factors in reference to their baseline factor levels. The vertical line represents the effect of the reference level. The right column reports the marginal means (MM) for the different factor levels on crossing probabilities, holding the other factors constant at their proportions. Points indicate AME/MM, horizontal lines the 95% CIs. Effects based on results of GLMM.

on the crossing decision might be caused by their passive programming and autonomous nature. To test whether the decision to cross is influenced by their autonomous nature and whether the effect of social control changes under equal risk distributions between AV and HDV, we conducted a second analysis, excluding those observations where the risk of a crash with an HDV was unknown.

The results of the Generalized Linear Mixed Effects Model to model individuals' risk-controlled crossing decisions are provided in **Table 2**, and the average marginal effects and marginal means for the different treatments are illustrated in **Figure 7**. Similar to **Table 1**, models 1, 2, and 3 show the results for the main effects of vehicle type, task urgency, and social control. Models 4 and 5 indicate the interaction between vehicle type × task urgency and vehicle type × social control.

With all else being equal and holding the effect of other factors constant at their proportions, we see no effect of AV compared to HDV when we controlled for the risk ($\beta = -0.03$, z (524) = -0.15, Pr ($>|z|$) = 0.87) (see **Figure 7**, top left). When the crossing probability in front of AVs was 71%, the crossing probability in front of HDVs was 72% (see **Figure 7**, top right). The effect of urgency remained significant when crossings were controlled for the risk. Compared to non-urgent scenarios, urgent scenarios increased crossing probabilities by 10% ($\beta = 0.55$, z (524) = 2.78, Pr ($>|z|$) < 0.01) (see **Figure 7**, middle left). Their own effect on crossing probabilities was observed as 78% for urgent and 66% for non-urgent scenarios; **Figure 7**; middle right). Compared to

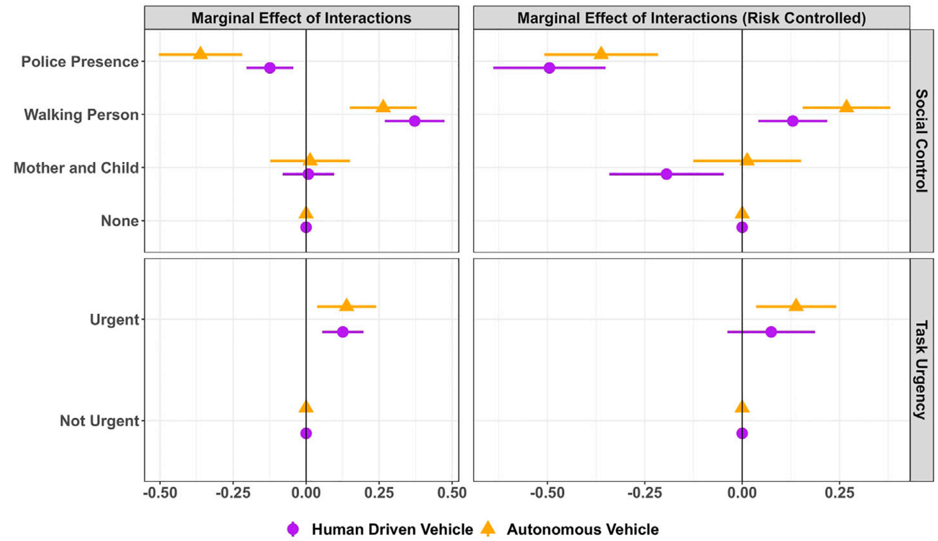

FIGURE 8 | Effect of social control and task urgency conditioned by vehicle type. Note: the figure illustrates the average marginal effects on crossing probabilities of social control and task urgency, conditioned on vehicle type, both for the baseline crossing decision under uncertainty of HDV behavior (left side) and interactions where participants were faced with the equal risk of collision between AV and HDV (right side). Purple points represent HDV, and orange triangles represent AV. Horizontal lines show 95% CIs. Vertical lines represent the average crossing probability of the reference level.

baseline social control condition, as police presence significantly decreased crossing probabilities by 42% ($\beta = -2.05$, z (524) = −6.97, Pr (>|z|) < 0.001), the walking person increased it by 20%, which was not significant ($\beta = 18.18$, z (524) = 0.020, Pr (>|z|) = 0.98). Mother and child lead to a decrease in 8%, which remained insignificant ($\beta = -0.47$, z (524) = −1.56, Pr (>|z|) = 0.11) (see **Figure 7**, bottom left). The effect of social control levels on crossing probability, when kept constant at their proportions, was observed to be 36% for police presence, 100% for the walking person, 73% for mother and child, and, lastly, 81% when participants were alone in the scene (see **Figure 7**, bottom right).

4.3 Exploring Interactions

Given the lack of empirical evidence on a potential interaction effect between social control and vehicle type, that is, whether social control might have a different effect on AV compared to HDV, we further explored potential interactions with GLMM models 4 and 5 for general crossings at **Table 1** and risk-controlled crossing at **Table 2**. The average marginal effects for the interactions, AMEs of Social Control and Task Urgency conditioned on vehicle type, are illustrated in **Figure 8**.

When general crossings are considered, compared to being alone, the presence of police decreased crossing in front of AVs by 36% and HDVs by 12%. This interaction was not significant ($\beta = -0.58$, z (860) = −1.07, Pr (>|z|) = 0.28). Walking person increased crossing probability in front of AVs by 26% and HDVs by 37%. However, this interaction was also insignificant ($\beta = 14.61$, z (860) = 0.03, Pr (>|z|) = 0.97). Mother and child had an effect of increasing crossing probability in front of AVs by 0% and HDVs by 1%, which was an insignificant result ($\beta = 0.02$, z (860) = 0.04, Pr (>|z|) < 0.96) (see **Figure 8**, top left).

When we controlled for the risk and checked the interaction of vehicle type × social control, compared to being alone, police presence decreased the crossing probability in front of AVs by 36% and HDVs by 49%. However, this interaction was not significant ($\beta = 0.94$, z (524) = 1.54, Pr (>|z|) = 0.12). The walking person increased the crossing probability in front of AVs by 26% and HDVs by 12%. The interaction was not significant ($\beta = 0.97$, z (524) = 0.001, Pr (>|z|) = 0.99). The mother and child condition increased crossing probability in front of AVs by 1% and decreased the crossing probability in front of HDVs by 19% and this interaction was significant (β = 1.33, z (524) = 2.09, Pr (>|z|) < 0.05) (see **Figure 8**, top right).

The interaction of vehicle type by task urgency did not yield significant results in both general and risk-controlled results. Considering general crossings and compared to non-urgent situations, in urgent scenarios, participants' crossing probability in front of AVs increased by 12% and in front of HDVs by 13% ($\beta = 0.03$, z (860) = 0.10, Pr (>|z|) = 0.91) (see **Figure 8**, bottom left). When controlled for risk for the same interactions, participants' crossing probability in front of AVs increased by 13% and HDVs by 7% ($\beta = 0.32$, z (524) = 0.79, Pr (>|z|) = 0.42) (see **Figure 8**, bottom right).

5 DISCUSSION AND CONCLUSION

Will individuals bully or abuse AVs for individual gain? We had run a two-step analysis in the results section where we tested crossing decisions when the anticipated risk for AV was low and the anticipated risk for HDV was higher in the first step. This step mimicked the expected future mixed traffic environment with imbalanced costs of exploiting an HDV and an AV. Our results indicated a higher deviant behavior toward AVs when the risk distribution was not balanced. These results support the findings of Moore et al. (2020), in which they observed deviant behavior toward self-driving vehicles in their field observation. Moreover, our results are also corroborated by remarks from our respondents. When we asked whether different vehicle types influenced their crossing behavior, more than half of the answers indicated an existing effect. Participants stated that they crossed the street "without hesitation" in the presence of AVs, relying on the passive stance of AVs, and they were more willing to cross in front of AVs. One respondent explained in AV conditions that he crossed even without waiting for the blue deceleration signal of AVs. These results are in the direction of "Overtrust" toward AVs problem, as Holländer et al. (2019) argued. However, in the second step of the analysis, when we balanced the risk distribution by only including HDV trials where HDVs could yield if participants negotiated with them, our data could tell if there were remaining differences in crossing behavior stemming from the sole effect of automation attributes of vehicles. As we ran the analysis, we observed that the existing difference between crossing predictions among HDVs and AVs simultaneously disappeared when the crash risk of HDVs disappeared. These results emphasize the importance of risk avoidance in participants' crossing decisions more than the automation status of vehicles, which is in line with the remarks of Dommès et al. (2021) that pedestrians rely mainly on vehicle dynamics and locomotion cues before taking a crossing decision. Therefore, we can only confirm H2 that when the collision risk is introduced in HDVs when AVs stay risk-free, deviant behavior toward AVs increases, as Millard-Ball (2018) anticipated with his game theory-derived remarks.

Kalatian and Farooq (2021) observed in their VR study derived models that pedestrians' waiting time before crossing was longer in mixed traffic and only AV scenarios than in only HDV scenarios. Their study did not report trials where vehicles did not stop; hence, the risk distribution among vehicle type levels seemed equal. When we compare their results with our risk-controlled crossings, we fail to observe a similar effect in the crossing behavior of pedestrians in terms of crossing predictions. This could be due to our strategy of priming participants before the experiment by informing them about the different characteristics of AVs and HDVs that AVs would always yield to them to prevent a collision and HDVs may or may not yield to them. We have done this to approximate pedestrian behavior once they are accustomed to conflict-avoidant AVs after long-term exposure in the future. Hence, the difference between our results and those of Kalatian and Farooq (2021) might indicate differences in the novel and primed mental models of pedestrians when they encounter AVs. Furthermore, Kalatian and Farooq (2021) reported that some teenage participants performed deviant behavior against virtual vehicles once they realized that vehicles react according to their crossing behavior. Participants then would play with them by moving back and forth on the street. The authors pointed out future implications of deviant behavior toward AVs in their work, and their statements are in line with our general crossing results and the study of Moore et al. (2020) in this regard.

Moreover, Colley et al. (2022) tested pedestrian behavior in the presence of constant oncoming AVs, which would not yield for participants. Their results showed that after a couple of passing AVs, pedestrians relied on the prior information of an emergency braking system of AVs and preferred crossing for saving time. However, they have only tested this condition for AVs. In our experiment, we utilized always yielding AVs and yielding and non-yielding HDVs. To draw a clearer picture of whether pedestrians treat AVs and HDVs differently, a follow-up study including non-yielding HDVs and non-yielding AVs can support our risk-controlled results from another perspective.

The gamification of our experiment further enabled us to manipulate conditions that directly affect individual gains in the form of earning points and earning extra reimbursement in euros. Task urgency was directly linked to maximizing the incentive participants would gain. Generally, we found urgent scenarios to predict higher chances of crossing instead of waiting, confirming that participants showed more deviant behavior under time pressure, in line with Morrongiello et al. (2015), Schneider et al. (2019), and our theoretical expectations formulated in H1.

Results of our analysis also indicate that different forms of social control, indeed, influence individuals' decisions to jaywalk. We find the mere presence of cues signaling formal norm enforcement (police presence) to deter individuals from crossing, hence confirming H3c. This finding is likewise corroborated by participants' responses: participants state that police played a role in the majority of their decisions. In this condition, our approach and application of formal traffic norm cues differ from the work of Jayaraman et al. (2019) in essence. As Jayaraman et al. utilized signalized and non-signalized pedestrian crossings as a factor for investigating the effect of formal traffic rules on pedestrians' crossing decisions, we have placed the police officer character as a mere cue for the presence of legal authority. Moreover, this character did not have a definite effect on traffic rules as in the case of a traffic light that Jayaraman et al. used. In our experiment, jaywalking was not illegal and police presence did not directly signify a punishment if participants jaywalked. Moreover, 50% of the time, the police were not effective in the trials. Another difference in our approach from Jayaraman et al. is that we tested for deviant behavior of pedestrians in the presence of legal authority, whereas they tested for pedestrian trust in automated vehicles in the presence or absence of a formal traffic sign. Our results are also in line with Camara and Fox (2020). They suggested that rare large penalties could be replaced with milder and more frequent negative utilities, hence preventing pedestrians from acting deviant. In our study, the mere cue of legal norms without certainty of sanctioning seemed to deter our participants from crossing.

Looking at the effect of negative social cues, that is, the effect of cues signaling low levels of social conformity, we see a strong increase in deviant behavior with a crossing probability up to 100%. These results match with the results of Colley et al. (2022) and the reporting of Faria et al. (2010), where they observed an increase in crossing behavior probability when other pedestrians started to cross. As this finding indicates the negative effect of cues signaling low levels of norm compliance on deviant behavior of participants, this strong effect might also result from our experimental design. Compared to a mere cue, our implementation of the negative bystander effect stopped the oncoming traffic, thereby transforming the individual decision to jaywalk into a decision to free-ride. Moreover, Mahadevan et al. (2019) reported an insignificant effect of crossing group behavior on participants' crossing decisions on their pedestrian simulator, which is opposite to our findings. Hence, we cautiously confirm our hypothesis H3b, and overall, negative social cues are worth deeper research.

In our experiment, positive social cues represented the social sanctioning in the forms of a mother and a child character. We did not observe a difference in crossing behavior predictions in this condition when compared to being alone in the scene. As a result, we failed to confirm H3a. However, when we explicitly asked participants how their behavior would differ in real traffic situations, the majority stated that they would generally abide by the rules in the presence of children and police. Overall, this seems indicative that even though participants were in a low-fidelity virtual environment with a delivery task assigned to them, they were affected by the social control of bystanders. However, social sanctioning might play a bigger role in real-life interactions than in the virtual environment.

When we explored the potential interaction effects of vehicle type by task urgency or social control on crossing predictions, we have only found a significant difference between AVs and HDVs in the mother and child condition compared to being alone. This effect existed only in risk-controlled trials, meaning that when the risk of collision is balanced, having the mother and child in the scene decreased the crossing probability in front of HDVs, whereas it did not change the crossing probability in front of AVs. A potential explanation might be that when mother and child existed in the scene, participants were more risk-avoidant and cautious about crossing in front of HDV, whereas they still relied on the defensive nature of AVs, and they did not alter their behavior in the presence of the mother and the child. On the whole, to our knowledge, no study regarding pedestrian–AV interaction considered the effect of social norms by focusing on the effect of bystanders as we utilized.

In conclusion, it seems that AVs of the future will be the inferior counterpart of interaction with humans if they remain risk aversive and if there is an imbalanced distribution of crash risk among human-driven and automated vehicles. When the costs of deviant behavior are balanced while crossing in front of these vehicles, the sole effect of automation attributes does not influence the crossing behavior, which supports the idea that, in essence, people would treat the AVs the same as HDVs if they behave similarly. As the defensive nature of AVs is essential for the safety of future mixed traffic and for the acceptance of AVs, this might incentivize individuals to exploit them in the long term. Lastly, our exploration of social norm dynamics reveals that social control, especially legal cues, carries the potential of being the regulator of humans' deviant behavior.

5.1 Limitations and Future Directions

We used the gamification approach to eliminate task fatigue in the experiment and make the participants more involved with the task. Most participants seemed to enjoy the idea of earning points. Furthermore, the point system helped us establish costs and benefits in a more realistic way than leaving these concepts to participants' imaginations in our VR study. We have observed that gamification fitted well with repetitive tasks because it had placed these tasks conceptually in a meaningful context. However, because we used gamification, we took the liberty of keeping the environment in low fidelity. The effect of this decision was reflected in the experienced realism ratings of participants in IPQ results. Benefiting from a more realistic environment in the next iteration can improve experienced realism, hence an overall more immersive experience, which might provide for more fine-grained results.

Because we primed our participants that AVs would always be conflict-avoidant and yield to them, we did not include non-yielding AVs in our design. A future study where we introduce non-yielding AVs can help us to position our current results regarding risk control in a more validated place.

We had a rather young sample with individuals from similar educational backgrounds. Deb et al. (2017b) reported, in their PRQF scale validation study, that younger people were more receptive toward AVs. We could confirm this finding with our young sample. However, a more diversified sample could draw a more realistic picture of the existing traffic dynamics. Moreover, we arranged the traffic flow unidirectional in our experiment to keep the task less complicated and make sure that participants would not miss the target vehicle. However, this can be enhanced with some alterations in the study design. Furthermore, we have given participants the repetitive task of crossing the same street. Even though we have emphasized the pizza delivery task in our instructions, and on our game concept, benefiting from different virtual streets could have blinded our manipulations even better.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**. Further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the Research Ethics Committee of the University of Oldenburg. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

HŞ planned the research design, developed the VR experiment, conducted data collection and analysis, and contributed to writing. SH planned the research design, conducted data analysis, and contributed to the writing. SB supervised the process and contributed to the writing.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frobt.2022.885319/full#supplementary-material

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APPENDIX A LIST OF OPEN QUESTIONS.

- What have you paid attention to when you were playing the game?
- Did police or other pedestrians affect your crossing decisions? How?
- Did timers or urgency symbols affect your crossing decisions?
- Did vehicle types influence your crossing decisions?
- How would your street-crossing behavior differ in real-life situations?

  -When you see people who wait for the cars to go first.

  -When you see people who do not wait for the cars to go first.

  -When you see children around.

  -When you see police around.

  -When you are in a hurry.

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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

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Future automated vehicles (AVs) of different sizes will share the same space with other road users, e. g., pedestrians. For a safe interaction, successful communication needs to be ensured, in particular, with vulnerable road users, such as pedestrians. Two possible communication means exist for AVs: vehicle kinematics for implicit communication and external human-machine interfaces (eHMIs) for explicit communication. However, the exact interplay is not sufficiently studied yet for pedestrians' interactions with AVs. Additionally, very few other studies focused on the interplay of vehicle kinematics and eHMI for pedestrians' interaction with differently sized AVs, although the precise coordination is decisive to support the communication with pedestrians. Therefore, this study focused on how the interplay of vehicle kinematics and eHMI affects pedestrians' willingness to cross, trust and perceived safety for the interaction with two differently sized AVs (smaller AV vs. larger AV). In this experimental online study ($N = 149$), the participants interacted with the AVs in a shared space. Both AVs were equipped with a 360° LED light-band eHMI attached to the outer vehicle body. Three eHMI statuses (no eHMI, static eHMI, and dynamic eHMI) were displayed. The vehicle kinematics were varied at two levels (non-yielding vs. yielding). Moreover, "non-matching" conditions were included for both AVs in which the dynamic eHMI falsely communicated a yielding intent although the vehicle did not yield. Overall, results showed that pedestrians' willingness to cross was significantly higher for the smaller AV compared to the larger AV. Regarding the interplay of vehicle kinematics and eHMI, results indicated that a dynamic eHMI increased pedestrians' perceived safety when the vehicle yielded. When the vehicle did not yield, pedestrians' perceived safety still increased for the dynamic eHMI compared to the static eHMI and no eHMI. The findings of this study demonstrated possible negative effects of eHMIs when they did not match the vehicle kinematics. Further implications for a holistic communication strategy for differently sized AVs will be discussed.

Keywords: automated vehicles, vehicle size, pedestrians, external human-machine interface (eHMI), vehicle kinematics

INTRODUCTION

Participation in today's road traffic requires mutual consideration among all traffic participants (TPs) (German Road Traffic Regulations StVO, 2013; Färber, 2016). In particular, pedestrians are highly dependent on mutual consideration and communication with other TPs as traffic accidents with pedestrians have the highest risk of causing serious injury of any type of road accident (World Health Organisation, 2013). This risk is even higher for pedestrians when they interact with larger vehicles (Tyndall, 2021). Therefore, communication is overall highly relevant to clarifying misunderstandings which can have fatal consequences (Färber, 2016; Rasouli et al., 2017).

In today's traffic, pedestrians communicate implicitly and explicitly with other TPs (Rasouli et al., 2017). Pedestrians typically use implicit communication signals, i.e., driving behavior, to anticipate the vehicle's actions and to plan their behavior accordingly (Dey and Terken, 2017; Ezzati Amini et al., 2019; Lee et al., 2020). However, informal explicit communication signals between vehicles and pedestrians become highly relevant in short distances and in low-speed scenarios, e.g., via eye contact (Färber, 2016; Dey and Terken, 2017; Lee et al., 2020). Explicit communication signals are perceived as supportive to clarify misunderstandings before they can cause accidents (Merat et al., 2018; Stanciu et al., 2018; Schieben et al., 2019a). Overall, both, implicit and explicit, communication signals make it possible to communicate in today's traffic. Nonetheless, the question arises to what extent the interplay of implicit and explicit communication will influence pedestrians' interaction with AVs.

