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# Deliverable 2.5

## *Design strategies and prototype HMI designs for cyclists, pedestrians, and (non-automated) cars*

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**List of Associated Partners**

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| Asymptotic AI | https://www.asymptotic.ai |
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Note 1: The term Early-Stage Researcher (ESR) is used extensively in this document. The ESRs are PhD candidates funded by the SHAPE-IT project.

Note 2: This document has been submitted to the EC for acceptance as a deliverable in the SHAPE-IT project. If changes are requested by the EC, the document will be updated.

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# Executive Summary

This work provides a summary of work within the project SHAPE-IT (Supporting the interaction of Humans and Automated vehicles: Preparing for the Environment of Tomorrow) concerning HMI design for pedestrians, cyclists, and to some extent car drivers.

We present the lessons learned from doctoral candidates (ESRs) who were involved with HMI design using augmented reality and connectivity. The lessons learned, which are discussed in this work, relate to if and how human-machine-interface (HMI) information should be presented to end users.

The underlying philosophy is that through augmented reality (AR) and connectivity, virtual information in the form of warnings, instructions, and affordances can essentially be displayed at any location in the environment, or even be removed from the environment, to, for example, create transparent objects. However, just because something falls within the realm of technical possibilities and is theoretically interesting, does not imply that users will understand the information and can process it efficiently, or whether they would find it worthwhile and acceptable compared to no information or more traditional forms of HMI communication.

This deliverable should serve as a useful reference for researchers and HMI designers who are involved in road transport. The report is structured as a core with accompanying already published journal articles as appendices.

# 1 Introduction

As automated vehicles (AVs) become more widespread on public roads in the future, new considerations must be made regarding the communication between AVs and other road users such as cyclists, pedestrians, and non-automated vehicles (De Winter & Dodou, 2022; Schieben et al., 2019). With AVs expected to operate differently than human drivers, there may be a need to develop human-machine interfaces (HMIs) that allow intuitive communication between AVs and vulnerable road users (VRUs) and drivers of manual vehicles. Such HMIs may be worn by the cyclist or pedestrian either as a mobile device or augmented reality (AR) glasses, may be present in the handlebar of the bicycle or otherwise integrated into the bicycle frame, or may be mounted on the exterior of the AV (so-called external human-machine interfaces, eHMIs), or may be present in the cockpit of the manual car. The introduction of HMIs may prove critical for establishing trust, conveying intent, and ensuring safe AV-VRU interactions. The eventual goal of HMIs is to integrate AVs onto public roads by giving all users a clear understanding of the AV's next actions.

While HMIs could aid communication between AVs and VRUs, HMIs may not be readily accepted by other road users. Additionally, it has been argued that eHMIs on the exterior of AVs may not even be required (Moore et al., 2019; for a review, see De Winter & Dodou, 2022). Reasons cited include the fact that road users, such as cyclists, pedestrians, and drivers of manual vehicles, rely on implicit information like a vehicle's speed and distance when crossing roads, and therefore do not benefit from additional explicit communication.

The use of implicit and explicit communication in manual driving has been made clear in research by Jokhio et al. (2023a, 2023b). In the first study (Jokhio et al., 2023a), it was discovered that a substantial number of manual drivers failed to properly use turn signals (a form of explicit communication) when changing lanes. In the second study (Jokhio et al. 2023b), which considered lane changes with turn signal usage, it was revealed that the timing of lane change initiation by manual drivers could be predicted based on implicit cues, such as the gap relative to other vehicles and the speed of the ego-vehicle. Given the findings of Jokhio et al., it is worth considering whether explicit communication through eHMIs on surrounding AVs is essential for certain manoeuvres, such as lane changes. That is, the turn indicator is already an explicit form of communication that resembles an eHMI (see also De Winter &

Dodou, 2022), and the driver of a manual car already processes a vital implicit cue; introducing eHMIs might potentially lead to confusion.

There are also concerns that eHMIs may go unnoticed if other road users are distracted or are not expecting them (Cefkin et al., 2019). Additionally, eHMIs that are large and conspicuous enough to grab attention may be impractical, add clutter to AVs' exteriors, and be prohibitively expensive to implement across entire AV fleets. With AVs expected to behave cautiously around VRUs, some believe implicit communication through actions like slowing down may suffice; the argument is that if AVs drive responsibly, additional external interfaces may be superfluous.