A change toward a mixed traffic environment, including AVs, manually-driven vehicles, and other traffic participants (TPs), is going to happen in the foreseeable future. This mixed traffic will require adequate communication between all TPs to ensure safety, efficiency, and acceptance (Habibovic et al., 2018; Schieben et al., 2019a; Dey et al., 2020b). Implicit and explicit communication means for AVs have been under investigation and results showed that both communication means have the potential to enhance pedestrians' communication with AVs in future mixed traffic (Lee et al., 2019; Bengler et al., 2020; Dey et al., 2020a; Rettenmaier et al., 2020; Schieben et al., 2020; Rettenmaier and Bengler, 2021). However, in most studies either the implicit communication or the explicit communication was varied and the interplay of both was not considered sufficiently yet, in particular, for differently sized AVs. Therefore, this study aims to investigate the interplay of both communication means for pedestrians' interaction with two differently sized AVs in a shared space as an example of a low-speed and low-distance traffic scenario.

Role of Implicit Communication

Implicit communication signals are sent directly to the traffic environments, however, the perception and further interpretation within the relevant context are needed to understand the signals' message (Färber, 2016; Risto et al., 2017; Bengler et al., 2020; Markkula et al., 2020; Schieben et al., 2020). Current studies indicate that pedestrians primarily use implicit communication to cooperate with other TPs (Risto et al., 2017; Bengler et al., 2020) and base their crossing decision mostly on implicit signals (Beggiato et al., 2017; Dey and Terken, 2017; Lee et al., 2020).

Focusing on future urban traffic, implicit communication remains a highly relevant indicator for pedestrians' crossing decisions, e.g., the vehicle kinematics (Rasouli et al., 2017; Ackermann et al., 2019a,b; Dietrich et al., 2020). The vehicle kinematics can serve as a communication mean for AVs to transmit implicit information, including lateral or longitudinal motions, to the surrounding traffic environment (Risto et al., 2017; Ackermann et al., 2019b; Bengler et al., 2020; Rettenmaier and Bengler, 2021). For example, the initiated vehicle's deceleration at a crossing could be interpreted by pedestrians as a sign that the vehicle gives way (Bengler et al., 2020). Dietrich et al. (2020) investigated the effect of different deceleration rates and pitch angles on pedestrians' interaction with AVs. The results showed that pedestrians initiated their crossing significantly earlier when the AV showed a defensive deceleration. The relevance of the deceleration for the interaction with pedestrians was also demonstrated by Ackermann et al. (2019b), i.e., shorter reaction times by pedestrians to indicate the vehicle's deceleration with higher deceleration rates. Overall, implicit communication, i.e., vehicle kinematics, is a highly relevant indicator of pedestrians' crossing behavior (Ackermann et al., 2019b; Dey et al., 2020a).

Role of Explicit Communication

Explicit communication signals transmit direct information to the surrounding traffic environment, e.g., via eye contact or hand gesture (Färber, 2016; Markkula et al., 2020; Schieben et al., 2020). Recent studies showed that explicit communication signals could serve as an additional safety check-in low-speed and low-distance traffic situations to clarify misunderstandings in uncertain and ambiguous traffic situations (Dey and Terken, 2017; Sucha et al., 2017; Kitazaki and Daimon, 2018; Lee et al., 2020). In future mixed traffic, pedestrians will no longer be able to communicate explicitly with AVs as they are used to due to the absence of a human driver (Merat et al., 2018; Faas et al., 2020; Schieben et al., 2020; Li et al., 2021).

To enable the explicit communication with AVs, an external human-machine interface (eHMI) positioned on the outside of the vehicle transmits explicit communication signals to the surrounding traffic environment, e.g., about the vehicle's automation status (VAS) or the vehicle's intention (Schieben et al., 2019a; Bengler et al., 2020; Dey et al., 2020b). External HMIs are beneficial to solve ambiguities and clarify misunderstandings in low-speed and low-distance, e.g., in unsignalized and signalized traffic situations (World Health Organisation, 2013; Merat et al., 2018; Schieben et al., 2019b; Faas et al., 2020, 2021; Kaleefathullah et al., 2020; Lee et al., 2021; Wilbrink et al., 2021). Light-based eHMIs present a promising solution to transmit explicit information (Mahadevan et al., 2018; Schieben et al., 2019a; Dey et al., 2020a; Faas et al., 2020). Moreover, light-based eHMIs could present different levels of information richness, e.g., the VAS, the vehicle's intention, or the vehicle's perception (Schieben et al., 2019a; Faas et al., 2020; Lau et al., 2021a; Wilbrink et al., 2021). Previous research showed that pedestrians preferred a dynamic eHMI that presented explicit information about the vehicle's intention plus the VAS and were not satisfied with the mere static presentation of the automation status (VAS) (Faas et al., 2020; Lau et al., 2021a; Wilbrink et al., 2021).

Regarding the effects of eHMIs, pedestrians perceived an AV with eHMI as generally more trust-worthy (Kaleefathullah et al., 2020) and felt safer in interactions with eHMI compared to no eHMI (Kettwich et al., 2019; Schieben et al., 2019a,b). Focusing on pedestrians' willingness to cross, contrasting results exist for pedestrians' interaction with AVs. On the one hand, studies clearly showed that pedestrians were more willing to cross when the interacting AV communicated via eHMI compared to no eHMI (Böckle et al., 2017; Lundgren et al., 2017; Deb et al., 2018; Habibovic et al., 2018; Clercq et al., 2019; Dey et al., 2019, 2022; Ackermans et al., 2020). On the other hand, Clamann et al. (2017) conducted a field study and did not find any effect of an eHMI on pedestrians' willingness to cross compared to no eHMI. However, the participants in this study stated that an eHMI is beneficial for their interaction with an AV (Clamann et al., 2017).

Joint Role of Implicit and Explicit Communication

The combination of both communication means could support the future interaction with AVs toward a holistic communication approach when both means are well-coordinated (Dey et al., 2020a,b; Dietrich et al., 2020). In a realistic vehicle study by Dey et al. (2020a), pedestrians interacted with an automated car that showed different motion patterns regarding the vehicle kinematics in combination with a light-based eHMI on an unsignalized crossing. Results indicated that gentle braking with a deceleration rate of 2.4 m/s^2 which started at a distance of 45 m away from the pedestrian and stopped at a 5-m distance could contribute to the overall traffic safety in combination with an eHMI showing the vehicle's intention (Dey et al., 2020a). If the vehicle kinematics contradicted the message of the eHMI, pedestrians primarily based their willingness to cross on the vehicle kinematics rather than the eHMI communication (Dey et al., 2020a). In contrast, a study by Kaleefathullah et al. (2020) revealed that when the eHMI was on, but the AV did not indicate a braking process, pedestrians still crossed the street. This result demonstrated possible negative effects, i.e., over-trust, which have been also found by other studies (Kitazaki and Daimon, 2018; Holländer et al., 2019; Lee et al., 2021). Lee et al. (2021) investigated the effect of text-based eHMIs and showed that the participants behaved less carefully when interacting with an AV equipped with eHMI. As an explanation, the authors described an over-trust in the communication abilities of the AV (Lee et al., 2021). Overall, such negative effects would come at high risk for pedestrians due to their vulnerability and, thus, need further investigation (Färber, 2016; Rasouli et al., 2017).

A possible explanation for the occurrence of negative effects of eHMI could be that humans do not always interpret the communication signals correctly (Smeets et al., 1996; DeLucia, 2008; Ackermann et al., 2019b; Lee et al., 2022). According to the Elaboration Likelihood Model (Petty and Cacioppo, 1986), humans can elaborate communication signals by two routes: the central and the peripheral route. The central route describes the careful consideration of all the presented information. The peripheral route describes the consideration of simple salient cues which are signals that attract human perception and direct human attention, e.g., light or acoustic signals (Petty and Cacioppo, 1986; Wickens, 2021). Regarding pedestrians' interaction with AVs, one would assume that pedestrians carefully consider what AVs communicate implicitly and explicitly (central route), in particular, as miscommunication comes with a high risk to get injured (Ackermann et al., 2019a). However, studies that demonstrated the negative effects of eHMIs manifested that humans do not always focus on the correct information but rather direct their attention to the explicit signals that the eHMI presented (peripheral route). This might be due to the fact that urban traffic presents a complex environment in which pedestrians need to make fast decisions under the influence of various factors, e.g., the interaction with other TPs. This in turn could lead to mistakes (Rasouli and Tsotsos, 2020; Wickens, 2021). Therefore, it becomes highly relevant to investigate how pedestrians elaborate the presented implicit and explicit communication signals, i.e., vehicle kinematics and eHMIs, to define an AV's holistic communication strategy that does not endanger pedestrians in future urban traffic.

All in all, both means of communication, i.e., vehicle kinematics and eHMI, have the potential to support pedestrians' interaction with AVs in future urban traffic. However, the combination of both means and their precise coordination needs further clarification for AVs' communication with pedestrians toward a holistic communication strategy. Additionally, it needs to be addressed to what extent the vehicle size will affect pedestrians subjectively, i.e., pedestrians' willingness to cross, trust, and perceived safety as current research on the interplay of vehicle kinematics and eHMI does not address the effect of vehicle size for the interaction with pedestrians (Dey et al., 2020b).

Role of Vehicle Size

The vehicle size can influence pedestrians' interaction with differently sized vehicles in urban traffic (Caird and Hancock, 1994; DeLucia, 2008, 2013; Petzoldt, 2016). This has been investigated by focusing on objective and subjective measurements (Horswill et al., 2005; DeLucia, 2013; Petzoldt, 2016; Beggiato et al., 2017; Levulis et al., 2018). Regarding objective measurements, results showed that humans perceived larger vehicles to arrive earlier compared to smaller vehicles (Petzoldt, 2016; Beggiato et al., 2017; Petzoldt et al., 2017). These findings stood in line with the size-arrival effect which describes that large objects are perceived to arrive earlier than small objects although they had the same arrival time (DeLucia, 2008, 2013). Moreover, pedestrians selected larger time gaps for a larger vehicle compared to smaller vehicles, i.e., showed a more conservative crossing behavior (Petzoldt et al., 2017; Hensch et al., 2021). As a possible explanation, Petzoldt et al. (2017) pointed out that the perceived risk of an accident and pedestrians' individual state or traits could influence the expected time-of-arrival (TTA) and their gap acceptance. Regarding subjective measurements, pedestrians also evaluated larger vehicles as more threatening and stronger compared to smaller ones (Petzoldt, 2016; Dey et al., 2017). Overall, previous research manifested an effect of vehicle size on pedestrians' subjective evaluation and their actual crossing behavior. There is a clear connection between pedestrians' subjective evaluation and their actual decision to cross the street (Ezzati Amini et al., 2019). Therefore, it is highly relevant to address the question if differently sized AVs could also affect pedestrians' willingness to cross, trust, or perceived safety.

Research Aim and Hypotheses

This study aims to investigate pedestrians' interaction with two differently sized AVs (smaller AV vs. larger AV) focusing on the interplay of eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI) and vehicle kinematics (yielding vs. non-yielding) on a shared space. Very preliminary results of this study have been already published (Lau et al., 2021b).

Overall, this study investigated the effects of vehicle size, vehicle kinematics, and eHMI status individually as well as the interplay of vehicle kinematics and eHMI status on pedestrians' willingness to cross, trust and perceived safety. Based on the previously given theoretical background, the following is hypothesized:

Hypothesis 1 (H1): *Pedestrians' willingness to cross, trust and perceived safety* is higher for a smaller AV compared to a larger AV.

Hypothesis 2 (H2): *Pedestrians' willingness to cross, trust and perceived safety* is higher for both vehicle sizes when the AV yields compared to when it does not yield.

Hypothesis 3 (H3): *Pedestrians' willingness to cross, trust and perceived safety* is higher for both vehicle sizes when the AV is equipped with a dynamic eHMI compared to a static eHMI or no eHMI at all.

Hypothesis 4 (H4): The effect of vehicle kinematics on *pedestrians' willingness to cross, trust and perceived safety* differs depending on the eHMI status for the interaction with both vehicle sizes.

Hypothesis 5 (H5): When the AV does not yield, *pedestrians' willingness to cross, trust and perceived safety* will be based on the vehicle kinematics and not the eHMI communication for both vehicle sizes.

METHODS

This experimental study used an online-based methodological approach to investigate pedestrians' interaction with two differently sized AVs (smaller vs. larger AV) in an urban environment. Both AVs were equipped with an LED light-band eHMI and displayed different eHMI statuses (no eHMI vs. static eHMI vs. dynamic eHMI). Moreover, the vehicle kinematics were varied for both AVs (yielding vs. non-yielding).

Participants

This study was conducted with 149 participants (48 women) aged between 19 and 71 years ($M = 35.41$; $SD = 12.68$). To evaluate the extent to which the participants use technology, the participants completed the affinity for technology interaction (ATI) questionnaire which consists of nine items (Franke et al., 2018). The participants indicated a mid-ranged ATI with $M = 4.38$ ($SD = 0.90$) on a 6-point scale (from 1 = "completely disagree" to 6 = "completely agree") (Franke et al., 2018). To assess the participants' familiarity with the experimental setting, it was questioned how and where they carry their errands on a regular basis. Of all participants, 92 participants stated that they frequently run errands on foot. Moreover, 123 participants reported that they move primarily in urban areas and only 26 participants stated that they move primarily in rural areas. All participants have heard of AVs ($N = 149$) and were interested in AVs ($M = 3.93$, $SD = 1.08$; from 1 = "completely disagree" to 5 = "completely agree"). In accordance with the Declaration of Helsinki, informed consent was obtained from all participants before the experiment. The participants were recruited from social networks and from an internal database. During the experiment, the participants were allowed to stop the study at any point without justification or consequence. As an expense, the participants could participate in a raffle of four online vouchers in the amount of 25 euros on a voluntary basis. For their participation in the raffle, they could enter their email address which was saved separately from the experimental data to ensure anonymity.

As this study was conducted online, a great emphasis was placed on the video functionality, validity, and diligence of the participants' ratings. Before the experimental phase, the video functionality was tested with a test video. All participants ($N = 149$) indicated that they were able to play the test video properly. After the experimental phase, further questions on participants' perception of the light-band and the vehicle kinematics for both vehicles separately were asked. Overall, 29 participants answered that they were unsure or did not perceive changes in the vehicle kinematics and, therefore, were excluded from further analysis. Moreover, 4 participants denied that they could see the light-band well and were also excluded. Additionally, it was asked how carefully they conducted the questionnaire on a 5-point Likert scale (from 1 = "very careless" to 5 = "very careful"). All participants answered with rather careful ($N = 26$), careful ($N = 83$) and very careful ($N = 40$).

Study Design

This study was conducted as a $2 \times 2 \times 3$ research design with vehicle size (smaller AV, larger AV), vehicle kinematics (yielding, non-yielding), and eHMI status (no eHMI, static eHMI, and dynamic eHMI) manipulated within the participants. This research design consisted of a non-matching condition for each vehicle size in which the dynamic eHMI falsely indicated that the vehicle yields, although no yielding behavior was shown by the vehicle kinematics.

Independent Variables

Vehicle Size

The videos showed two differently sized vehicles. Based on Schieben (2020), the smaller AV was related to a BMW model i3 which was also investigated in other studies (e.g., Weber et al., 2019; Wilbrink et al., 2021). The larger AV was related to a Mercedes Benz future public bus. Both vehicles presented the same eHMI communication strategies (**Figure 1**).

Vehicle Kinematics

The vehicle kinematics were varied at two levels, yielding and non-yielding. For the yielding conditions, the overall procedure consisted of four steps (**Figure 2**). The video started when the AV was at a distance of 32.5 m from the pedestrian (Step 1). After this, the AV performed a two-step deceleration. The first deceleration (30–20 km/h) started at a 25 m distance to the pedestrian and was performed with an average deceleration rate of -1.92 m/s^2 over 10 m (Step 2). The second deceleration (20 to 2 km/h) started at a 15 m distance to the pedestrian and was performed with an average deceleration of -3.83 m/s^2 within 4 m (Step 3). The video stopped at a predefined distance of 11 m (Step 4). At this point, the vehicle still had a speed of 2 km/h. Overall, the deceleration of the AVs was set with the goal to create a traffic situation with high uncertainty without provoking a conflict. For the non-yielding conditions, the video also started at a distance of 32.5 m to the pedestrian. After this, the vehicle drove at a constant speed of 30 km/h toward the pedestrian. The video stopped at the predefined distance of 11 m. Distances were measured from the vehicle's bumper to the pedestrians' position.

eHMI Status

Both vehicle sizes (smaller AV and larger AV) were equipped with a LED light-band eHMI positioned under the vehicle's windshield that presented different eHMI communication strategies. The static eHMI showed a continuously enlightened LED light-band eHMI from the beginning of the video. This indicated the vehicle's automation status (VAS). The dynamic eHMI showed the vehicle's yielding intention on top of the VAS. In conditions with dynamic eHMI, the LED light-band eHMI was continuously enlightened from the start of the video and started to pulsate at 25 m (distance measured from the vehicle's bumper to the pedestrians' position) at a frequency rate of 0.66 Hz. The distance of 25 m was chosen to ensure no advantage of the communication via eHMI over the vehicle kinematics or the other way around. The experimental condition "no eHMI" was without LED light-band eHMI and served as a baseline.

FIGURE 1 | Experimental setting of this study: The smaller AV (left) with static eHMI and the larger AV (right) with pulsating dynamic eHMI approached the pedestrian from the left-hand side on the shared space.

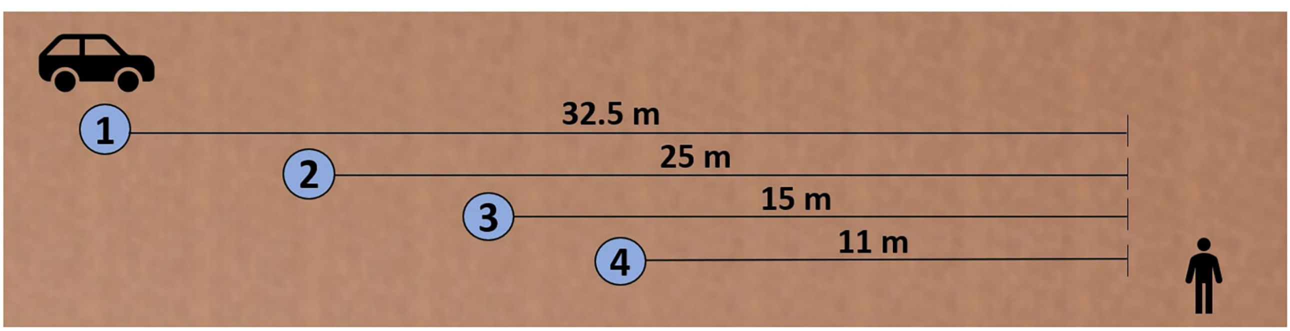

FIGURE 2 | Procedure for the yielding conditions in this study: 1. Video starts in 32.5 m, 2. First deceleration from 30 to 20 km/h starting in 25 m, 3. Second deceleration from 20 km/h to 2 km/h starting in 15 m, 4. Video stop in 11 m (distances measured from the vehicle's bumper to the pedestrians' position; m = meter).

Dependent Variables

After each video presentation, the participants evaluated their willingness to cross, trust, and perceived safety. Pedestrians' willingness to cross was measured with the question "What is your willingness to cross in front of the vehicle at the end of the video?" on a 7-point Likert scale (from 1 = "very low" to 7 = "very high"). Participants' trust ("How much would you trust the vehicle to stop for you?") and perceived safety ("For my personal safety, I found the behavior of the vehicle to be safety-enhancing.") was assessed on a 7-point Likert scale from 1 = "disagree" to 7 = "agree." To get a deeper insight into the effects of vehicle kinematics and eHMI on pedestrians' willingness to cross, two additional subjective measurements were included, i.e., the perceived support of the vehicle kinematics ("The vehicle behavior has helped me to assess my willingness to cross in front of the vehicle.") and the perceived support of the eHMI ("The light band has helped me to assess my willingness to cross in front of the vehicle."). Both items were evaluated on a 7-point Likert scale (from 1 = "disagree" to 7 = "agree"). The perceived support of the vehicle kinematics was evaluated after each video presentation and the perceived support of the eHMI was only evaluated for conditions in which the eHMI presented information (static eHMI, dynamic eHMI).

Procedure

The online experiment started when the participants clicked on the website link. The conduction and data recording took place with the SoSci questionnaire software (Leiner, 2019). In the beginning, the participants were informed about the conditions of participation, and they gave their consent to participate. Moreover, they were instructed the following: Firstly, to conduct the questionnaire on a computer and not a tablet or smartphone, secondly, to dim light sources in their environment, and, thirdly, to play the following videos in full-screen mode. On the first page of the questionnaire, the participants were asked to fill out the demographic questionnaire and ATI questionnaire (see Section Participants). Before the experimental phase started, the participants were informed step-by-step about the experimental setting, the two AVs, and the eHMI communication strategies with short tutorial videos and additional written instructions. This step was done to give the participants detailed information about the experiment and to let them familiarize themselves with the online environment.

In the experimental phase, each of the participants saw twelve video sequences which were shown from an egocentric perspective (**Table 1**). The video length for the yielding conditions was 9 s and for the non-yielding conditions 7 s. The traffic environment was designed using the software Unreal Engine (Version 4.24.2.). The traffic scenario was a shared space and the same for all conditions (**Figure 1**). Shared space was chosen for investigation as in this low-speed and low-distance scenario the right of way is not clarified yet and not explicitly defined by the traffic signs in this case and, thus, misunderstandings could occur. Previous research has shown that explicit communication is highly relevant when misunderstandings occur (Dey et al., 2017; Lee et al., 2019). All twelve experimental conditions were presented in randomized order to prevent any learning effects (**Table 1**). At the beginning of each video, the participants stood in the same position and looked to the left from where the smaller and larger AV drove toward them. All videos stopped at a predefined distance of 11 m. The stopping point should represent the point of high uncertainty without frightening the participants and was set based on previous internal evaluations. At the end of the experiment, the participants were asked to rate their interaction with both AVs separately (smaller AV vs. larger AV) regarding a set of eight adjectives (threatening, large, pleasant, dangerous, strong, familiar, safe, close) on a 7-Likert scale (from 1 = "disagree" to 7 = "agree") which was based on by Petzoldt (2016). The whole online experiment took ∼25 min.

TABLE 1 | Overview of this study's experimental conditions presented in the short video sequences (presented in randomized order).

Experimental conditions	Vehicle size	Vehicle kinematics	eHMI status
1	Smaller AV	Yielding	No eHMI
2			Static eHMI
3			Dynamic eHMI
4	Smaller AV	Non-yielding	No eHMI
5			Static eHMI
6			Dynamic eHMI
7	Larger AV	Yielding	No eHMI
8			Static eHMI
9			Dynamic eHMI
10	Larger AV	Non-yielding	No eHMI
11			Static eHMI
12			Dynamic eHMI

RESULTS

Statistical Approach

The data analysis started with a data validation check to evaluate the participants' assessment of the vehicle's characteristics with both AVs (smaller AV vs. larger AV) in the videos. For the t-tests, Cohen's d_z was used and interpreted as effect size [d_z = 0.2 (small effect), d_z = 0.5 (medium effect) and d_z = 0.8 (large effect)] (Cohen, 1988). Furthermore, we used a 2 × 2 × 3 repeated-measures ANOVA to investigate the effect of vehicle size, vehicle kinematics, and eHMI status (all within-participants) on pedestrians' willingness to cross, trust, and perceived safety. The assumption of normally distributed data was given due to the sample size (Field, 2009). Sphericity was calculated with Mauchly's W test and Huynh-Feldt corrections were applied when the assumption of sphericity was violated (Field, 2009). Partial eta-squared (η_p^2) was used as effect size and for interpretation: $\eta_p^2 \leq 0.01$ (small effect), $\eta_p^2 \leq 0.06$ (medium effect) and $\eta_p^2 < 0.14$ (large effect) (Cohen, 1988). For post-hoc tests, all additional t-tests were conducted with a Bonferroni-corrected p-value ($p < 0.003$). In additional comparisons, the effect of eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI) was compared for each AV (smaller and larger AV) for the non-yielding conditions. This was done to investigate the conditions in which the displayed eHMI information was consistent with the vehicle kinematics (no eHMI, static eHMI) or inconsistent (dynamic eHMI) for both differently sized AVs individually. To get a deeper insight into the effects of vehicle kinematics and eHMI on pedestrians' willingness to cross, the relationship between pedestrians' willingness to cross, the perceived support of the vehicle kinematics, and the perceived support of the eHMI was investigated for both AVs with Pearson's r ($N = 149$). According to Cohen (1988), Pearson's r correlations were interpreted as followed: $r < 0.3$ (small effect), $r = 0.3$–0.5 (medium effect) and $r > 0.5$ (large effect).

Data Validation Check

As this experimental study was conducted online, we wanted to check to what extent the demonstrated AVs in the videos led to a similar subjective assessment on the vehicle's characteristics as described in previous studies (Petzoldt, 2016; Dey et al., 2017). The statistical results are displayed in **Table 2** and boxplots in **Figure 3**.

The results showed that a larger AV was perceived as significantly more threatening, larger, less pleasant, more dangerous, stronger, and closer compared to the smaller AV in this study (**Figure 3**). Thus, it can be assumed that the vehicles presented in the videos were evaluated differently which stands in line with previous studies (Petzoldt, 2016; Dey et al., 2017).

Willingness to Cross

The inferential statistical analysis showed a significant main effect for vehicle size [$F_{(1,148)} = 6.69$, $p = 0.006$, $\eta_p^2 = 0.043$], however, with a rather small effect size (**Figure 4**). The willingness to cross was higher for the smaller AV ($M = 3.59$, $SD = 1.07$) compared to the larger AV ($M = 3.45$, $SD = 1.07$; $p < 0.01$) (**Figure 4**). Additionally, a significant main effect was found for vehicle kinematics [$F_{(1,148)} = 255.67$, $p < 0.001$, $\eta_p^2 = 0.633$] indicating that the yielding vehicle led to a higher willingness to cross ($M = 4.59$, $SD = 1.41$) compared to the non-yielding vehicle ($M = 2.46$, $SD = 1.17$; $p < 0.001$) (**Figure 4**). Furthermore, the results showed a significant main effect for eHMI status [$F_{(1.48,216.49)} = 136.09$, $p < 0.001$, $\eta_p^2 = 0.479$] (**Figure 4**). Pairwise comparisons with Bonferroni correction revealed that the willingness to cross was higher for the dynamic eHMI ($M = 4.63$, $SD = 1.42$) compared to the static eHMI ($M = 3.12$, $SD = 1.28$; $p < 0.001$) and no eHMI ($M = 2.82$, $SD = 1.22$; $p < 0.001$).

There were no significant interactions for vehicle size*vehicle kinematics [$F_{(1,148)} = 1.29$, $p = 0.26$, $\eta_p^2 = 0.009$], vehicle size*eHMI status [$F_{(1.96,290.13)} = 1.17$, $p = 0.31$, $\eta_p^2 = 0.008$], vehicle kinematics*eHMI status [$F_{(1.88,278.84)} = 0.17$, $p = 0.84$, $\eta_p^2 = 0.001$] and vehicle size*vehicle kinematics*eHMI status [$F_{(1.99,295.79)} = 1.82$, $p = 0.16$, $\eta_p^2 = 0.012$].

Pedestrians' Willingness in Relation to Vehicle Kinematics and eHMI

The relationship between pedestrians' willingness to cross (**Table 3**) and, firstly, pedestrians' perceived support of the vehicle kinematics (**Table 4**) and, secondly, pedestrians' perceived support of the light-band for their crossing decision (**Table 5**) was investigated for each experimental condition. This was done to further focus on pedestrians' perceived support of the vehicle kinematics and the eHMI to indicate their willingness to cross.

Firstly, there were high correlations between pedestrians' willingness to cross and the perceived support of the vehicle kinematics for both AVs when the vehicle yielded in combination with no eHMI (smaller AV: $r = 0.69$, $p < 0.001$; larger AV: $r = 0.68$, $p < 0.001$), the static eHMI (smaller AV: $r = 0.65$, $p < 0.001$; larger AV: $r = 0.7$, $p < 0.001$), or the dynamic eHMI (smaller AV: $r = 0.6$, $p < 0.001$; larger AV: $r = 0.58$, $p < 0.001$) with large effect sizes. When the vehicle did not yield, but the dynamic eHMI indicated so, there were significant correlations for both AVs (smaller AV: $r = 0.24$, $p < 0.001$; larger AV: $r = 0.3$, $p < 0.001$) with small and medium effect sizes. No significant correlations were found when the vehicle did not yield in combination with no eHMI or a static eHMI for both AVs ($p > 0.05$).

TABLE 2 | *T*-test results comparing participants' assessment of vehicles' characteristics (smaller vs. larger vehicle).

	Smaller AV		Larger AV					
	M	*SD*	*M*	*SD*	*df*	*t*	*p*	d_z
Threatening	2.77	1.77	3.99	1.85	148	−7.29	0.001**	0.59
Large	1.93	1.10	5.81	1.24	148	−29.03	0.001**	1.00
Pleasant	4.34	1.51	3.72	1.31	148	4.42	0.001**	0.36
Dangerous	2.79	1.51	3.81	1.64	148	−7.33	0.001**	0.59
Strong	2.88	1.35	5.03	1.49	148	−14.99	0.001**	1.23
Familiar	4.18	1.59	4.13	1.55	148	0.43	0.67	0.03
Safe	4.30	1.45	4.28	1.40	148	0.18	0.86	0.02
Close	4.05	1.49	4.86	1.25	148	−6.42	0.001**	0.53

**$p < 0.001$.

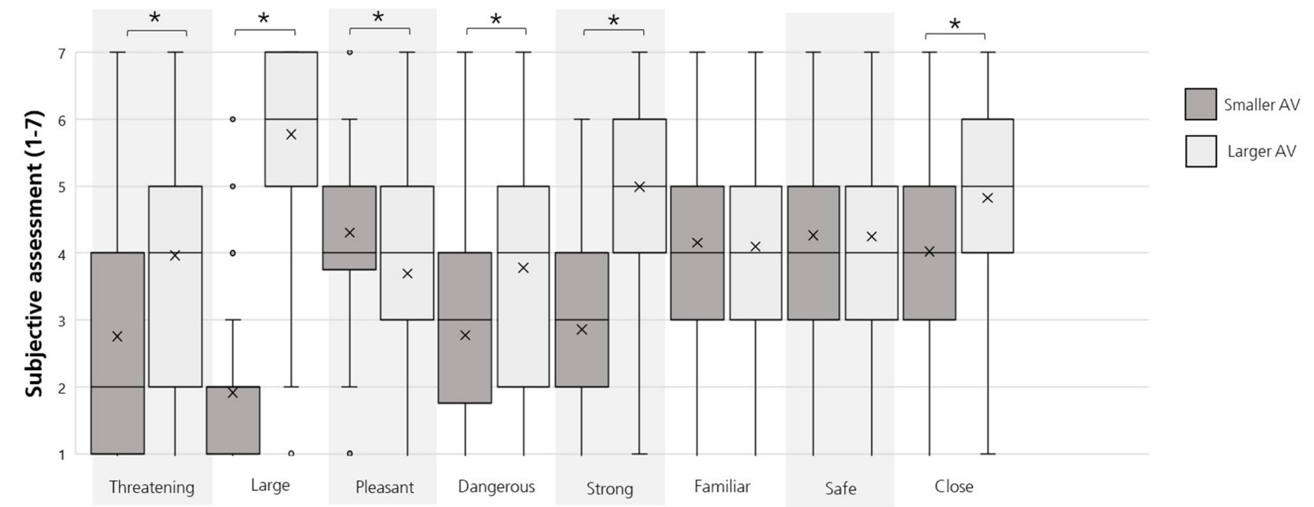

FIGURE 3 | Boxplots for participants' subjective assessments on each vehicle's (smaller AV vs. larger AV) characteristics for their interactions in the videos. *Note*. Crosses = means; lines = medians. Bonferroni-corrected *p*-value * < 0.003.

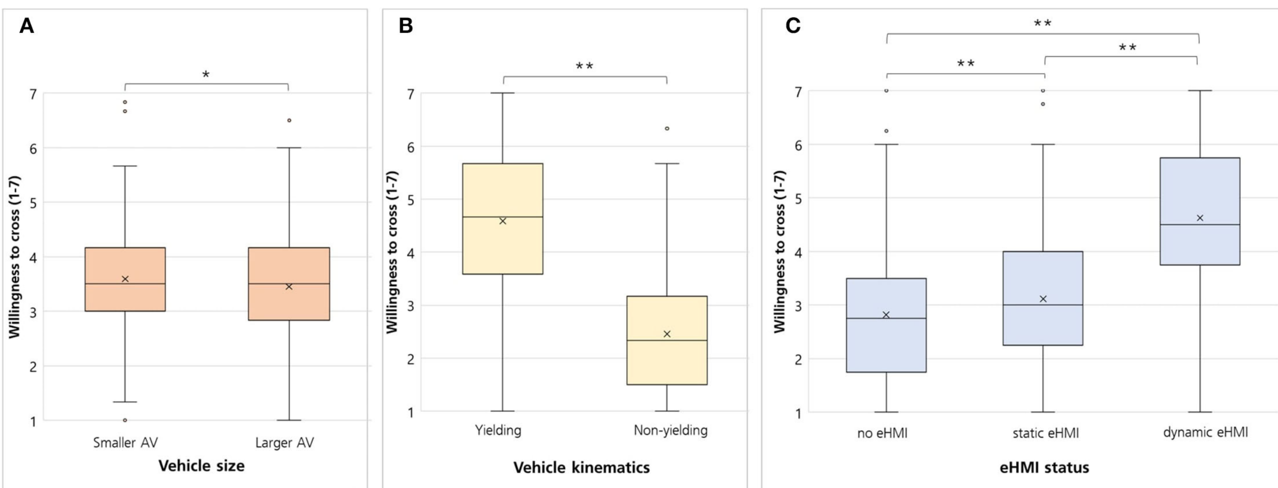

FIGURE 4 | Boxplots for pedestrians' willingness to cross focusing on the variables **(A)** vehicle size (smaller vs. larger AV), **(B)** vehicle kinematics (yielding vs. non-yielding), and **(C)** eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI). Crosses = means; lines = medians; $^{**}p < 0.001$ $^{*}p < 0.01$.

Secondly, there were significant correlations between pedestrians' willingness to cross and the perceived support of the eHMI for both AVs when the vehicle yielded and was equipped with dynamic eHMI (smaller AV: $r = 0.53$, $p < 0.001$; larger AV: $r = 0.5$, $p < 0.001$). When the vehicle did not yield but the dynamic eHMI indicated so, pedestrians' willingness to cross still highly correlated with the perceived support of the eHMI (smaller AV: $r = 0.81$, $p < 0.001$; larger AV: $r = 0.73$, $p < 0.001$). No correlations were found between pedestrians' willingness to cross and the perceived support of a static eHMI for both AVs ($p > 0.05$).

Trust

A significant main effect for vehicle kinematics was found [$F_{(1,148)} = 212.59$, $p < 0.001$, $\eta_p^2 = 0.59$; **Figure 5**]. The participants indicated higher trust ratings when they interacted with the yielding vehicle ($M = 4.27$, $SD = 1.49$) compared to the non-yielding ($M = 2.46$, $SD = 1.20$; $p < 0.001$; **Figure 5**). Moreover, a significant main effect for eHMI status was found [$F_{(1.53,226.34)} = 133.85$, $p < 0.001$, $\eta_p^2 = 0.475$; **Figure 5**]. Pairwise comparisons with Bonferroni-correction revealed significant differences between all three eHMI statuses, i.e., the dynamic eHMI ($M = 4.38$, $SD = 1.45$) lead to higher trust ratings vs.

TABLE 3 | Pedestrians' mean willingness to cross regarding the vehicle size (smaller AV, larger AV), vehicle kinematics (yielding, non-yielding), and eHMI status (no eHMI, static eHMI, dynamic eHMI).

	Smaller AV			Larger AV		
	No eHMI	**Static eHMI**	**Dynamic eHMI**	**No eHMI**	**Static eHMI**	**Dynamic eHMI**
Yielding	3.96 (*1.99*)	4.17 (*1.98*)	5.75 (*1.52*)	3.78 (*2.06*)	4.17 (*1.92*)	5.67 (*1.60*)
Non-yielding	1.89 (*1.35*)	2.22 (*1.54*)	3.55 (*2.02*)	1.66 (*1.13*)	1.89 (*1.34*)	3.54 (*2.12*)

1 = "very low; 7 = "very high". Mean (Standard deviation [italics]).

TABLE 4 | Perceived support of the vehicle kinematics regarding the vehicle size (smaller AV, larger AV), vehicle kinematics (yielding, non-yielding), and eHMI status (no eHMI, static eHMI, dynamic eHMI).

	Smaller AV			Larger AV		
	No eHMI	**Static eHMI**	**Dynamic eHMI**	**No eHMI**	**Static eHMI**	**Dynamic eHMI**
Yielding	4.51 (*2.04*)	4.76 (*1.89*)	5.68 (*1.42*)	4.51 (*1.99*)	4.72 (*1.86*)	5.62 (*1.57*)
Non-yielding	3.73 (*2.24*)	4.30 (*2.10*)	4.23 (*2.06*)	3.73 (*2.24*)	4.21 (*2.24*)	4.34 (*2.15*)

1 = "very low; 7 = "very high". Mean (Standard deviation [italics]).

static eHMI ($M = 2.97$, $SD = 1.35$; $p < 0.001$) vs. no eHMI ($M = 2.74$, $SD = 1.25$; $p < 0.001$). There was no significant main effect for vehicle size [$F_{(1,148)} = 2.21$, $p = 0.07$, $\eta_p^2 = 0.015$] and no significant interactions for vehicle size*vehicle kinematics [$F_{(1,148)} = 1.59$, $p = 0.21$, $\eta_p^2 = 0.011$], vehicle size*eHMI status [$F_{(2,296)} = 0.78$, $p = 0.39$, $\eta_p^2 = 0.006$], vehicle kinematics*eHMI status [$F_{(1.9,281.4)} = 1.46$, $p = 0.23$, $\eta_p^2 = 0.01$] and vehicle size*vehicle kinematics*eHMI status [$F_{(1.97,291.41)} = 1.62$, $p = 0.20$, $\eta_p^2 = 0.011$].

Perceived Safety

The interaction between vehicle kinematics and eHMI status was significant [$F_{(1.59,234.61)} = 19.33$, $p < 0.001$, $\eta_p^2 = 0.116$; **Figure 6**]. The ordinal interaction underlined the interpretability of the two main effects for vehicle kinematics and eHMI status. The main effect for vehicle kinematics was significant [$F_{(1,148)} = 129.7$, $p < 0.001$, $\eta_p^2 = 0.467$]. The perceived safety was higher when the vehicle yielded ($M = 4.40$, $SD = 1.33$) vs. not yielded ($M = 3.03$, $SD = 1.29$; $p < 0.001$). Moreover, the main effect for eHMI status was significant [$F_{(1.57,232.96)} = 120.99$, $p < 0.001$, $\eta_p^2 = 0.45$]. Pairwise comparisons with Bonferroni correction revealed that the perceived safety was higher for the dynamic eHMI ($M = 4.62$, $SD = 1.34$) vs. static eHMI ($M = 3.50$, $SD = 1.31$; $p < 0.001$) vs. no eHMI ($M = 3.02$, $SD = 1.3$; $p < 0.001$). There was no significant main effect for vehicle size [$F_{(1,148)} = 0.05$, $p = 0.41$, $\eta_p^2 = 0.000$] and no significant interactions for vehicle size*vehicle kinematics [$F_{(1,148)} = 0.37$, $p = 0.54$, $\eta_p^2 = 0.003$], vehicle size*eHMI status [$F_{(1.91,282.5)} = 0.73$, $p = 0.48$, $\eta_p^2 = 0.005$] and vehicle size*vehicle kinematics*eHMI status [$F_{(2,295.37)} = 2.14$, $p = 0.12$, $\eta_p^2 = 0.014$].

Post-hoc comparisons revealed that, when the smaller AV did not yield, the participants gave significantly lower ratings of perceived safety when the smaller AV was equipped with dynamic eHMI ($M = 3.58$, $SD = 1.97$) vs. static eHMI ($M = 3.17$, $SD = 1.79$; $t = 2.29$, $p = 0.023$, $n = 148$, $d_z = 0.19$) and vs. no eHMI ($M = 2.37$, $SD = 1.62$; $t = 6.73$, $p < 0.001$, $n = 148$, $d_z = 0.55$). When the larger AV did not yield, pedestrians' perceived safety was higher with dynamic eHMI ($M = 3.73$, $SD = 2.05$) vs. static eHMI ($M = 2.97$, $SD = 1.89$; $t = 3.93$, $p < 0.001$, $n = 148$; $d_z = 0.32$) vs. no eHMI ($M = 2.37$, $SD = 1.57$; $t = 7.08$, $p < 0.001$, $n = 148$, $d_z = 0.58$).

Evaluation of Hypotheses

In conclusion, it was hypothesized that pedestrians' willingness to cross, trust, and perceived safety is higher for a smaller AV vs. a larger AV (H1). According to the results, H1 is confirmed only partially, i.e., pedestrians' willingness to cross was higher for a smaller AV vs. larger AV, however, with a rather small effect size. Moreover, it was hypothesized that pedestrians' wiliness to cross, trust and perceived safety is higher when the vehicle yielded compared to when it did not yield for both vehicle sizes (H2). This can be confirmed for all variables. Furthermore, it was hypothesized that pedestrians' willingness to cross, trust, and perceived safety is higher when the AV is equipped with dynamic eHMI vs. static eHMI vs. no eHMI for both vehicle sizes (H3). Overall, this can be confirmed. Additionally, it was hypothesized that the effect of vehicle kinematics differs depending on the eHMI status for all dependent variables for both vehicle sizes (H4). According to the results, H4 was confirmed only for pedestrians' perceived safety. Moreover, it was hypothesized that, when the vehicle did not yield, pedestrians tended to rely on the explicit communication signals rather than the implicit communication signals for both vehicle sizes (H5). All in all, H5 was only confirmed for the perceived safety.