These perspectives suggest HMIs may not provide added value in all situations, and that a refined approach is required depending on the usage context. In other words, researchers and designers must weigh prospective benefits against potential drawbacks like cost and complexity as external HMI proposals are considered. Such a consideration requires that AV engineers and human factors scientists cooperate in AV development.

The essential role of human factors research is also emphasised in an interview study performed with experts in human factors and AV engineering conducted by Muhammad et al. (2023). Results from these interviews revealed that, particularly in light of the rapid decision-making in AV design, the integration of proper human factors knowledge into the AV design process is not standard or guaranteed. Therefore, to ensure that human factors are effectively incorporated into the AV design, proactive measures are essential. This can be realised by embedding human factors specialists within design teams, as well as by establishing guidelines, offering training, undertaking human factors experiments, and ensuring effective dissemination of acquired 'lessons learnt' (Muhammad et al., 2023). The current deliverable aims to communicate results and lessons learned regarding findings on interface design for communication between manually operated drivers (cyclists, pedestrians, manually driven cars) and AVs.

# 2 HMIs for pedestrians: Lessons learned

Within the SHAPE-IT project (2019), various studies have reviewed and developed HMIs for pedestrians (Tabone et al., 2021a, 2021b, 2023a, 2023b) and cyclists (Berge et al., 2022, 2023a, 2023b, 2023c). In the context of pedestrian interaction, Tabone et al., 2021a, 2021b) identified different frameworks within which HMIs can be developed. One such framework posits the **segregation** of AVs from general traffic, while another suggests that pedestrians and other vulnerable road users will be in **direct interaction** with AVs, particularly in congested urban settings (Tabone et al., 2021a).

The latter framework offers various avenues for innovation, such as the projection of a 'field of safe travel'—a zone in which pedestrians should not be present (Tabone et al., 2021b). Such solutions could be realised through AR technology. Survey-based and experimental research by Tabone et al. (2023a, 2023b), however, has indicated that pedestrians tend to prefer HMIs that adhere to classical HMI design principles (as stipulated by Wickens et al., 2004).

In particular, the **principle of redundancy**—where information is displayed through multiple modalities such as text, icons, and intuitive colour schemes—was found to be critical. Indeed, a prior study on external human-machine interfaces (eHMIs) for AVs (Bazilinskyy et al., 2019) found that people often do not understand eHMIs mounted on AVs, especially when coloured lights are displayed without context. Providing text, such as "WALK", can add clarity, but a downside is that VRUs may view overt text as intrusive or commanding rather than advisory. Additionally, text may not be ideal for sensing via peripheral vision (Eisma et al., 2023). Findings showed that providing redundant cues, such as combining text and coloured lights, can aid VRUs in making appropriate decisions (Tabone et al., 2023a).

A study conducted by Yang et al. (2023) highlighted the importance of **familiarity and top-down processing**. In their CAVE-based experimental study, pedestrians turned their heads less frequently before initiating a crossing after multiple interactions with the AV without an eHMI, indicating a learning effect. In other words, as pedestrians became more familiar with the predictable movements of AVs, they felt less need to be cautious, such as looking around extensively before crossing. However, the overall head-turning frequency was lower, and the learning pattern less pronounced, when an eHMI was present. This suggests that some pedestrians relied on the eHMI and checked the environment less compared to situations without the eHMI. The absence of a learning effect could also mean that some participants failed to become familiar with the eHMI. This in turn, indicates the importance of ensuring that eHMIs are not only visually salient but also comprehensible. While innovation is essential, it is equally important to ensure that these new designs correspond with what pedestrians are familiar with and can understand without training or instruction.

The above statements about familiarity correspond with work of Tabone (2023a; 2023b), which also showed that **familiarity and top-down processing** are important principles. HMIs based on existing interfaces like traffic lights and crosswalks were found to be well-accepted and yield fast crossing designs, presumably because pedestrians are accustomed to them already. More creative types of HMIs, like the "field of safe travel" concept based on affordance theory and ecological psychology, were found to be less effective if they violated these principles. For instance, some participants interpreted the *field of safe travel* as an invitation to enter rather than an area to avoid.