DISCUSSION

This study investigated the interplay of vehicle kinematics and eHMI for the interaction between pedestrians and two differently

TABLE 5 | Pedestrians' perceived support of eHMI regarding the vehicle size (smaller AV, larger AV), vehicle kinematics (yielding, non-yielding), and eHMI status (static eHMI, dynamic eHMI).

	Smaller AV		Larger AV	
	Static eHMI	**Dynamic eHMI**	**Static eHMI**	**Dynamic eHMI**
Yielding	2.75 (*1.88*)	5.60 (*1.68*)	2.95 (*1.97*)	5.51 (*1.73*)
Non-yielding	3.46 (*2.20*)	3.97 (*2.23*)	3.48 (*2.26*)	4.21 (*2.25*)

1 = "very low; 7 = "very high". Mean (Standard deviation [italics]).

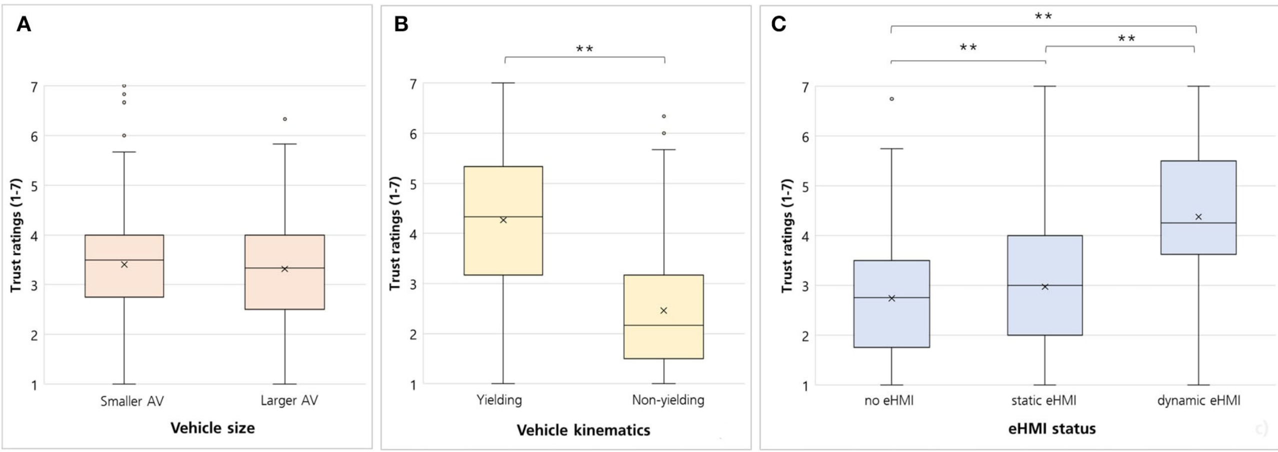

FIGURE 5 | Boxplots for pedestrians' trust focusing on the variables **(A)** vehicle size (smaller AV vs. larger AV), **(B)** vehicle kinematics (yielding vs. non-yielding), and **(C)** eHMI status (no eHMI vs. static eHMI vs. dynamic eHMI). Crosses = means; lines = medians; $^{**}p < 0.001$.

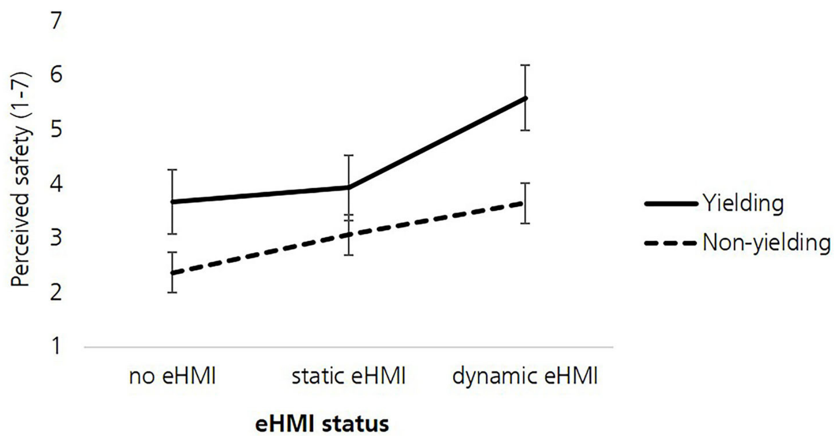

FIGURE 6 | Perceived safety regarding the eHMI status and vehicle kinematics. Error bars: ± 1 *SE*.

sized AVs in a shared space as an example of a low-speed and low-distance traffic scenario. The results indicated that pedestrians' willingness to cross is influenced by the size of the AV. Moreover, the use of vehicle kinematics and eHMI communication can lead to high willingness to cross, and high trust- and safety ratings. Nevertheless, when the dynamic eHMI indicated a yielding intent by the vehicle, although the vehicle did not yield, pedestrians' perceived safety still increased compared to when no contradictory explicit information was given by the eHMI.

AV's Joint Communication via Vehicle Kinematics and eHMI

Previous research showed that implicit communication signals, i.e., vehicle kinematics, helped pedestrians to decide whether to cross a street or not (Dey and Terken, 2017; Lee et al., 2020).

This was also found to be true for pedestrians' interaction with AVs (Risto et al., 2017; Dey et al., 2020a). The results of this study also supported the high relevance of vehicle kinematics for pedestrians' interactions with two differently sized AVs in a shared space. Pedestrians focused on what the AV implicitly communicated and were more willing to cross, indicated a higher trust, and felt safer when a yielding intent was communicated implicitly by the AV. However, it needs to be addressed that the AVs decelerated in two steps in the yielding conditions. Therefore, no clear assumption can be made about how exactly each deceleration might have influenced pedestrians' willingness, trust, and perceived safety and when exactly. Nevertheless, the two-step deceleration presents a realistic motion pattern for AVs as in shared spaces multiple TPs will interact together and, thus, AVs will need to adapt to their surrounding dynamically. This should be further investigated in more complex traffic scenarios including more than just one pedestrian. Regarding explicit communication, previous research manifested that additional explicit communication can be beneficial in low-speed and low-distance traffic areas to clarify misunderstandings before they could actually result in accidents (Färber, 2016; Habibovic et al., 2018; Lee et al., 2020). In this study, both AVs were perceived as more trustworthy and safer when they were equipped with a dynamic eHMI compared to a static eHMI or no eHMI at all. Furthermore, the participants indicated a higher willingness to cross when a dynamic eHMI was presented which is consistent with previous findings (Clercq et al., 2019; Dey et al., 2019; Schieben et al., 2019a,b; Ackermans et al., 2020; Kaleefathullah et al., 2020; Lau et al., 2021a). Nevertheless, it needs to be pointed out that the online-based experimental approach and the experimental setting could have had an effect on pedestrians' subjective evaluation which needs to be addressed in future studies for further interpretation and comparison (Fuest et al., 2020).

Regarding the interplay of vehicle kinematics and eHMI, pedestrians' perceived safety increased with an explicitly communicating dynamic eHMI in combination with an implicitly communicated yielding intent (kinematics). Additionally, the support of the vehicle kinematics and the dynamic eHMI was perceived as rather high for pedestrians' willingness to cross when the vehicle yielded. This stands in line with previous studies showing that a yielding intent that is communicated implicitly and explicitly can support the interaction between pedestrians and AVs (Dey et al., 2020a; Rettenmaier and Bengler, 2021). Surprisingly, the dynamic eHMI still increased pedestrians' perceived safety when the vehicle did not yield. In this non-matching condition, the dynamic eHMI falsely communicated a yielding intent although the vehicle did not yield. Additionally, when the AV did not yield but the dynamic eHMI indicated so, the participants seem to overestimate the support of the vehicle kinematics and the dynamic eHMI. Overall, these findings indicated possible negative effects of eHMIs which were described in previous studies (Kitazaki and Daimon, 2018; Holländer et al., 2019; Lee et al., 2021). However, these results stand in clear contrast to a study by Dey et al. (2020a) that showed that pedestrians tended to rely on the implicit communication signals, i.e., the vehicle braking behavior when the eHMI signal contradicted the vehicle behavior. In this study, the pedestrians did not elaborate on the presented information signals correctly but rather shifted their attention to salient explicit communication signals to make assumptions about the vehicle's intention (Moussaïd et al., 2011). According to Petty and Cacioppo (1986), one would assume that pedestrians tended to elaborate on the presented information via the peripheral route in this study. In urban traffic, pedestrians' over-trust in eHMIs would present a high-risk traffic scenario and could have safety-critical consequences for pedestrians.

In conclusion, the results highlighted the importance of the interplay of vehicle kinematics and eHMI. If the information by vehicle kinematics and eHMI are well-coordinated, the combination showed a great potential to positively influence pedestrians' interaction with differently sized AVs. Nonetheless, if both communication means were not well-coordinated, negative effects did occur, i.e., pedestrians' safety was influenced by the dynamic eHMI even though it transmitted contradictory signals to the vehicle kinematics. Therefore, this study demonstrated the importance of a well-coordinated holistic communication approach to enable a safe and efficient interaction between pedestrians and AVs.

Effect of Vehicle Size

This experimental online study compared two differently sized AVs, a smaller AV, and a larger AV. The results supported previous assumptions about the effect of vehicle size, i.e., a larger AV was perceived as significantly more threatening, more dangerous, less pleasant, stronger, and closer compared to the smaller AV in the videos. Furthermore, pedestrians indicated a higher willingness to cross for a smaller AV compared to a larger AV. However, no effect of the vehicle size was found on pedestrians' trust and perceived safety. This stands in contrast to previous findings by Lau et al. (2021a) who showed that a smaller AV was perceived as safer and affectively more positive compared to a larger AV. Nevertheless, this study's video sequences presented only short interactions and, thus, a realistic interaction could have been limited. However, the idea was to create short and uncertain situations in which the pedestrians should make a fast and intuitive decision. This was done with the overall goal to get insights into pedestrians' subjective experiences.

For both AVs, the combination of dynamic eHMI and an implicit yielding intent via the vehicle kinematics supported pedestrians' willingness to cross, trust, and perceived safety in this study. Nevertheless, when the dynamic eHMI showed contradictory signals to the vehicle kinematics, pedestrians became equally indecisive for both AVs although pedestrians perceived higher risk by the larger AV (according to the data validation check). As previously mentioned, this finding showed that pedestrians might have resorted to salient explicit communication signals even for their interaction with a larger-sized AV. Previous studies that revealed possible negative effects of eHMI communication, i.e., over-trust, primarily focused on pedestrians' interaction with a smaller AV (Holländer et al., 2019; Lee et al., 2021). This study also illustrated possible negative effects of eHMIs on pedestrians' interaction with a larger AV. If pedestrians would have initiated a crossing under these conditions in real urban traffic, their interaction with AVs could have had fatal consequences.

All in all, the results supported the assumption that the effect of size could also influence the future interaction between pedestrians and differently sized AVs. When the dynamic eHMI was presented in line with a yielding behavior, eHMIs supported the interaction with both AVs. However, when the dynamic eHMI contradicted the vehicle kinematics, pedestrians' perceived safety was influenced in a negative manner. In conclusion, this study could contribute to further research on the effect of vehicle size focusing on pedestrians' interaction with AVs in terms of subjective measurements and the investigation of a shared space.

Limitations

This study was an experimental online study in which the participants took part from their private computers. Therefore, pedestrians' perception of the vehicle sizes and the perception of the driving behavior could be limited due to the experimental setting (Petzoldt et al., 2018; Fuest et al., 2020). If the perception is limited, a greater focus can possibly be placed on the visually present stimulus, i.e., the eHMI. Thus, further investigation of the parameter (vehicle size, vehicle kinematics) in a more ecologically valid environment is required. Although we provided detailed guidelines for the participation in this study, the experimental setting could not be fully controlled, e.g., light sources or the monitor size. Thus, the internal validity might also have been limited due to the experimental setting. Moreover, the participants were not able to ask further questions during the experiment. Nevertheless, a major focus was placed on the video functionality and a manipulation check and a data validation check were conducted before and after the experiment. Future studies should be conducted in-person and under more controlled experimental conditions to avoid any influencing factors by the testing environment. Furthermore, the participants rated all dependent variables (willingness to cross, trust, perceived safety) after they saw the videos. Therefore, changes in the subjective evaluation during the video presentation could not be addressed and no specific determination time points can be identified for the subjective measures. This study focused primarily on subjective measurements to investigate pedestrians' interaction with differently sized AVs. However, it needs to be addressed how pedestrians' crossing behavior could be influenced by, e.g., the vehicle size, by focusing on objective measures (Petzoldt, 2016; Beggiato et al., 2017; Ackermann et al., 2019b; Hensch et al., 2021).

Future Work

Future work will focus on the investigation of the interplay of vehicle kinematics and eHMI in more ecologically valid experimental settings, e.g., virtual-reality environments or real traffic. The overall goal is to enable the participants a realistic interaction with the differently sized AVs. Moreover, future studies will focus on possible cultural differences in the communication with AVs in general and how culture might affect the interaction with differently sized AVs presenting implicit and explicit communication signals with a larger sample size (Färber, 2016; Weber et al., 2019). Additional future work should focus on more complex environments, i.e., more than only one pedestrian interacting with one AV, and on the consideration of different age groups, e.g., older pedestrians. Furthermore, the vehicle kinematics were only manipulated in two stages (yielding, and non-yielding). In future studies, the vehicle kinematics should be varied in more stages in combination with an eHMI and with a focus on differently sized vehicles Additionally, future studies should focus on the continuous recording of pedestrians' willingness to cross, trust, and perceived safety to be able to put the subjective measurements in relation to the vehicle kinematics during the vehicle's approach. Furthermore, qualitative feedback from the participants at the end of the experiment could also help to receive further insights into participants' experiences and should be included in future studies.

CONCLUSION

This study investigated pedestrians' interaction with two differently sized AVs in a shared space as an example of a traffic scenario of low-speed and low-distance. Current research lacks not only standardized requirements of eHMIs for AVs but also, official requirements for a holistic communication approach, i.e., the combination of vehicle kinematics and eHMI for differently sized AVs. This study underlined the great potential of a holistic communication approach when both communication tools are well-coordinated. Nevertheless, the findings also highlighted possible negative effects of eHMIs when they were not coordinated correctly, i.e., when the eHMI message contradicted the vehicle kinematics. The consequences are fatal and would even be more serious for pedestrians' interaction with larger-sized AVs. This study's results showed that a holistic communication strategy that consisted of well-coordinated implicit and explicit communication signals by the vehicle kinematics and the eHMI contributed to a well-working interaction. However, the major focus should be put on the precise coordination of eHMI and vehicle kinematics as the participants tended to focus on explicit communication signals even though they were contradictory to the vehicle kinematics in this study. A well-coordinated holistic communication strategy will set the standard on how pedestrians will safely interact with differently sized AVs in future urban traffic.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Ethics boards of the German Aerospace Center

(DLR), Cologne, Germany. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

ML: conceptualization, methodology, data curation, writing—original draft, visualization, validation, resources, formal analysis, investigation, software, writing—review and editing, and project administration. MJ: writing—review and editing and supervision. MO: conceptualization, methodology, visualization, validation, writing—review and editing, resources, supervision, project administration, and funding acquisition. All authors contributed to the article and approved the submitted version.

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External communication of automated shuttles: Results, experiences, and lessons learned from three European long-term research projects

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Automated shuttles are already seeing deployment in many places across the world and have the potential to transform public mobility to be safer and more accessible. During the current transition phase from fully manual vehicles toward higher degrees of automation and resulting mixed traffic, there is a heightened need for additional communication or external indicators to comprehend automated vehicle actions for other road users. In this work, we present and discuss the results from seven studies (three preparatory and four main studies) conducted in three European countries aimed at investigating and providing a variety of such external communication solutions to facilitate the exchange of information between automated shuttles and other motorized and non-motorized road users.

KEYWORDS
automated shuttles, eHMI, user studies, shuttle2vehicle communication, shuttle2pedestrian communication

1 Introduction

Vehicle automation is considered a crucial aspect of "Vision Zero", that is, the aim to achieve a state where there are no longer on-road accidents involving vehicles with fatal consequences. The efforts to automate mobility encompass both private and public means of transport, with automated shuttles being one of the currently more prominent facets of the latter, exploring not only automated mobility in terms of safety but also new mobility patterns, for example, mobility on demand.

Shuttles are, in essence, buses with smaller passenger capacities, which make them suitable for a variety of contexts (urban city centers or other areas with high amounts of pedestrian traffic, airports, or rural areas with lower demand in terms of number of passengers). These contexts are characterized by different traffic conditions and subsequent requirements when compared to contexts with higher volumes of motorized vehicles and higher speed limits (e.g., motorways, highly frequented roads, city peripheries, and a.s.o). Since other road users are either less frequent (especially in last mile or airport contexts) or simply a lot slower and/or pose less of a threat (pedestrians, cyclists, and scooters), such contexts could already see the deployment of (low velocity) automated shuttles, even without the technology being fully realized, due to these different circumstances and lower risk of accidents.

The transition to full vehicle automation is not yet complete and will not be for some time (e.g., Sheffi, 2015; Mraz, 2017; Lubitz, 2020). During this transition time, there is an increased need for clear communication of these vehicles with their (non-automated) environment, since the technology often responds differently to actions and maneuvers than a human would and there is no human behind the wheel that could serve as a fallback when a miscommunication or conflict occurs. Once automated vehicles are commonplace across traffic contexts and common interaction patterns have been established, these additional communication requirements are likely to diminish accordingly, although might not disappear entirely, especially in terms of fallback communication and conflict resolution. Since automated shuttles have now already seen deployment for several years and in a variety of contexts, there are already a good number of results and lessons learned to determine the way forward in terms of communication of automated shuttles with their traffic environment.

In this study, we collect and present the results from a series of studies concerning communication of automated shuttles with other road users. This study is a collaborative effort between three automated shuttle projects: the Austrian national flagship projects *auto.Bus—Seestadt* and *Digibus® Austria*, and the Horizon 2020 European project *Drive2TheFuture*. We present conceptual and field evaluations of interaction designs for communicating with motorized and non-motorized road users and draw results and design recommendations with regard to the complexity level of the information presented for both of these communication contexts.

2 Related work

The advent of automated vehicles has created a gap in communication of intent, which was usually maintained mainly *via* gestures and eye contact between human drivers (Rasouli et al., 2017; Kaleefathullah et al., 2020). Whether external human–machine interfaces (eHMI) can compensate for the lack of this communication is yet to be decided (e.g., Löcken et al., 2019; Kaleefathullah et al., 2020; De Clercq et al., 2019; Velasco et al., 2019). Several studies suggest that eHMIs can influence the confidence, trust, or perceived safety of crossing pedestrians (e.g., Löcken et al., 2019; Kaleefathullah et al., 2020; Kooijman et al., 2019; Velasco et al., 2019; De Clercq et al., 2019; Rettenmaier et al., 2020; Faas et al., 2021).

On the opposite side of the argument, there has been evidence suggesting that other road users base their decisions mostly on the implicit communication with the automated vehicles through its actions (e.g. Clamann et al., 2017; Palmeiro et al., 2018) Rettenmaier et al., 2019; Dey and Terken, 2017), with some arguing for the vehicle's behavior being more intuitive than the dedicated interface (e.g., Moore et al., 2019). Despite the lack of definitive answer as to the effect of those systems, eHMIs could be one of the ways of increasing the trust in and acceptance of highly automated vehicles, especially in times of transition from manual to full vehicle automation.

Within those who do find value in the eHMIs as a way of communication with other road users, there is no consensus, though, as to the specifics of that communication (e.g., Faas et al., 2020; Mahadevan et al., 2018; De Clercq et al., 2019; Ackermann et al., 2019; Merat et al., 2018). Literature surveys which analyzed and categorized existing concepts (Löcken et al., 2019; Colley et al., 2020; Dey et al., 2020a; Schieben et al., 2019; Mahadevan et al., 2018) found the textual and symbolic communication as the most common due to its ability to convey more complex messages. Dey et al. (2020b) proposed well-established red for "stop" and green for "go" and more neutral cyan for yielding could be used for communication *via* light band eHMI, and U e was used for an often indecisive research field. The SAE Recommended Practice J3134 (SAE, 2019) advises using two symmetrical, continuously lit blue-green light signals as a way of communicating an automated state.

The true value of eHMIs for automated vehicles has yet to be determined. Still, both for traditional and automated public road transportation means, a number of issues and application areas related to a lack of communication have been identified. Rapid acceleration and harsh braking while arriving at or leaving a bus stop, for example, often lead to injuries of passenger waiting, boarding, off-boarding, as well as on board on the bus or shuttle (Wretstrand et al., 2014). Apart of being potentially dangerous for the passengers, docking the vehicle into a bus stop is also a stressful moment for the driver who needs to both perform the maneuver, as well as to communicate with waiting, boarding, off-boarding, and on-board passengers.

There is evidence suggesting that the automation of the docking procedure could increase safety and lower drivers' stress levels (Ahlström et al., 2018). Tests in contexts ranging from dedicated lanes of Bus Rapid Transit (BRT), test tracks, and open urban roads, further showed improved precision (Collet et al., 2003; Huang and Tan, 2016; Tan et al., 2002; Yoshioka et al., 2014), improved ease of access and waiting time for all passengers, and loading and unloading time for those with special needs (Huang and Tan, 2016).

A study by Collet et al. (2003) indicates that automated docking, after initial habituation, reduced drivers workload as they no longer have to maneuver the vehicle but only monitor the process. A similar decrease in workload would not be observed when the drivers were unfamiliar with the system or faced with an error or takeover. eHMIs can be a solution in such situations of a higher communication need by providing additional, universally understandable, and always-available communication means, which can support not only the drivers but also the passengers in automated traffic transportation environments, especially in situations of risk and conflict.

Due to the challenging nature of designing and assessing eHMIs in real traffic, research in this particular area is still rather scarce (Colley and Rukzio, 2020; Dey et al., 2020a). Most eHMI research has been conducted in, for example, Colley et al. (2020); Dey et al. (2021); Faas et al. (2021); and Mahadevan et al. (2018) and about various forms of simulated traffic so far (e.g., Hoggenmüller et al., 2021), but studies in real traffic contexts are still scarce.

3 Studies overview

The starting point for this publication was the work that had been conducted throughout the Austrian national flagship project Digibus® Austria. The general aim of this project was to investigate the integration of fully automated shuttles into the existing traffic infrastructure as a last-mile solution. Working on eHMI solutions for communication with pedestrians and other road users was only one of several facets within the project. Along the project, initial user requirements were gathered, and eHMI solutions were proposed and conceptually evaluated for a variety of interaction contexts and multiple types of road users. As things usually go in these kinds of investigations, only a subset of these solutions could be carried forward for the field tests and were evaluated in some—but not all—of the contexts that had been identified as critical in the initial analysis.

Although this is par for the course for virtually any research activity, we had been in touch with the two other research projects, *auto.Bus—Seestadt* and *Drive2TheFuture*. We found that together the three projects covered a wide and very synergistic area, which, in addition, addressed the initial scope of *Digibus® Austria* quite well. We decided to pool our resources and results together to provide a more comprehensive overview of what worked (and what did not) in terms of eHMIs for external communication of automated shuttles.

This study describes the preliminary activities and preparatory studies from *Digibus® Austria* and then branches out to describe four main studies from all three participating projects (see Figure 1 for an overview). The preliminary studies identified a number of critical scenarios and provided two online evaluations of eHMI designs to address a wide range of them, along with an initial field trial in-between. The eventual field study (MS1) could cover eHMI designs to communicate with motorized vehicles in crossing situations but none of the other relevant scenarios. A field study conducted in Norway (MS2, *Drive2TheFuture*) investigated an eHMI to reduce dangerous overtaking situations, whereas a co-simulation study in Sweden (MS3, *Drive2TheFuture*) and another field study in Austria (MS4, *auto.Bus—Seestadt*) investigated eHMIs to support pedestrian/passenger communication for bus stop docking and boarding operations. All preliminary studies as well as MS2 and MS4 are original, previously unpublished research. MS1 and MS3 have both been published individually; the full publications are referenced in the respective study sections, and the sections contain abridged summaries of setups and results to convey the essential findings and lessons learned.

4 Preparatory work and preliminary studies

Traffic configurations—both in terms of the physical environment as well as traffic participants—are manifold. Thus, the first step consisted in identifying the most relevant of these traffic configurations and then focuses the research efforts accordingly. To this end, one of the first activities in the *Digibus® Austria* project was an expert workshop in October 2018, where these configurations were identified and captured as concrete interaction scenarios. For each of these, a number of eHMI concepts were developed for automation-critical situations (i.e., situations, where there was an additional challenge due to the shuttle's automated nature and not only it being difficult to handle traffic situation in general). These were then conceptually evaluated *via* an online questionnaire in April 2019. Based on the lessons learned from that study, a second iteration of the eHMIs was created and deployed in the first field trial in November 2019 and then evaluated in a second online questionnaire in March–May 2020. These three activities constitute the preparatory studies, which we will report in the following. A selection of the eHMIs was then realized for the eventual main field study, which will be reported in Section 5.

4.1 Interaction scenarios and preparatory eHMI designs

The first preparatory study was a scenario-based, online evaluation of three different eHMIs that were designed to support an automated shuttle in communicating its driving intentions to other groups of road users in potentially

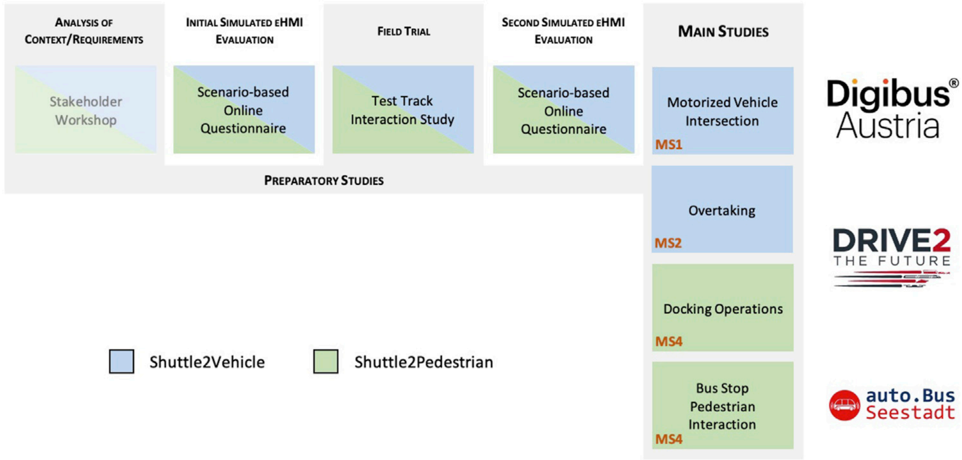

FIGURE 1
Overview of all studies included in this publication from each participating research project. Note: The stakeholder workshop was the general starting point feeding into all further research activities. For reasons of clarity and scope, its exact procedure will not be discussed further in this study, but the key data and essential findings are outlined as part of Section 4.1, as its essential findings were immediately applied in the first online questionnaire study.

ambiguous traffic scenarios. The traffic scenarios that the eHMIs would address were chosen based on an expert stakeholder workshop. The workshop was a half-day workshop, and the experts were from a variety of different backgrounds; from representatives of the public transport sector to urban transport planners to spokespersons for vulnerable road users. The scenarios, which the experts, finally, agreed on to hold a lot of potential for ambiguous driving and communication behavior to occur, when an automated shuttle and other groups of road users meet in traffic, were the following:

- **Crossing (C):** The shuttle approaches a zebra crossing and communicates that it has recognized the pedestrians, who are about to pass, and that it will stop in front of the zebra crossing accordingly.
- **Unregulated junction (UJ):** The shuttle and another road user (car, motorbike, and bicycle) are approaching an unregulated T-junction at the same time from different directions. From the other road user's perspective, the shuttle is coming from the right therefore has right of way and, also, communicates that it will pass the intersection and not give up on its right and wait for them to pass.
- **Regulated junction (RJ):** The shuttle and the oncoming traffic have a green light at a regulated junction and are allowed to continue driving straight ahead. However, the shuttle wants to turn left at the crossing, but then it has to abort its turn before it crosses the oncoming lane due to pedestrians crossing in the side street. The shuttle is communicating that it has stopped for the pedestrians in the side street and is not driving any further as long as the way is not clear.
- **Boarding (B):** A prospective passenger approaches the shuttle stop or is already standing in the shuttle stop and wants to know if they can still make it onto the shuttle in time, or are still allowed to board the shuttle. The shuttle communicates that it is time to get on board the shuttle and alerts the passengers in the vicinity that it is about to leave, before it closes its doors.
- **Passing (P):** The shuttle passes an oncoming pedestrian on the side of a road without pavement and communicates that it has recognized the pedestrian and that it is keeping enough distance while passing them, so they can proceed walking unaffected.

For the first questionnaire, these were adapted directly, resulting in eHMI evaluations across five interaction scenarios. For the second questionnaire, the crossing and junction scenarios were further refined into two separate sub-scenarios each (A and B). For the crossing scenarios, A had the shuttle approach the crossing from a distance, whereas B had the shuttle stopped in front of the crossing and attempting to accelerate. Likewise, the junction scenarios were differentiated by the shuttle approaching the junction from a distance (A) or waiting at the junction (B). Passing was dropped, since it had turned out to be difficult to realize during the field trial, whereas Boarding remained a single scenario. This resulted in a different number of scenarios for the second questionnaire (seven in total), although both questionnaire studies are based on and are consistent with the base scenarios described before.

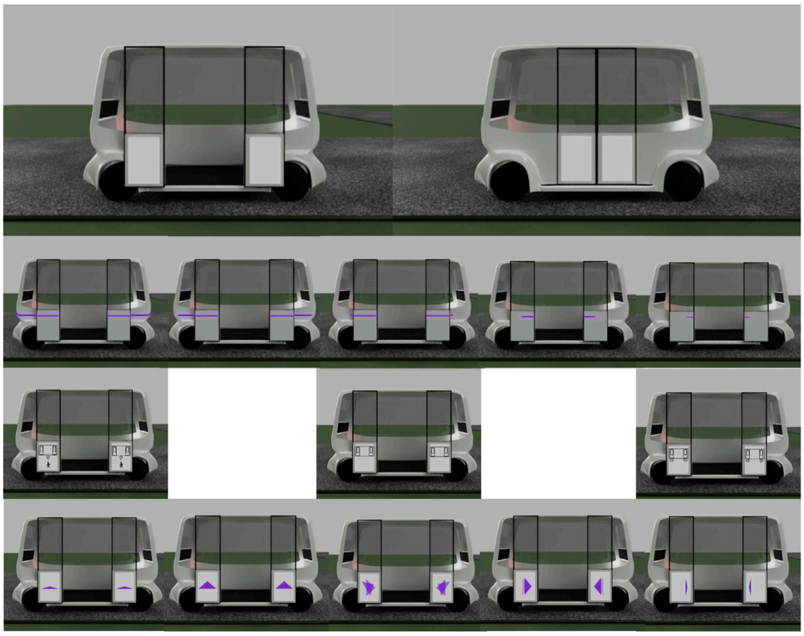

FIGURE 2
Boarding—overview of all initial designs.

4.1.1 Initial eHMI designs

The three eHMI designs (see Figure 2 for a representation of each in a boarding scenario) were developed internally by a team of user experience (UX) and design researchers in a half-day creative workshop, for which the five traffic scenarios provided the parameters for. After a process of freely creating several solutions, ideas were sorted, refined, and iterated, which, finally, led to three general design paradigms, each of which was able to be applied in all five traffic situations. These were as follows:

- **Morphing arrows** that can provide information about trajectory, acceleration, and braking behavior as well as detected objects in the immediate vicinity of the shuttle *via* shape change and rotation.
- **Icons** that can provide information about the traffic environment perceived by the shuttle. In addition, escalation steps can be indicated by changing from a static display to flashing.
- **LED bars**, mounted laterally around the shuttle, that can provide information on the intended driving behavior and, to a limited extent, also on the detected traffic environment by means of light frequency, rhythm, movement, and range.

In order to avoid associations with already existing light signals in road traffic, a light shade of violet was chosen as the uniform color of light signals. Furthermore, in order to counteract potential liability issues, it was defined that the information communicated by the shuttle only addresses currently available sensor information and current or immediately planned driving behavior and intentions, whereas transmissions of instructions or information, which could directly or immediately prompt other road users to take action, were explicitly excluded. These designs were evaluated in the first online study.

4.1.2 Iterated eHMI designs

Based on the lessons learned from the first online study and the technical and contextual characteristics of the shuttle and the driving track, an internal workshop was conducted to derive and define the next iterated set of eHMI designs (see Figures 3–5).

- **Countdowns:** Three different designs of animated 5-s countdowns were implemented. The goal with these was to compensate for the shuttle's extended start interval and clearly communicate the driving initiative (i.e., the exact point in time, when the shuttle would depart). In this regard, they were also intended to be particularly helpful in resolving "deadlock situations" (e.g., at unregulated intersections, where both vehicles are at a standstill). Also, due to the conflicting aspects of readability and visibility over distance, now that people were no longer sitting in front of a screen but observing the shuttle from a far as pedestrians and car drivers, a numbers-only design, a design with numbers embedded in a half pie and a full pie

FIGURE 3
eHMI design countdown as applied for the field study.

design without any additional numbers, was implemented. The animation sequence for each of the countdown-based eHMI designs consisted of one animation cycle counting down from five to zero or from five empty to five filled segments, followed by a 2-s flashing interval of the final animation for all types of countdowns. So, in total, it took about 7 s for one animated countdown to be fully displayed.
- **Icons and arrow animation:** In alignment with the results from the first online questionnaire, where the icons and animated arrow eHMI designs were received as the most suitable designs to communicate the shuttle's driving intentions, two standard icons, one for a stop and one for a pedestrian crossings, were implemented. Also, the animated arrow design from the first study was changed to a simpler but easier to perceive version, which should also address the issue of readability and visibility over distance. The design goal was not only to communicate the shuttle's intentions but also information on the contextual awareness of the shuttle to the car drivers and pedestrians.
- **Animated bars:** As an alternative design to compensate for the extended start interval of the shuttle as well as to possibly gain insights into the level of detail and concreteness necessary to communicate the driving initiative, two additional simplified and animated eHMI designs were realized. They came in two shapes (bars and circles) and at three different speeds. The bar design was mimicking an LED strip, basically, and was an approach to further pursue the communication capacities of an LED-like information design, as the LED bars were not received positively in the first online study. The circle design was more of a creative approach to address the issue of recognizeability through a kind of twitchy, unconventional but attention-seeking design. Both eHMI were animated to expand or contract to or from the center depending on the chosen direction (in-out or out-in) at speeds of 3, 4, or 5 s. An additional design goal was to communicate the planned start or planned stop of the shuttle in advance (i.e., before any acceleration or deceleration is apparent from the driving behavior) to make the shuttle's driving intentions even clearer to car drivers and pedestrians.

These designs were used for both the initial field trial as well as the second online study. The only exception was the animated circle design (see Figure 5). Since there were no meaningful advantages and only disadvantages (distraction and confusion) reported during the initial field trial, it was not carried forward afterward and only the straight bar design remained.

4.2 Study setups and methods

The main research goals of all three preparatory studies was to find out whether or to what extent the eHMIs could help other road users better anticipate the shuttle's driving intentions. The guiding research questions (RQ) were as follows:

- RQ1: Are the eHMIs recognized by other road users as relevant to them?
- RQ2: Are the eHMIs successful in communicating the intended content?
- RQ3: How suitable are the eHMIs for resolving, due to the lack of a human driver, potentially ambiguous traffic scenarios?

4.2.1 Online questionnaires

The traffic scenarios were first drawn as storyboards with a short text description from the first-person perspective of a road user approaching the shuttle for use in the online evaluation. For the first online questionnaire, the scenarios were implemented as 3D animations, based on a simplified model of the shuttle (the template of which we had received from the shuttle manufacturer, Navya). The scenarios were created in Blender and then embedded in Photoshop. The three initial eHMI designs (LED bars, morphing arrows, and icons) were implemented as part of the shuttle's eHMI for each traffic scenario (see Figure 6). The second questionnaire used videos from the actual shuttle on the test track, overlaid with the iterated animations (see Figure 7).

FIGURE 4
eHMI design icons and arrows as applied for the field study.

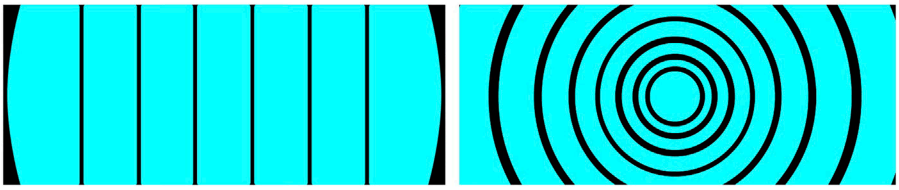

FIGURE 5
eHMI design animated bars as applied for the field study.

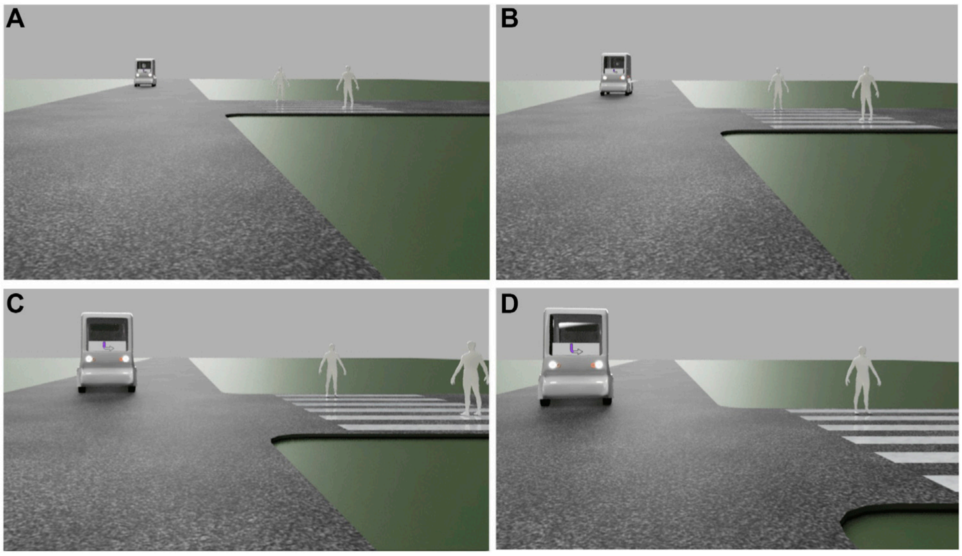

FIGURE 6
Visualization example [animation stills, sequence from **(A–D)**] of how the scenarios were presented in questionnaire 1.

The online questionnaires were both set up in LimeSurvey and followed the same structure and format. The interaction scenarios were realized as animated gif images and integrated into the survey to constantly loop so that participants would be able to watch every scenario several times without missing anything. Before the scenarios were introduced, participants were asked for some demographic data (age, gender, driving license possession,

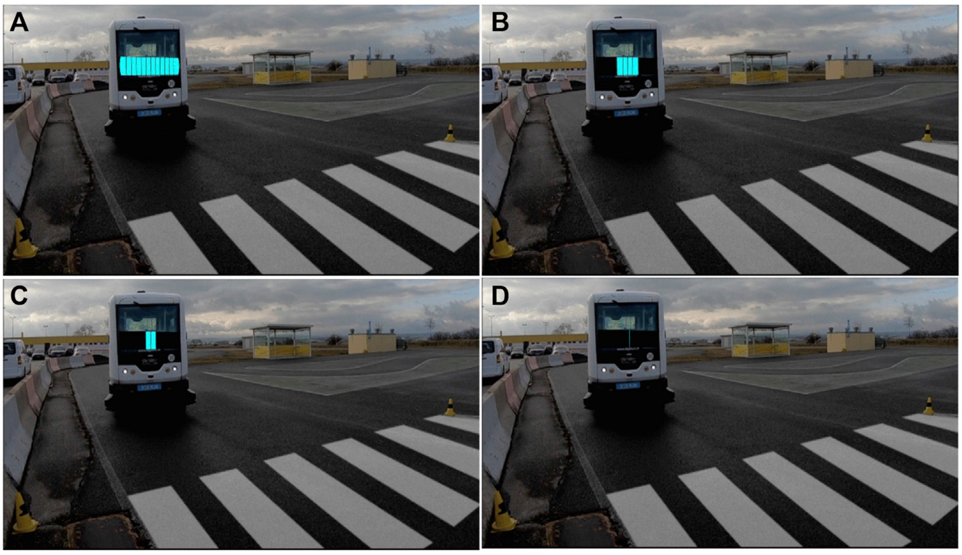

FIGURE 7
Visualization example [animation stills, sequence from **(A–D)**] of how the scenarios were presented in questionnaire 2.

frequency and mode of transportation usage, and experience with automated vehicles). Then they were presented with the scenarios in a random order.

For each condition in each scenario, participants had to give their opinion on the following statements to evaluate their interpretation of the situation and the shuttle's driving intentions:

- **safety:** I feel safe to continue my journey.
- **action2:** It is clear to me that the shuttle is going to turn left in front of me.
- **perception1:** It is clear to me that the shuttle has noticed me.

Furthermore, to evaluate participants' opinion on the general recognizability and interpretability of the eHMI at display, they were asked to rate four more statements:

- **visualization1:** I would assume that most people would quickly recognize what the visualization means. (*SUS7*)
- **visualization2:** I find the visualization unnecessarily complex. (*SUS2*)
- **visualization3:** I understand the meaning of the visualization straight away. (*SUS10*)
- **visualization4:** I find the visualization superfluous.