It is also imperative that the HMI adheres to the principle of **minimal information access cost**. An HMI becomes less effective if the road user is required to rotate their head or eyes multiple times to comprehend both the HMI and the surrounding traffic conditions. The research by Tabone et al. (2023a; 2023b) has revealed major benefits to an HMI that is always within the pedestrian's field of view, as it provides information about oncoming traffic without requiring identification of specific approaching vehicles. A downside, however, is that pedestrians may cross prematurely, i.e., before confirming the road is clear, representing a form of misuse (Tabone et al., 2023b; see also Kaleefathullah et al., 2022). There are also advantages to an HMI coupled to or located on the approaching vehicle (i.e., an eHMI). A key benefit is that pedestrians only need to monitor one location in the environment, though a drawback is the moving vehicle itself must first be identified within the environment (Lingam et al, 2023; Tabone et al., 2023b). Tabone et al. (2023b) also exposed how divided attention can severely impact pedestrians; a signal like a traffic light across the road requires focused attention, yet the pedestrian must still check left and right to confirm the approaching vehicle behaviour matches the colour of the traffic light. In more recent work (Peereboom, Tabone, et al., 2023), the authors have experimented with removing information through diminished reality, which is another technique that can be used to minimise information access costs. To sum up, humans have restricted virtual attentional resources and must rotate their heads and eyes to take in information. HMI designs must account for divided attention across multiple locations. Approaches that minimise demands on visual sampling, identification, and confirmation hold promise for HMI design.

Key lessons learned are that HMIs should provide redundant cueing through familiar interfaces that align with road users' existing mental models. While novel designs may hold promise, they require extensive validation to ensure understandability, acceptance, and integration with

VRUs' instinctive behaviours. In conclusion, a central theme in the HMI research for pedestrian-AV interaction within the Shape-IT project, which largely used AR to provide various innovative HMIs, has underlined the importance of legacy design principles. Innovation is not an end, but foundational principles of human information processing are essential to be considered. In our case, we focused on **redundancy, familiarity, and minimising information access cost**.

The research conducted by Tabone et al. has resulted in various elegant solutions that rely on innovative AR technology while simultaneously adhering to legacy design principles. These innovative interfaces follow foundational human-centred design guidelines related to redundancy, familiarity, and minimising effort. The work of Tabone et al. highlights how AR can push the boundaries of interface design while still elegantly fulfilling essential human needs for usability and understandability.

Figure 1 provides an overview of HMIs tested by Tabone et al. (2023a, 2023b), where redundancy was implemented in most of them. Still, some designs such as the *field of safe travel* (No. 4) and *phantom car* (No. 7) were deemed relatively unintuitive by pedestrians, presumably because they violated some legacy HMI design principles.

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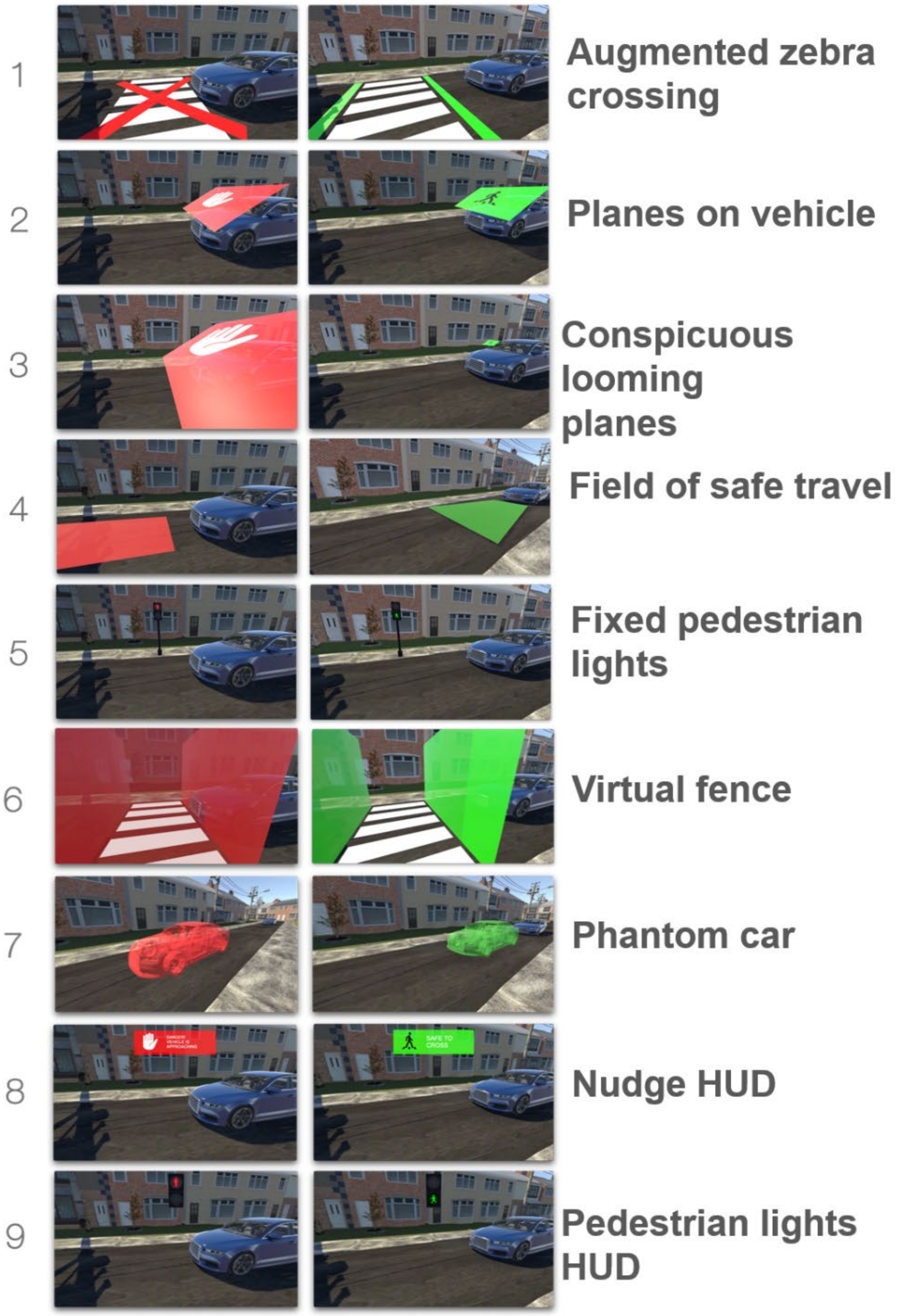


*Figure 1 – Human-machine interfaces (AR interfaces) tested by Tabone et al. (2023a) in an international online questionnaire. The same interfaces were tested in an immersive virtual pedestrian simulator (Tabone et al., 2023b).*

# 3 HMIs for cyclists: Lessons learned

While Tabone's work focused on HMIs for pedestrians, presented using AR, the work of Berge et al. (2022, 2023a, 2023b, 2023c) were tailored towards cyclists' interactions with AVs.

Interviews by Berge et al. (2022) with cyclists in Norway and the Netherlands revealed hesitancy among some cyclists about on-bike devices to communicate with AVs. Cyclists prefer **separation** from AVs via infrastructure and want AVs to confirm the detection of cyclists. However, cyclists were reluctant about bearing responsibility for communicating with AVs via new on-bike HMIs. While HMIs present opportunities to facilitate cyclist-AV interaction, they should support rather than overly alter cyclists' existing ways of cycling. HMIs should also be designed to prevent over-reliance on technology to communicate with AVs. Further studies on user acceptance and other solutions beyond on-bike HMIs are warranted.

In addition to the interview research, Berge et al. (2023a) conducted a literature review to summarise current research on communication technologies, HMIs, and other technological systems available to cyclists interacting with AVs in complex traffic environments. The specific objective of the review was to identify and categorise existing technologies with potential to aid cyclist-AV and extrapolate their benefits and implications. Analysis of 92 support systems using a taxonomy of 13 attributes revealed cyclist wearables, on-bike devices, and AV systems as the most common types. Based on the literature review, visual communication modalities were found to be dominant over other modalities such as haptics and audition (Figure 2). The review suggests accommodating cyclists through AV visibility and two-way communication. Finally, the review highlighted ethical implications of connected road users. The review recommended an inclusive and less vehicle-centric approach that shifts the safety burden away from cyclists. In line with the design principles used by Tabone et al. (2021b), cyclist-friendly solutions should be used over strictly technology-driven approaches requiring cyclists to adapt or process non-intuitive information.