Finally, to learn something about participants' preferences regarding the eHMIs per scenario, participants were asked which visualization was the best to detect the shuttle's driving intentions. The statements on safety, action2, and perception1 were adapted in phrasing to fit the respective scenario at hand (e.g., for the boarding scenario, the statement on safety read like this: *I feel safe to be able to get on the shuttle in time.*) The first three statements on visualization (1–3) were taken from the System Usability Scale (SUS). For the control condition, which was not displaying any visualizations, only the statements safety, action2, and perception1 were used. For all statements, answers ranged from *not at all (1)* to *absolutely (5)* on a five-point Likert scale. For the question for the preferred eHMI, the selection was single-choice with an additional *none of the shown* option.

The first questionnaire evaluated four conditions (the three initial eHMI designs and a control condition without designs) across the five defined interaction scenarios, and the second one across seven scenarios (see Section 4.1).

4.2.2 Initial field trial

The initial field trial was conducted on a test track at a driver training center (see Figure 8), where the actual shuttle equipped with the different eHMI, car drivers, and pedestrians interacted with each other under semi-realistic traffic conditions. The field trial was conducted after the first online questionnaire and used the iterated eHMI designs described earlier. The main objective of the study was the *in situ* evaluation of the iterated eHMI designs. To this end, RQs 1–3 were extended with the following evaluation targets:

- **Visibility/recognisability:** How well are the designs recognizable to the other road users (pedestrians, car drivers)? Do they attract their attention or not?

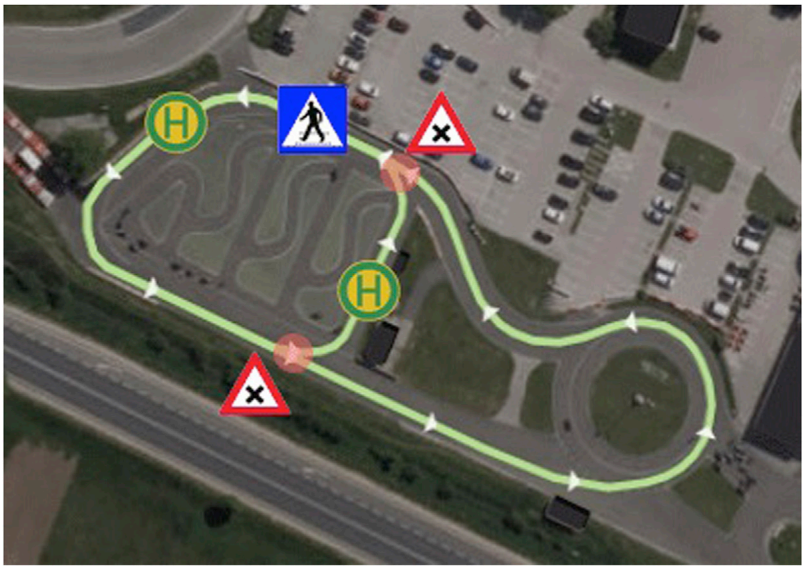

FIGURE 8
Top-down view of the test track showing the pedestrian crossing, vehicle intersections, and bus stops.

- **Directedness:** Do the other road users feel addressed?
- **Comprehensibility:** How do the other road users interpret the meaning of the designs?
- **Usefulness:** How useful do the other road users experience the designs?
- **Trust:** How much do the other road users trust the behavior of the bus based on the designs?
- **Subjective safety:** How safe/unsafe do the other road users feel in the respective situation? Are the designs perceived as promoting safety?
- **Alternative design suggestions:** Do the other road users have alternative suggestions for what the designs could look like?

Quantitative data was collected along these factors *via* a post-interaction questionnaire, with one item for each of the initial six (visibility–subjective safety) to be answered on a 5-point Likert scale. The items asked were closely related to the research questions and the wording was adapted to fit pedestrian as well as car driver scenarios. An observation log was used to record contextual information such as the date, time, duration, weather, and group size (for pedestrian and passenger groups), and whether or not the currently displayed eHMI in the respective situation led to a successful completion of the scenario.

In a final interview, the participants were asked which of the eHMI designs they had consciously noticed and for their interpretation of the information provided. Additional questions concerned the perceived eHMI addressees, whether the eHMI was perceived as helpful or unnecessary, whether the eHMI contributed to perceived safety, and suggestions for improvement. Basic demographic data (age, gender, place of residence, information on visual or hearing impairments, and previous experiences with automated vehicles) was collected as well.

4.3 Preparatory studies results

In the following, the results from the questionnaires and initial field study are reported. All analyses were conducted using R, SPSS, and Excel unless indicated otherwise. The questionnaire results are limited to which design was preferred by the participants per scenario. The complete results regarding the performance of each design within each individual condition from both online questionnaires are reported in the Supplementary Material. Due to the low N and procedural difficulties (explained in more detail below), the field study results are focused on the qualitative data.

4.3.1 Online questionnaire 1 results

The first online questionnaire was answered fully by 83 individuals (mean age 45 years (SD = 19.5): 52 men (62.7%) and 30 women (36.1%) (missing = 1). Almost all participants (97.6%, N = 81) stated that they had a driving license. About half of the respondents (53%) stated that they had never been traveling with a self-driving vehicle, while 47% had already experienced riding in one before (subways 51%, automated buses 19%, trains 15%, and cars 13%).

In general, the participants preferred the icon-based eHMI most frequently in all scenarios except for the regulated junction

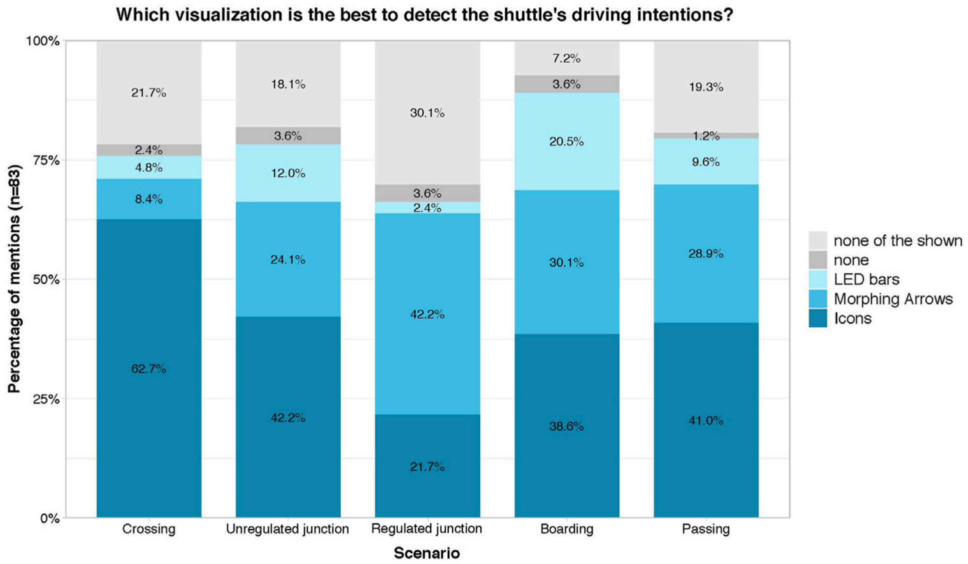

FIGURE 9
Preferred eHMI for detecting the shuttle's intentions.

scenario, (see Figure 9). At the same time, the respondents generally seemed to find an eHMI necessary in order to recognize and understand what the automated shuttle is about to do. The proportion of people who stated that they can best recognize the shuttle's intention without any design was very low in all scenarios (between 1.2% and 3.6%).

In the scenarios crossing, boarding, and passing, the icon design is chosen by about 40% of the people, followed by the arrows design with about 25–30%. The LED visualization is chosen significantly less often in all scenarios. Only in the boarding scenario is the proportion higher, at 20.5%. It is also noticeable that the distribution of the answers to the different eHMI designs is most balanced in this scenario. This is also consistent with the individual evaluations, in which the designs perform very similarly for boarding. At the same time, in this scenario only 7.2% of the respondents indicate, that they did not find any of the variants shown to be the best.

In contrast, in the regulated junction scenario, the proportion of those who are not satisfied with any of the variants shown is significantly higher (30.1%), and the highest compared to all other scenarios. In this scenario, the icon design is also chosen less often (21.7%) and the morphing arrows design is preferred more strongly instead (42.2%). One reason for this is that, in comparison, the arrows eHMI was rated more often to be rather comprehensible and immediately understandable for many people, while the icons eHMI was rated as unnecessarily complex and at the same time not very comprehensible. In general, however, none of the presented eHMI seemed to be able to convey an adequate sense of safety or a sufficient level of information of what the shuttle is up to in the regulated junction scenario. Ratings regarding these aspects are generally lower in this scenario.

Overall, participants preferred at least one of the eHMI designs over having none eHMI at all in each of the presented traffic scenarios. However, the results were inconclusive with respect to RQ1 and RQ2 (are eHMIs recognized by road users and do they communicate the intended content?) and also varied greatly depending on the individual eHMI and the respective traffic scenario. For the regulated junction scenario in particular, no eHMI was perceived as overly successful in communicating the intended information. Regarding RQ3 (Can the eHMI resolve ambiguous traffic situations?), the icons-based eHMI was received as most suitable, for all but one traffic scenario, the regulated junction, where the morphing arrows performed best.

Communication *via* the LED bars turned out to be surprisingly ineffective across all scenarios and resulted in it being the least preferred of the three designs. For the following implementation and field tests, a combined solution of improved icons- and arrow-based eHMI was decided as the most logical next step in the development process, with LEDs being excluded for the same reason.

4.3.2 Initial field trial results

A total of 14 participants participated in the field trial: four car drivers and ten pedestrians. Among the participants were nine men and five women. The two youngest subjects were two children aged nine, the oldest participant was 70 years old. The average age was 42. The majority (10 out of 14 people) had not had any experience with automated vehicles before.

Conducting the study was difficult due to a variety of factors, including highly volatile weather conditions during the testing period, presence of other lights and indicators on the shuttle that could not be deactivated (nor could the shuttle's signaling behavior be controlled directly) and issues with properly simulating the interaction on the test track due to the participants' often non-realistic interaction with the shuttle due to curiosity (reported separately in Mirnig et al., 2020).

Overall, according to the car drivers, the external communication means of the shuttle were well recognized. But this result has to be interpreted with caution, as it became apparent from the interviews that the participants most probably most of the time referred to the totality of external communication means including the shuttle's indicator and hazard warning lights and not only the displayed eHMI. The standard behavior of the shuttle during soft stops, which led by default to an activation of the hazard warning lights, contributed to participants' ambiguous perception of the communication means.

The crossing scenarios in which the bus was in motion were in most cases manageable without any further assistance by additional eHMI due to the study design and the low level of risk. Interestingly, however, the assessments of the predictability of the shuttle's behavior was rated very negatively. Therefore, a general need for further information but no communication success of the implemented designs can be deduced.

Only one person gave way to the bus in the T-junction scenario, although the car drivers would have been expected to let the shuttle enter the intersection first. It can be concluded that the information the eHMI provided was either not considered as relevant or was not even properly perceived to begin with. Countdowns half-pie + numbers and full pie turned out to be less understandable than numbers only, with the countdowns being, generally, not being perceived fully or just ignored.

For the pedestrian scenarios, however, the countdowns turned out to be more useful, as in all but the countdown conditions, the shuttle was not able to depart as scheduled or had to stop again after having already initiated the start-up. This was, also, due participants' curiosity and novelty effects, which obstructed compliant participant behavior (see Mirnig et al., 2020).

Also, in the boarding scenario, participants experienced some uncertainty with respect to getting on board in time. Although the eHMI designs were largely not perceived as superfluous, it was not possible to identify one design as clearly more successful and helpful than the others. An overall advantage of the different eHMI designs over the control condition was still noticeable, though, and, also, confirmed in the qualitative results.

Although the sample size was not sufficient for a meaningful quantitative data analysis, the interviews quickly revealed that, especially for the shuttle-to-vehicle interaction designs, a larger sample size would not have changed much, as the issues lay on a more fundamental level. Visibility of the eHMI was limited and would decrease as the vision angle increased. In addition, the reality of traffic interaction meant that the participants' gazes wandered constantly and did rarely remain on the displays for long enough to see the full animation, which was especially true for the countdown, circle, and bar animations. As a result, overall comprehensibility was low, regardless of how well the animations might have worked in isolation, as they were simply not seen in their entirety most of the time. The eHMIs fared better in the pedestrian interaction scenarios overall but the low number of participants still meant that validation from a quantitative standpoint was not possible.

Due to the high amount of effort required to conduct the study and the number of difficulties encountered, the field trial was ended prematurely after the 14 participants. Since the obtained results were primarily qualitative, it was decided to conduct the second online evaluation to provide the said quantitative validation.

4.3.3 Online questionnaire 2 results

A total of 112 completed responses were recorded. The youngest participant in the sample was 16, the oldest 82 years old (M = 44.37 years; SD = 21.11 years). The gender distribution was almost equal with 55 men and 56 women (one person preferred not to answer). A majority (73%) of the participants came from Austria, another 9% from Germany. The remaining mentions (with an N between 1 and max. 3) were from Belgium, Colombia, Denmark, Estonia, France, Latvia, the Netherlands, Norway, Portugal, Slovenia, Spain, and Sweden. Only 7 participants did not have a driving license at the time the study was conducted. 40% had prior experience with automated vehicles.

4.3.3.1 Pedestrian crossing scenarios

In the Crossing A scenario most participants chose the icon-based eHMI as their preferred design (see Figure 10). While the percentage of people who indicated that they could best discern the shuttle's intent without design was very low in both A and B, it was still higher than *Bar (in-out)* in Crossing A and higher than all three *Countdowns* in B. This means that none of these can be considered viable for either scenario. Both bars performed considerably better in B, with *Bar (in-out)* being rated highest of all visualizations, followed by *Icons*, then *Bar (out-in)*. Overall, *Icons* appear to be sufficient to communicate when the shuttle approaches (A) whereas *Bar (in-out)* is best suited for communicating the shuttles acceleration intention (B), although *Icons* would be decently to well-suited here as well. While it was not terribly high, the number of preferences for *none of the shown* suggest investigating further alternatives, especially for A.

For the boarding scenario (see Figure 11), *Countdown 2* (numbers+pie) turned out to be the most suitable one, followed by *Countdown 1* (numbers only). *Countdown 3* (full pie) was rated surprisingly low and *Icons* only slightly higher. Both *none* and *none of the shown* received very low ratings, confirming a

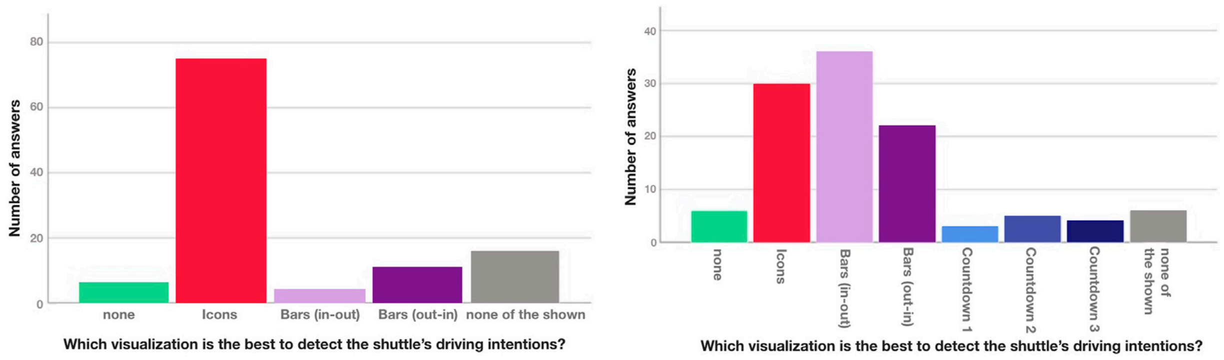

FIGURE 10
Preferred eHMI for detecting the shuttle's intentions at Crossing A and B.

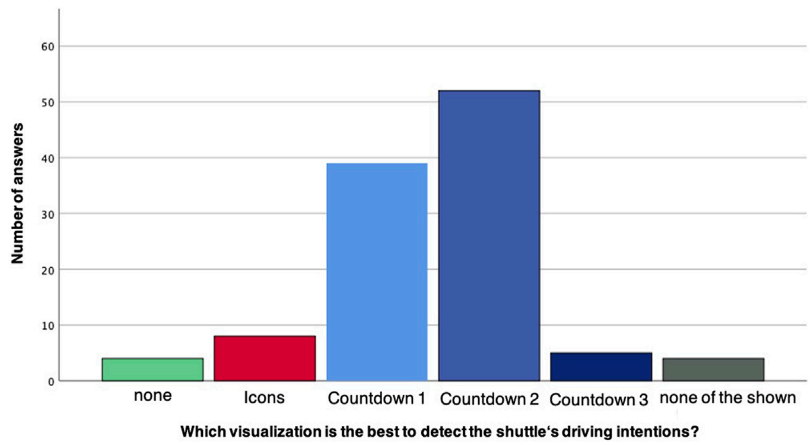

FIGURE 11
Preferred eHMI for detecting the shuttle's intentions during Boarding.

need for an eHMI for boarding and *Countdown 2* as a very viable solution.

4.3.3.2 Vehicle interaction scenarios

For both T-junction scenarios (see Figure 12), *Arrows* were the highest rated design and the low number of ratings for *none* shows that the participants did feel a need for additional visualizations. However, in both scenarios *none of the shown* was rated very high—almost as high as *Arrows* in A and the highest in B, implying that *Arrows* is far from being the best possible solution. For B in particular, it was assumed that countdowns might be preferred due to giving a clearer indication as to when the shuttle will depart but *Countdown 1–3* all performed worse than even *Arrows*, with 1 and 2 receiving decent ratings and three being rated particularly low.

The unregulated junctions were rated similarly (see Figure 13): While in A, the viewing angle (front) allowed use of the frontal display (*Bar out-in*), this condition was only rated slightly higher than *none*. *Arrows* was again the highest rated design, with *none of the shown being rated highest*, suggesting *Arrows* to be viable but not optimal. Unregulated junction B was almost identical to T-junction B: *Arrows* was the highest rated design, followed by *Countdown 1–2*, with *Countdown 3* and *none* being the lowest. *None of the shown* was again the highest rated option.

4.4 Results summary

The results showed a rather clear interaction path for the pedestrian scenarios: *Icons* work well for communicating the

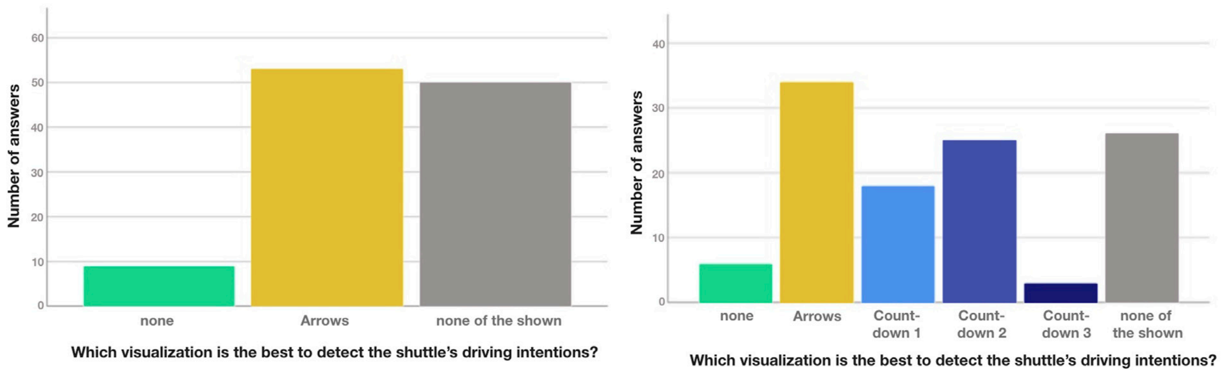

FIGURE 12
Preferred eHMI for detect shuttle's intentions at T-junction 1A and 1B

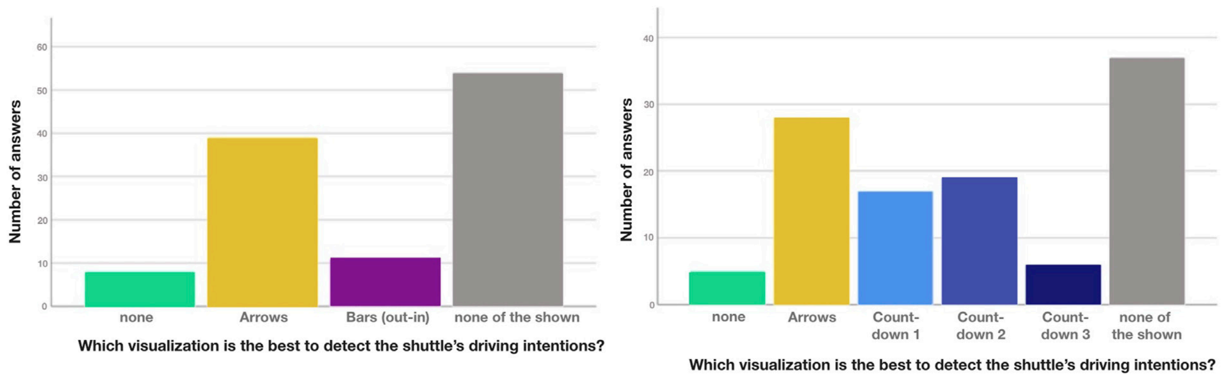

FIGURE 13
Preferred eHMI for detect shuttle's intentions at Unregulated junction 2A and 2B

shuttles intent when approaching a crossing and can also be used to communicate its intention to depart, with an animation that shows its intention to accelerate (*Bars in-out*) bringing additional benefit. For boarding, numeric countdowns seemed to work very well, with a visually supported numeric countdown (*Countdown 2*) being the most successful. Interestingly, the abstract countdown design *Countdown 3* (full pie) was rated very low, implying that any countdown design should always have a numerical component in order to be suitable for this scenario.