To effectively design HMIs for AV-cyclist interaction, a number of factors must be considered, in particular the interaction behaviour of AVs and cyclists. For this reason, Berge et al. (2023c) made a survey of key scenarios of AV-cyclist interaction. The authors triangulated three sources: a literature review of previous cyclist-automated vehicle research, interviews with traffic safety and automation experts, and a questionnaire. This resulted in 20 prototypical cyclist-automated vehicle interaction scenarios, categorised into four groups based on direction of movement: crossing, passing, overtaking, and merging. The survey indicated right-turning vehicles, dooring incidents, and complex situations have the highest accident likelihood. Passing and merging scenarios are particularly relevant for studying communication solutions, as they involve negotiation between road users. Overall, their study identified key cyclist-automated vehicle scenarios and provided guidance for critical areas of future HMI design research. One focus area for future HMI research on cyclist-automated vehicle interaction—in line with statements made in the introduction of this deliverable—is the role of implicit versus explicit communication. Another recommendation that followed from the scenario analysis of Berge et al. (2023c) was that an eHMI should ideally be positioned all around the vehicle or be omnidirectional to accommodate the movement patterns of cyclists. Moreover, the experts interviewed identified several challenges with implementing eHMIs, such as signalling to multiple road users and determining the type and timing of the information displayed.