The vehicle interaction results were less positive regarding the eHMI designs. While the arrows were moderately successful, the high ratings for *none of the shown* across all four vehicle interaction scenarios shows that they might work but are not optimal. Since the participants who answered the questionnaire were not under the time constraints that the participants in the field study had been, it can be concluded that the chosen designs were generally not suitable and that a different approach to the external communication was needed.

The lessons learned during the field study and the questionnaire results pointed toward two main issues: length and visual complexity of the eHMI designs. A suitable eHMI for shuttle-to-vehicle communication would need to be visible in its entirety in as few glances as possible (ideally one) and easily comprehensible in order to not increase cognitive load. Thus, the decision was made to revisit the one-dimensional LED stripes from the first questionnaire study, despite their rather poor performance there. The low resolution and limitation to one dimension would prohibit complex designs and light signals would be easier to see from multiple angles. The original goal had been to realize a comprehensive eHMI with displays for pedestrian interaction and LEDs for vehicle interaction, but only the latter would be realized for the resulting main study for several reasons, primarily the COVID-19 pandemic, which caused few to no pedestrians being on the road during that time.

5 Main studies

In the following, the four main studies (MS1–4) from the participating projects are reported. MS1 (conducted in late 2020 and early 2021) was a direct follow-up from the preparatory studies and investigated eHMI designs for resolving encounters with other vehicles in a joint study between *Digibus® Austria* and *auto.bus Seestadt*. MS2 (2020) investigated an eHMI for bicycle overtaking (very similar to the initial *passing*-scenario) in a field as part of the *Drive2theFuture* project. MS3 (2021) investigated passenger docking (entering and exiting the shuttle) scenarios *via* VR co-simulation and was also part of *Drive2theFuture*. Since the designs used LEDs, these well supplemented the ones used in MS1. MS4, a field study from *auto.bus Seestadt* also conducted in 2021, finally adds insights on docking and passenger turnover with eHMIs on not only the shuttle but the station and a wearable as well, thus rounding off the studies both from a methodical and an interface perspective.

5.1 Salzburg and Vienna, Austria—Shuttle2vehicle communication (MS1)

The field study that directly followed the preparatory studies, focused primarily on interactions with other road users in situations with crossing trajectories (intersections). This decision was made because the performance within these situations using the previously proposed indicators had still been the most unclear in the preceding questionnaire studies. At the same time, a focus on interaction with motorized road users was also considered to investigate a more unique aspect of eHMI-based communication, as opposed to, for example, boarding situations. At the time of the field study (Nov–December 2020, February 2021), the COVID-19 pandemic was at a high with even a soft lockdown being in effect during (the study days in 2020). This resulted in the scope having to be trimmed down further to only investigated encounters with motorized road users, as the number of pedestrians or cyclists on the road during that period was minimal. The results from the field study were published in Mirnig et al. (2021). In this study, we briefly outline the setup and highlight the most relevant results. For the full study report, please refer to the original publication.

Two designs were realized for this field trial, both *via* a front-mounted LED strip below the windshield, spanning the entire front of the shuttle and bending across to cover the areas front-right and front-left as well, so that the visualizations could be seen even when not being directly in front of the vehicle. The first design *RG* (Red-Green) used a simple traffic light metaphor to signal that the shuttle would either decelerate with the intention to yield (green) or accelerate with the intention to take precedence (red). The second design, *AN* (Animation) communicated the same information but used animations of the LED-bar filling (shuttle accelerates) or emptying (shuttle decelerates) in a neutral light blue color instead. See also Figure 14 for an overview of the conditions.

The study was conducted as a joint study between *Digibus® Austria*, *Drive2TheFuture* and *auto.bus Seestadt*. Each project equipped one shuttle with a frontal light band eHMI and deployed it with both conditions (plus a control condition, where the strip was off) on their respective public testing environment (the rural town Koppl bei Salzburg and urban environment Seestadt Aspern in Vienna). See Figure 15 for an example of the Shuttle on the track in Vienna during a drive in the RG condition. Both tracks featured a number of intersections with potentials for crossing vehicle trajectories. The data collection was performed *via* observation and logging, whether conflicts occurred and how situations where the shuttle encountered other vehicles were resolved. For each possible interaction (crossing other vehicles at intersections or joining roads) success and failure conditions were defined [who yields to whom, does an initiated maneuver have to be interrupted (e.g., sudden braking), etc.]. The conditions were then compared by the numbers of successes and failures across all situations.

The results showed an overall success of the eHMIs. There was an assumption that especially *RG* could be confusing, since the traffic lights could be understood in the standard sense (red: other vehicles need to stop) or in relation to the vehicle (red: shuttle stops, other vehicles can go). This assumption was not confirmed, however, as there were no significantly increased communication failure rates by *RG*. However, while both *RG* and *AN* performed well overall, the success rate was very high in general, even in the control condition, so while the benefit of an additional eHMI was there, the degree of success is limited in as far as the shuttle was able to navigate through traffic without the eHMI and the eHMI simply improved by further reducing the number of conflicts. There were also few differences in performance between *RG* and *AN*, which suggested an attention-drawing eHMI on the front of the shuttle being there to be the most important aspect, and the actual design of it being secondary.

5.2 Oslo, Norway—eHMI for close and risky overtaking situations (MS2)

Overtaking is a frequently encountered situation with a lot of potential risks associated with it. From a video observation study conducted in Oslo, close and risky overtaking had been identified

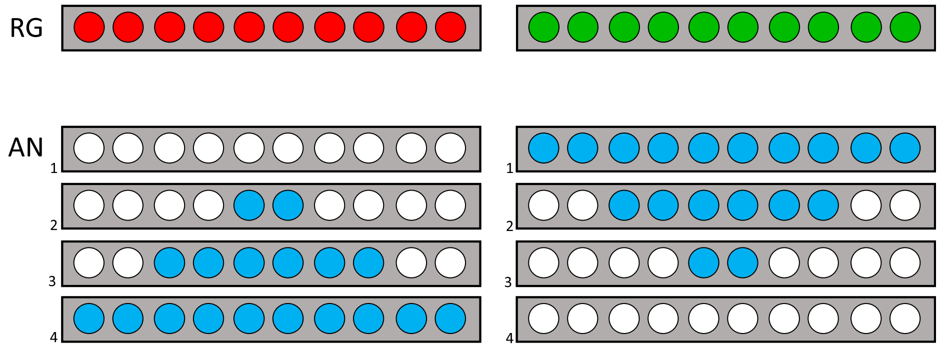

FIGURE 14
Overview of the two conditions Red-Green (RG) and Animation (AN).

FIGURE 15
Front-mounted LED on the Navya Arma on close-up (left) and while the shuttle is circulating on the Vienna track (right).

as one of the most critical scenarios for automated shuttles in mixed traffic Pokorny et al. (2021). Due to the shuttles' defensive driving style, other road users often decide to overtake the shuttle, even on locations where overtaking is not allowed or under risky circumstances (e.g., oncoming traffic or a limited sight distance). Furthermore, in many of these overtaking maneuvers, the drivers do not keep sufficient distance from the shuttle and finish the overtaking maneuver too close in front of the shuttle. This overtaking behavior can have negative safety consequences, such as abrupt stops of the shuttle when the overtaking road user enters the shuttle's safety zone or other traffic participants being endangered by the overtaking vehicle.

To mitigate these negative effects, an eHMI was designed specifically to affect the overtaking behavior of other road users in one of the trial projects in the Oslo region, on Ormøya island. Several shuttles (Navya Arma) were operated in 2020 on a 1.3 km long route in suburban neighborhood in mixed traffic, on a narrow curvy public road with a speed limit of 30 km/h. The shuttle had originally displayed the text message "Be careful when overtaking!" on a back display (see Figure 16).

On the basis of the results from the observations, the goal was to strengthen the message with use of an additional eHMI sign and evaluate its effect. The eHMI was conceived at TØI[1] *via* brainstorming sessions involving several researchers from associated domains (such as traffic psychologists and road safety experts) in order to find out how to convey the message to drivers that they should 1) take care during overtaking and 2) not come too close to the shuttle when overtaking. A decision was made to combine a textual message with a graphic illustration, resulting in a first draft of the eHMI sign. The draft was then iterated with a professional designer from the Oslo public transport provider RUTER who then prepared several design alternatives. The final design (see

1 https://www.toi.no/

FIGURE 16
One of the shuttles that roamed Oslo showing the overtaking eHMI.

Figure 16) was selected jointly by the expert panel and the graphic designer. It was then implemented in the shuttle display.

5.2.1 Method

The shuttles drove a total of 1357,4 km over the evaluation period, 269,3 km of which with the eHMI active. In order to assess the eHMIs performance, event data was extracted from the shuttles' autogenerated logs and roadside interviews were conducted with bystanders. In this publication, the focus will be on the roadside interviews and selected log data related to the shuttle's detection and braking behavior.

The roadside interviews were conducted as a small scale survey with $n = 28$ respondents.In order to explore whether traffic participants in the area had noticed the eHMI sign and comprehended its meaning, the survey was carried out in December 2020, when the eHMI sign in the shuttle had then been operational for about 1 month. The interviews took place along the shuttles' route, with people walking along the route or having just parked their car at a parking lot near the beginning of the route. All respondents signed for their consent. The interviewer asked the following questions:

- How often are you in this area?
- Do you have a driving license?
- Are you aware that the automated shuttle drives here?
- Have you ever used the shuttle as a passenger?
- Have you ever overtaken the shuttle (as a driver or a cyclist)?
- If yes, under what circumstances?
- Did the bus somehow react to being overtaken by you?
- Do you know the meaning of this sign?
- What do you think that this sign means?

The interview protocol was setup as an online questionnaire (using QuenchTec software) and the answers were entered with a notebook by the interviewer.

5.2.2 Results

Table 1 shows the sums of events (strong and severe braking, obstacles detected) identified from log data, their frequencies per km driven and the mean frequency of all events per km driven for the eHMI and control conditions. The frequencies per km are provided since the distances traveled by the shuttles was not identical for both conditions (269.3 with the eHMI, 326.3 without).

Looking at the individual type of events, there is an evident decrease in frequencies of *strong braking* and an increase of *obstacles detected* in the eHMI condition. For the shuttles without the eHMI sign, the tendency is the opposite in the after period (an increase in *strong braking* and a decrease in *obstacles detected*). As the sum of *strong braking* and *obstacles detected* events is almost similar for shuttles with and without the eHMI sign (494 and 519), we might assume that the number of drivers overtaking the shuttles with and without eHMI sign was about the same. However, their overtaking behavior might have differed, because the reactions to the shuttles differed: If those who were overtaking the shuttles with eHMI finished the overtaking maneuver further in front of the shuttle (an

TABLE 1 Events recorded in the shuttle log across both eHMI and control conditions.

Condition	Event	Sum	Frequency (per km)	Mean frequency
eHMI	Strong braking	232	0.86	0.70
	Severe braking	75	0.28	
	Obstacles detected	262	0.97	
Control	Strong braking	391	1.20	0.61
	Severe braking	77	0.24	
	Obstacles detected	127	0.39	

intended consequence of the design), they would more often just be registered as *obstacles detected*, while those who were overtaking the shuttles without eHMI sign would finished the overtaking closer in front of the bus, which led to more frequent instances of *strong braking*.

Results from the interviews show that the vast majority of respondents were familiar with the Ormøya area as they indicated to be there every day (n = 24, 86%), they were familiar with the shuttle (n = 26, 93%), and had a driver license (n = 25, 89%). More than a third (n = 10, 36%) had been a passenger on the shuttle. Most respondents reported that they had overtaken the shuttle after driving behind it as a car driver (n = 23, 82%), and one had overtaken the shuttle as a cyclist.

When asked in what situation they had driven/cycled behind the shuttle, 21% (n = 5) answered that this was while the shuttle was standing still at the stop, 16% (n = 4) while the shuttle was driving, and 63% (n = 15) in both situations. In most cases the shuttle did not react in any special way when they drove/cycled past it (n = 14, 74%). A few respondents answered that the shuttle stopped (n = 4, 21%) or braked (n = 1, 5%) when they drove or cycled past it.

Most road users recognized the sign and reported to understand its meaning. When asked "Do you understand what this sign means?", 82% (n = 23) understood the meaning of the sign, while 11% (n = 2) did not. Two respondents were indecisive. Furthermore, respondents were asked to describe in an open text format how they interpret the sign, or what they think when they see it. A variety of answers were provided, and it appears that they generally do not describe the exact message that was meant to be communicated. Most of the respondents did not directly provide an explanation of what the sign means. This might be due to only five of the respondents experiencing the shuttle changing its behavior (braking or stopping) as a cause of the overtaking maneuver.

Most respondents mentioned more general observations and opinions they associate with the sign. These indicate that the respondents are generally familiar with the fact that it is challenging to overtake the shuttle on this particular narrow road. They mentioned that the shuttle drives slowly, is difficult to overtake, that it is difficult to plan to overtake, and there is often a queue behind the shuttle ("it is difficult to get past the shuttle and it is slow"). A few mentioned that it is "annoying" or "irritating" that the shuttle drives so slow, particularly when there is a heavy vehicle on the route as well, whereas others mention the shuttle is "sweet", "good for old people", and that it is "nice and good".

5.2.3 Summary

Due to the various methodological challenges (e.g. different seasons in before and after periods, lack of good experimental control, the exact reasons for the events identified from log data are unknown, small sample size in the survey) it is difficult to make statistically solid conclusions regarding the effects of the eHMI sign. Therefore, the results should be interpreted with the utmost care. Analysis of log files indicate a positive effect of the eHMI sign on overtaking behavior. From comparison of log data, we see that the frequency of *strong braking* decreased and number of *obstacles detected* (without braking) events increased in the eHMI condition, while opposite trend was found for the shuttles without the sign. This may mean that the drivers overtook the shuttles with the sign more carefully and were just detected as an obstacle, not causing strong braking. The roadside survey shows that the respondents are familiar with the fact that it is challenging to overtake the shuttle on this particular narrow road. Most of respondents believed to understand the message displayed on eHMI sign, however they generally do not describe the exact message that was meant to communicate.

5.3 Linköping, Sweden—automated docking co-simulation (MS3)

A study in Linköping, Sweden, investigated the passengers' experience with automated docking. If buses with automated docking functions are introduced in regular public transport in mixed traffic, there is likely a need for vulnerable road users (VRU) in the surrounding to be informed whether an approaching bus is automated or driven manually. The study,

FIGURE 17
Bus with eHMI active viewed from the outside.

therefore, perfectly supplemented the previously described efforts as well as the same requirements that had been identified in the Digibus project, where there had only been a partially implemented solution (visuals in the doors) and limited validation.

The aim of the study was to develop and evaluate a co-simulation platform where the interaction between automated buses and VRUs could be evaluated. A second aim was to test alternative internal and vehicle-external HMI options for the vehicle–passenger and driver–vehicle interaction at bus transit points in simulated environments. In this study, the results regarding the second aim are reported. The eHMI used consisted of blue lights mounted along the windshield and steering wheel (see Figure 17) for a picture of the actual bus with the eHMI active. A more detailed description of the methods and results can be found in Sjörs Dahlman et al. (2022).

5.3.1 Method

For safety reasons, the interactions between the automated bus and VRUs was evaluated using virtual reality (VR). The specific scenario was a VR/VR co-simulation of an automated docking at a bus stop from both the passengers' and bus driver's perspective. The simulation was done using two VR-headsets from HTC; one HTC tobii and one HTC VIVE and each headset had two motion controllers. Both passengers and busdrivers wore headphones to simulate the sound from the bus.

Three different HMI concepts were tested, system A, B, and C (see Figure 18), with different solutions for communicating information about automation status to the driver and VRUs. System A provided the information by illuminating light strips around the windshield and on the steering wheel. The lights on the steering wheel could not be seen by VRUs outside the bus. Blue lights indicated that the bus was in automated mode and amber lights were used for the handover between manual and automated mode. System B had only the lights on the steering wheel that could not be seen outside the bus and thus looked like a regular bus from the passengers' perspective. System C had the same features as system A but it also played a bell sound, when the bus approached the bus stop. The sound could be heard outside the bus and the frequency increased as it came closer to the bus stop. The sound was not played inside the bus. Thus, system A and C were the same from the bus drivers' perspective.

Five bus drivers (one female and four male) and 15 passengers (seven female and eight male) participated in the trial. The age of the passengers ranged from 18 to 60 years and most of them (11 out of 15) were younger than 35 years old. The bus drivers were between 45–60 years old and had at least 2 years of experience in driving buses. The recruitment was done as a convenience sampling of people working or studying at the Linköping University campus area.

For most of the trials, one passenger and one bus driver performed the simulated docking scenarios at the same time as a co-simulation. Since there were fewer bus drivers than passengers, the test leader controlled the bus and acted as a bus driver for some of the passengers. The task for the bus drivers was to drive the bus (manually) between each stop, to hand over the control to the bus when approaching the bus stop, to take back control from the bus after the stop, and to open and close the doors. The passengers' task was to wait for the bus at each stop and get on the bus and take a seat. Each HMI solution was tested three times, resulting in a total of nine docking scenarios.

The participants' opinions about the automated docking and the different HMIs were investigated using questionnaires and interviews. The questionnaire included background questions, specific HMI related questions and instruments for measuring trust, acceptance, and usability. The chosen instruments were the Technology Acceptance Questionnaire (TAQ, Van Der Laan et al., 1997), the System Usability Scale (SUS, Brooke, 1996), the User Experience Questionnaire (UEQ, Schrepp et al., 2017), and the SHAPE Automation Trust Index (SATI, Dehn, 2008). The participants answered all questionnaires three times, once for each system. An interview was performed in the end of the test capture the participants' opinions about the sound in system C and the light in the windshield and on the steering wheel. They were also asked about any suggestions to improve the HMI systems.

The study was planned and conducted according to the Drive2theFuture project's ethical guidelines. Informed consent was collected from all participants. Since the study was conducted during the COVID-19 pandemic, specific routines to minimize risk of spreading COVID-19 were taken. The questionnaire data were analyzed descriptively and compared between systems using SPSS.

5.3.2 Results

5.3.2.1 Questionnaires

Figure 19 shows that most participants had a positive opinion about system A whereas the overall view of system B was neutral.

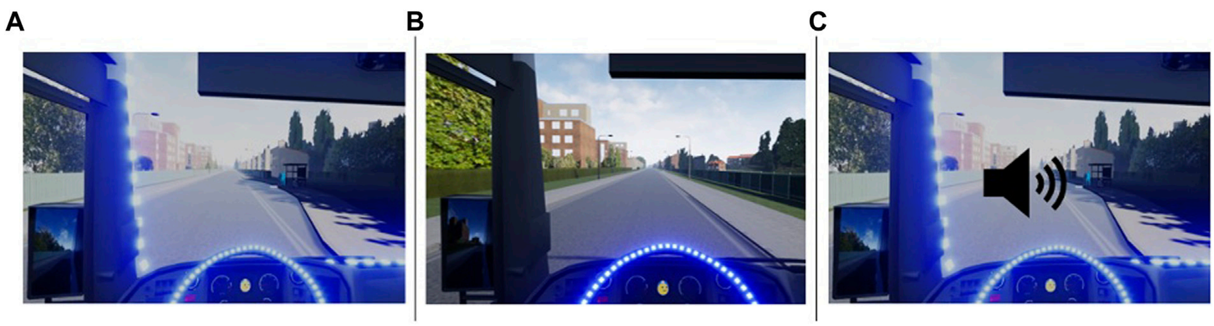

FIGURE 18
Three eHMI conditions viewed from the inside of the bus: steering wheel and windshield **(A)**; steering wheel only **(B)**; steering wheel, windshield, and sound cue **(C)**.