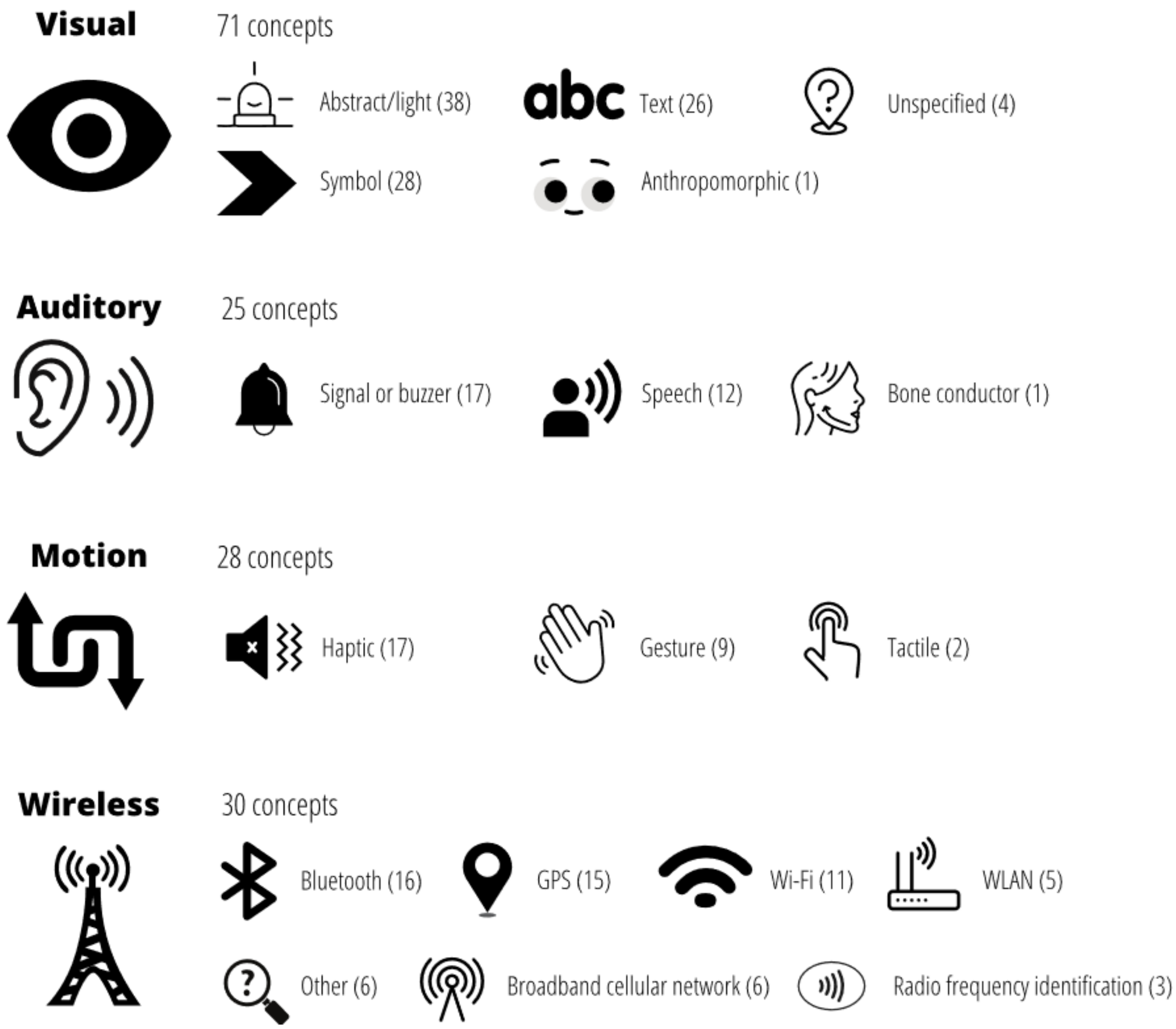


*Figure 2* – Overview of 92 cycling-system concepts from the literature, categorized according to modality of the concept/HMI (Berge et al., 2023a).

Based on the interview study by Berge et al. (2022), in which transcripts from 30 cyclists in Norway and the Netherlands were analysed, an HMI for cycling-AV interaction was designed. From the interview, a thematic analysis was performed on responses to questions regarding the information cyclists would require from automated vehicles and how a cyclist-oriented HMI should be designed. The eHMI design was further based on the scenario analysis by Berge et al. (2023c) and presented at the 28th International Conference on Intelligent User Interfaces (IUI '23) by Berge et al. (2023b).

The thematic analysis in Berge et al. (2023b) revealed two main themes: (1) Design Strategies and (2) Modality of Communication. Design strategies included the cyclists' primary needs for an HMI, which includes the importance of being seen and receiving confirmation of detection. Suggestions for the features of the HMI included a system detecting other road users and providing real-time information about their movements, as well as an indication that the cyclist has been detected by the automated vehicle. The Modality of Communication theme explored different communication methods, including auditory, visual, and haptic cues. Based on these findings, two HMI concepts were developed: CycleSafe (Figure 3), a mobile application, and an omnidirectional external HMI (eHMI) placed on the AV (Figure 4).

The designs are presented in Figure 3. The prior literature review revealed a preference for visual HMIs, although previous research indicates the auditory and haptic modalities may be effective as well. Therefore, further research is needed to assess the effects of different HMI communication modalities on cyclists.

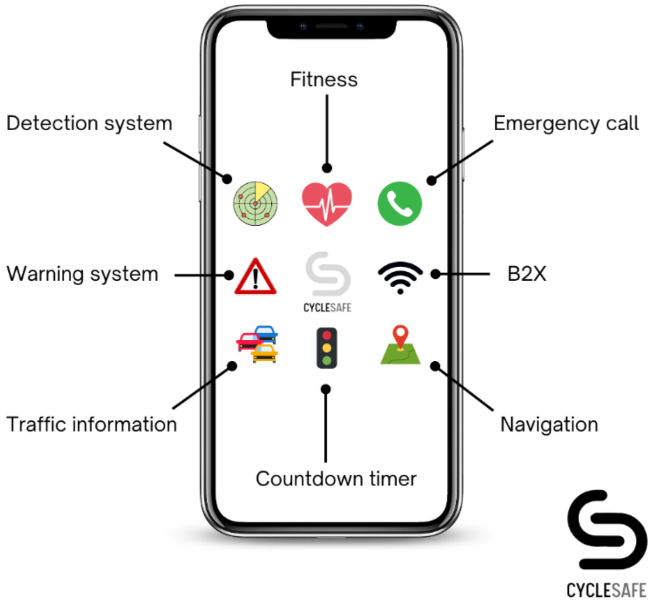


*Figure 3* – CycleSafe concept, a mobile application for cyclists.

*Figure 4* – Omnidirectional external human-machine interface (eHMI) mounted on an automated vehicle (AV) (Berge et al., 2023b).

# 4 HMIs for non-automated cars: Lessons learned

Although HMIs for non-automated car drivers are not the primary focus of the SHAPE-IT project, which mainly concentrates on pedestrians and cyclists in urban settings, one of our team members was involved in a relevant study on the topic of eHMIs for manually operated vehicles when interacting with AVs (Lingam et al., 2023). This study is briefly reviewed here.

In the driving simulation experiment by Lingam et al. (2023), participants manually drove a car and encountered an AV at intersections. The AV approached from the left at each intersection. In one session, the AV was equipped with an eHMI that indicated whether the AV would stop or not; in another session, the same eHMI information was available on the infrastructure, resembling conventional traffic lights; in a third session, no eHMI was present.