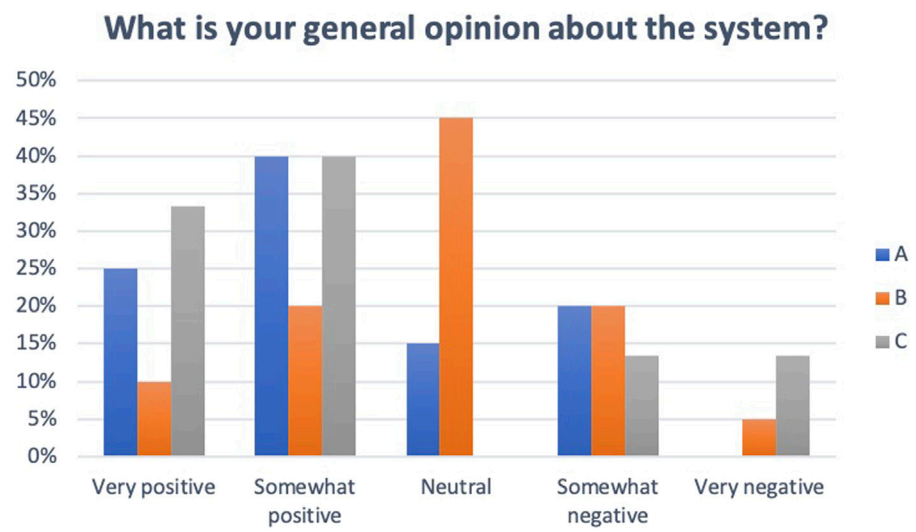

FIGURE 19
Participants' general opinion about the eHMI systems.

System C had more positive than negative ratings, but two individuals rated the system as very negative, indicating that system A had a better overall rating.

System C had the highest usefulness scores on the TAQ. The three systems had similar satisfying scores. Usefulness scores were 0.79 (SD 0.79) for system A, −0.05 (SD 1.12) for system B, and 1.30 (SD 0.74) for system C. Satisfying scores were 0.28 (SD 0.38) for system A, 0.26 (SD 0.35) for system B, and 0.22 (SD 0.74) for system C. System A and C had better SUS ratings on most items but system C was rated as unnecessarily complex by a few participants. The SUS score was 81.4 (SD 15.1) for system A, 77.0 (SD 16.5) for system B, and 82.5 (SD 14.0) for system C. The overall SATI trust scores were: A = 4.9 (SD 0.9), B = 4.1 (SD 1.5), and C = 5.1 (SD 0.8). The user experiences as measured by the UEQ were quite similar for systems A and C whereas system B was rated as less efficient, stimulating and novel (see Figure 20).

Specific questions regarding the participants' opinion about the three HMI systems revealed that system C was perceived as most safe and secure, and it was preferred by most participants (see Figure 21).

Perceived security for travelers inside the bus and people outside the bus was also rated by the participants (see Figure 22). System C was perceived as the best system regarding security for those outside the bus.

5.3.2.2 Interviews

The passengers expressed that it was important to them to be informed that the bus was automated and most of them

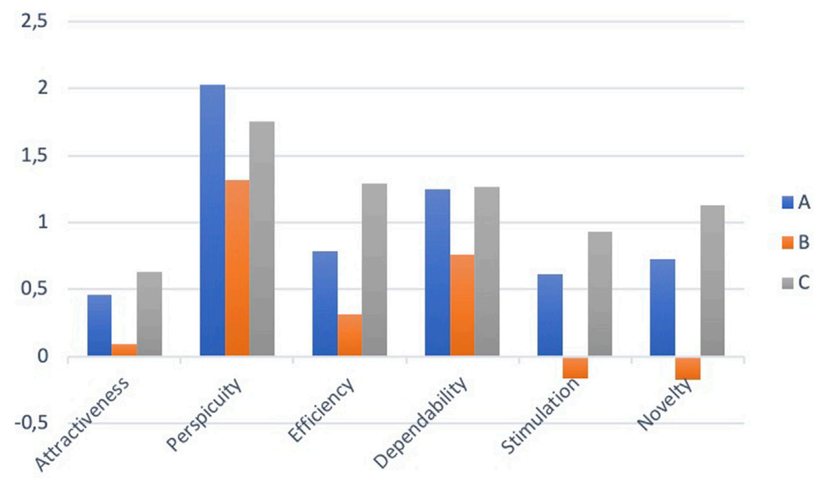

FIGURE 20
Subscale scores of the UEQ.

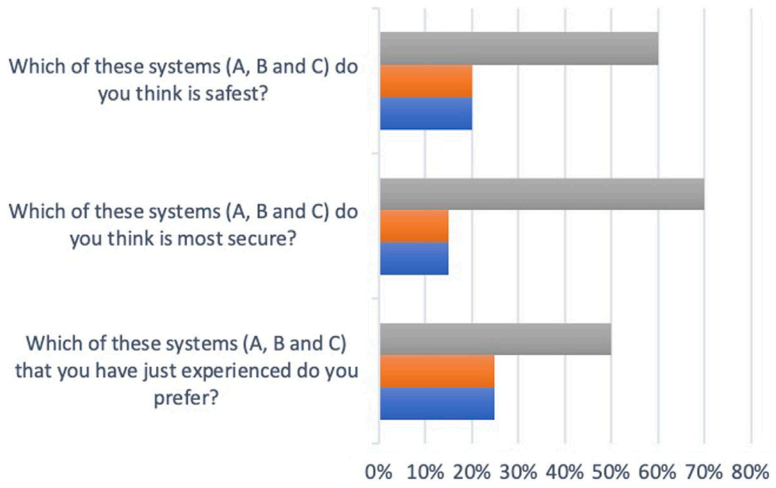

FIGURE 21
Perceived safety, security, and preference of the three HMI systems.

thought it should be visible on the bus. The perception of the sound was both positive and negative. The bus drivers expressed that they did not want to be disturbed by any sound. The perception of the light was mostly positive. The participants thought that the purpose of the light and sound was somewhat unclear. They expressed a need for an explanation about the purpose of the light and sound and about the meaning of the different colors. Most passengers did not change their behavior depending on the HMI but some passengers felt more attentive because they did not fully trust the autonomous bus. Suggestions of how to improve the HMI included making the light stronger or making the eHMI more dynamic to communicate if the VRUs were too close to the bus. There were also suggestions to include information about automation status at the bus stop.

5.3.3 Conclusion

The results of the HMI evaluation showed that system C (sound and lights in the windshield and on the steering wheel) and system A (lights in the windshield and on the steering wheel) were rated as more useful than system B (light on steering wheel only) on the TAQ. System C was also rated with highest scores on the SUS and

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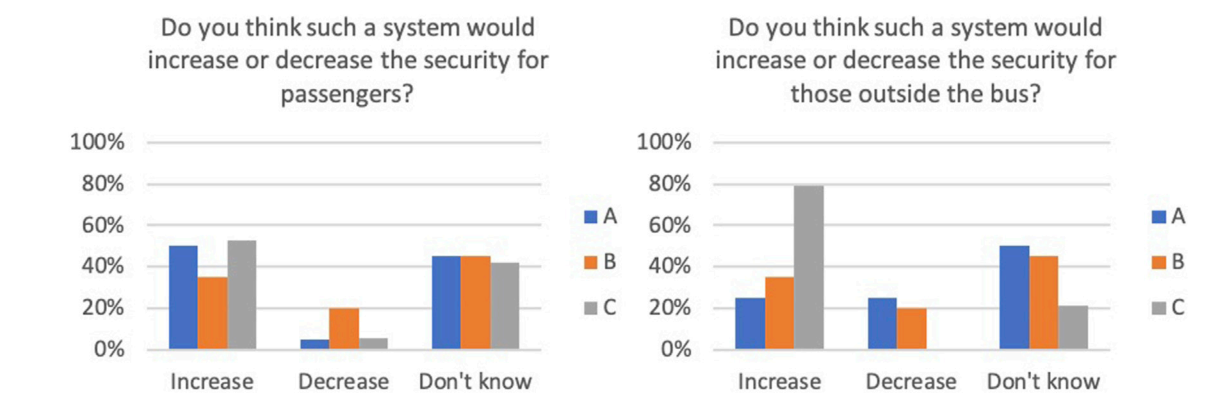

FIGURE 22
Perceived security outside the bus.

SATI. However, when it came to the general opinion about the system there were no major differences between A and C. From the interviews it was evident that passengers prefer to know if the bus is in automated mode or not when it approaches. The participants expressed a need for instructions or training on what the different components of the HMI are intended to communicate.

5.4 Vienna, Austria—eHMI location and modality during passenger changeover (MS4)

Managing passenger turnover through eHMIs was also investigated in an experiment of the auto.Bus—Seestadt. The focus was on two eHMI application scenarios of passenger turnover situations: information on that the bus is about to start (start announcement), and an indication when too many passengers are in the bus (capacity limit). The questions were as follows:

- Which modalities of presentation are conceived as supportive by passengers (audio, animation, screen with icon and text)?
- Where should eHMI be located (on the shuttle, at the station, or on a wearable, such as a smartwatch)
- Do preferences about eHMI presentation modality and location differ between usage scenarios, namely start announcement vs. capacity limit?

5.4.1 Method

To investigate the questions mentioned above, an experimental study with an automated shuttle in a protected area for intent communication displays was conducted. 31 participants, with a mean age of 45 years (from 25 to 66 years) and a balanced gender distribution (16 male, 15 female) were invited to the study. There were two experimental factors: eHMI location (on the bus, at the station, on the wearable), presentation modality (information screen, animation, audio) and an intermittent variable representing the two above mentioned passenger changeover scenarios. The combination of these three factors resulted in 9 different experimental conditions. Figure 23 shows the prototype realizations of these nine combinations. The test prototypes were operated using a Wizard of Oz setup.

Participants were welcomed and briefed about the study. They were then confronted with the nine test situations, each of which consisted of a combination of one presentation type and one presentation modality. In the test situations, participants waited for the shuttle arriving at the station, then entered the shuttle, sat down, rode to the next test station, and stepped out of the shuttle. During this process, they were exposed to the eHMI communication of the two scenarios (start announcement and capacity limit). After having experienced all of these situations, they were asked to fill in a survey in which they indicated which of the combinations they would like to be implemented for realizing the two scenarios.

5.4.2 Results

In general, for both investigated scenarios—the countdown information when waiting for the start of the bus and the indication on an overfilled bus—would benefit from eHMIs. However, as Figure 24 indicates, there were different patterns of preference, across the investigated factors. Providing the information on wearables was least preferred, especially when communicated through animations or audio. eHMIs mounted on the shuttle itself was most preferred, but not when provided through dynamic animations. Presenting information at the bus station was only wished when provided by a screen, especially when information on entering the bus was to be communicated. In general, animations were least preferred, screens with text and iconic information were

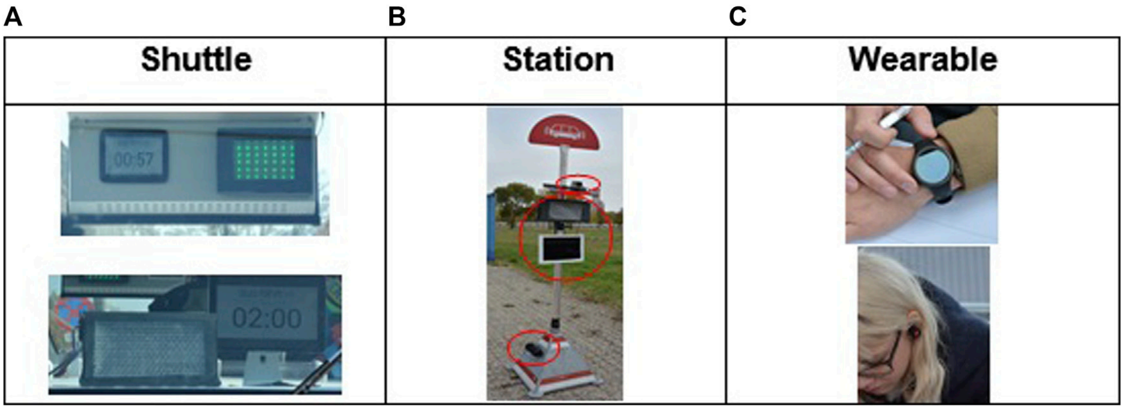

FIGURE 23
(A) Locations of screen and animations (LED array) on the bus interior facing inwards (picture at the top) and behind the windscreen facing outwards (bottom); the loudspeaker was mounted below the seats; **(B)**: locations of color animation (LED display at the top), screen (tablet in the middle), and loudspeaker (bottom); **(C)**: wearable (smartwatch) at the wrist (top) and bluetooth earplugs (bottom).

Presentation modality	Use Case	Presentation Location: Shuttle	Station	Wearable
Screen	Start Announcement	87%	97%	55%
	Capacity Limit	77%	68%	42%
Animation	Start Announcement	35%	29%	3%
	Capacity Limit	29%	32%	16%
Audio	Start Announcement	77%	26%	6%
	Capacity Limit	90%	42%	3%

FIGURE 24
Preference for each combination of modality and location in each of the two investigated scenarios. The percentages are the ratios of participants's answers whether or not they would like to see the eHMI variant in the respective scenario.

the most preferred display for the station and the wearable. For eHMIs mounted on the bus, audio and screen were similarly high. Presenting audio for indicating an overfilled bus received the highest preference among all combinations.

6 Discussion

In the following, we discuss a number of salient points that arose across the reported studies.

6.1 The right eHMI for the right situation

The situations where an eHMI can assist an automated shuttles' interaction are manifold, involving different stakeholders and other contextual variables. One main distinguishing characteristic is the recipient of information. Here, a difference in available time budget and resulting suitability of different eHMIs could be seen especially in regard to pedestrians vs. motorized road users: Pedestrians generally have a larger time budget available. As a result, more complex visualizations, including verbal information and extended animations, can be both useful and appropriate.

Conversely, for motorized road users, the shuttle is typically only one of many other external factors that a driver has to pay attention to. The time budget is very limited as a consequence and any driver's gaze cannot be expected to remain on the shuttle for long. Therefore, shorter, non-verbal cues are more appropriate here with visibility/noticeability having priority over richness of communicated content.

Despite contrary initial results in the preparatory studies, one-dimensional LEDs proved moderately effective for both shuttle-to-vehicle interaction (MS1) as well as shuttle-to-pedestrian (MS2) interaction. The most likely explanation for this are the contextual influences of weather and resulting different light conditions as well as the many different angles of approach of the other road users. A well-designed display that can't be seen or fully comprehended under most circumstances is ultimately less useful than a simple interface that is visible. When the circumstances can be controlled, such as when the message is always targeted in a specific direction (behind or in front on the same lane, or at the doors at the bus stop), then a high-resolution display containing even verbal information can be effective, as MS3 showed. Thus, the less controlled the interaction in terms of communication is, the simpler the eHMI cue has to be.

Finally, the shuttle's communication need not only encompass eHMIs on the shuttle (MS4). Pedestrians waiting at a bus stop do not necessarily need to wait for the shuttle to arrive in order to receive boarding-relevant information, reducing the need for additional on-shuttle eHMIs and resulting potential clutter or interference with other indicators. While the potential to use such solutions also for shuttle-to-vehicle-communication is limited, integration with traffic lights (both for pedestrian as well as vehicle crossings) is a possibility, provided the shuttle is connected to the infrastructure. Beyond that, wearables, while unlikely to be able to serve as a replacement, can provide additional assurance. For vehicle interaction, additional information could also be part of the vehicle's UI, although that would, once again, require the shuttle to be connected.

6.2 Subjective preferences vs. objective effects

A view on the results across all studies revealed a difference between the perceived subjective preferences and the objective effects of having an AV equipped with an eHMI. As suggested in the literature (Löcken et al. (2019); Kaleefathullah et al. (2020); Kooijman et al. (2019); Velasco et al. (2019); De Clercq et al. (2019); Rettenmaier et al. (2020); Faas et al. (2021)), eHMIs could be confirmed to often have positive effects on users' interactions with AV when it came to subjective ratings. There, differences to interaction without an eHMI were clearly visible with a considerable difference between control and eHMI conditions.

The objective assessments, on the other hand, showed more modest differences in performance. The video observations conducted in Oslo (MS3) did not show decisive results regarding a possible safety increase when the eHMI was active. Similarly, the field tests in Austria (MS1) showed rather modest performance increases of the eHMI over the control condition. The reasons for this discrepancy between subjective and objective results are difficult to identify, since there were several factors that influenced the field assessments: Different weather conditions meant different visibility conditions across assessments. In addition, while the interactions to be observed were pre-defined (overtaking in Oslo, intersections and crossings in Austria), the vehicle speeds, angles of approach, and distances between shuttle and other vehicles were varied, leading to further heterogeneity within the interaction scenarios, even when conceptually similar.

A further aspect to be considered is that, by necessity, the baseline safety across all conditions has to be high for a shuttle to be able to be deployed in public traffic (including but not limited to the shuttles driving at very low speeds). Since the eHMIs are primarily supposed to address safety concerns, any possible performance increases can only occur on the upper spectrum of making a sufficiently safe interaction potentially even safer. Still, without a clear indication of the exact source of the discrepancies, these results would support the position that implicit communication *via* the vehicle's behavior is a stronger influencing factor on safe interaction than the presence of any additional eHMIs (see Löcken et al., 2019; Kaleefathullah et al., 2020; Kooijman et al., 2019; Velasco et al., 2019; De Clercq et al., 2019; Rettenmaier et al., 2020; Faas et al., 2021; Moore et al., 2019).

6.3 Lab vs. field and the limits of both

Due to the lack of ecological validity, studies in virtual or online contexts are only partially suitable for evaluating the usability of eHMI in its entirety. While individual aspects such as colors or positioning can be tested, the experience of actual traffic situations is only possible to a limited extent, and insights gained may not prove reproducible in a real-world context. This is not a novelty in any way and part of standard scientific knowledge, which is why validation is usually eventually sought in field tests after initial laboratory or otherwise simulated settings.

What makes this a point particular to studying interactions with AV are the necessary constraints of any field trial involving them. As mentioned in the previous section, the interaction cannot be dangerous for the participants in any realistic degree or the study must not be conducted. By necessity, some aspects then have to be simulated even within the field setting or contextual variables have to be modified to reduce the risk level appropriately (e.g., driving at very low speeds). This generally limits the ecological validity of the results obtained, as the solutions are intended for a different (higher risk) context than they are evaluated in.

Also, adapting to a study context requires a cognitive effort on the part of the participants, which can be more or less challenging depending on the study setup. While VR technology offers the possibility to move safely in space and to interact with vehicles and traffic situations more realistically than is possible in an online questionnaire, the cognitive effort to familiarize oneself with the technology, operation, and aesthetics of the world is significantly higher. Symptoms of nausea and dizziness may occur. Field studies or online surveys, on the other hand, require less adaptation effort from the participants. Online assessments, however, do not achieve nearly as good a degree of realism or as high a level of involvement, while, as mentioned, in field studies certain situations cannot be reproduced due to safety aspects.

Thus, while it is difficult to prescribe an exact recipe here, we do conclude from the learnings across all studies that for a safety-relevant technology such as AV, simulations and controlled laboratory results can and should play a role to supplement field trials even within the final phases of validation.

7 Conclusion

In this study, we presented eHMI solutions and evaluation study results from three collaborating research projects in Europe: The Austrian flagship projects *Digibus® Austria* and *auto.bus Seestadt*, as well as the European Horizon 2020 project *Drive2theFuture*.

The preparatory activities opened a wide spectrum of critical interaction scenarios, ranging from pedestrian crossings, which are well-covered by existing approaches, to intersections with other road users, boarding and docking operations, as well as dangerous passing and overtaking situations, all of which are less covered by existing approaches.

Across all activities we found a difference between subjective and objective performance of eHMIs, where the subjective gain would be higher than the objective one regarding safety. This is due the situations being already rather safe than unsafe but also the constraints of the field context, where risks must be minimized as part of the study preparation, so any safety gain can only occur in the upper spectrum.

The discrepancy was also found in terms of simulated vs. field performance, where animations and verbal information, especially for shuttle-to-vehicle-communication, did not perform as well in the field due to contextual influences. Overall, simple light-based indicators were found useful both for crossing situations with motorized road users and docking operations (pedestrian/passenger communication) due to good visibility under multiple angles and weather conditions and the required information density being rather low in these circumstances. Dangerous overtaking—and by extension other interaction situations where the angle of approach and viewing the eHMI can be controlled—can be addressed *via* more high-resolution information, including verbal content. Finally, interaction at the bus stop, especially regarding itinerary and capacity management, need not be limited to eHMIs on the shuttle only, with smart station displays or even wearables sensibly extending both the physical and temporal reach of the shuttle.

Data availability statement

The datasets presented in this article are not readily available because sharing of datasets requires agreement of the respective consortia, which needs to be negotiated with the respective contributing authors. These decisions can be mediated but not fully made by the corresponding author alone. Requests to access the datasets should be directed to alexander.mirnig@plus.ac.at.

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. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

AM was the primary author, coordinated and edited all inputs, wrote the introduction, discussion, and conclusion sections, and supported the writing of the preparatory studies and main study 1. MG and VW mainly contributed the sections on preparatory studies and main study 1. PF contributed main study 4 and assisted with related work and discussion. AD and AA contributed main study 3. PP, MH, TB, and OA contributed main study 2. CD assisted with related work and preparatory studies; JS assisted with preparatory studies.

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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.

Publisher's note

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