The results of the experiment indicated that crossing decisions improved with eHMI compared to without it. Specifically, drivers adhered to the eHMI instructions and appreciated the clarity provided by the additional signal. Through questionnaires and post-session interviews, participants expressed a general preference for the presence of an eHMI over its absence. These findings correspond with previous research on eHMIs among pedestrians (see De Winter & Dodou, 2022, for a review).

Regarding the comparison between eHMI on the AV versus an infrastructure-based eHMI, the outcomes are consistent with the pedestrian-crossing work of Tabone et al. (2023b). More specifically, an analysis of interviews and brake response times revealed both advantages and drawbacks for both concepts (Lingam et al., 2023). An infrastructure-based eHMI has the advantage of being within the forward field of view of the driver and positioned at a familiar and consistent location. A drawback is that participants have to distribute their visual attention between this eHMI and the approaching AV. The benefit of having the eHMI on the AV is that explicit cues (i.e., the eHMI) and implicit cues (i.e., the speed and position of the approaching AV) can be perceived simultaneously. However, a limitation of an eHMI on the AV is that the driver of the manually-driven vehicle must first identify the oncoming AV in their field of view, and divert their attention momentarily from the road ahead. Overall, participants did not express a definitive preference for either eHMI placement.

In summary, Lingam et al. (2023) suggests that the design of eHMIs should account for information access costs, a finding that echoes previous studies among pedestrians (Tabone et al., 2023b).

# 5 Conclusions

In this deliverable, we undertook a review concerning HMIs for pedestrians, cyclists, and manually driven vehicles for the interaction with automated vehicles (AVs). This research revealed several key lessons, which are briefly summarised as follows:

- With the advent of new technologies like AR and connectivity, there exists an almost limitless potential for HMI design. As discussed in this deliverable, theoretically, it is possible to overlay any information onto physical locations or project virtual barriers or 'safe zones'. Moreover, through a technique called 'diminished reality', it is even possible to remove information from the environment. While there still are technical challenges, these are gradually being addressed as technology progresses.
- Within the Shape-IT project, a variety of empirical research was conducted involving human participants. This includes experiments within virtual environments such as a CAVE-based simulator, studies using head-mounted displays (HMDs), and surveys and interviews in which participants shared their experiences and preferences. The obtained empirical evidence unequivocally indicates that the design of (e)HMIs must adhere to fundamental interface design principles, including those outlined by Wickens et al. (2004).
- Key interface design principles that we identified as pertinent include:
  - **The principle of redundancy:** Elements like colour, text, icons, and potential motion cues must be congruent. According to information theory principles, every communication system faces potential noise or disturbances that can disrupt the intended message. Redundancy in HMI design introduces deliberate alternative indicators within the interface. By doing so, it ensures that even if one aspect is misunderstood or missed due to noise, the user can still grasp the intended information from the other cues.
  - **The principle of minimising information access costs:** Although sometimes it is necessary to position cues in different (or: fixed and familiar) locations, it is important to account for the human's limited foveal vision and attentional resources. When signals are placed at different locations in the environment, the human road user will

need to rotate their eyes or head to identify these signals, which costs time and physical effort. Such considerations are crucial when designing HMIs for immersive applications like traffic interactions.

    - Lastly, we recognized the **principle of familiarity, also referred to as the principle of top-down processing.** Even though various HMI forms might theoretically be effective, our experiments demonstrated the value of familiar signs or icons, like a traffic light. One reason is not only that a traffic light is inherently well-designed (adhering to the redundancy principle by encoding both position and colour), but it is also universally recognised and therefore deeply ingrained in people. This explains why established concepts, even if presented innovatively (such as in AR format), can be powerful.

- Lastly, we found it invaluable to seek the perspectives of potential end users. A relatively simple method, like a semi-structured interview, was shown to be able to offer essential insights. While participants might find it challenging to imagine future scenarios and currently non-existing technologies during interviews, their views on what they decidedly do NOT want are instrumental in preventing researchers from pursuing unproductive avenues.

In conclusion, our research on cyclists, pedestrians, and car drivers revealed certain general principles concerning human information processing, which must be incorporated into future HMI designs. Innovation is not an end in itself; the technology must gain acceptance and offer performance benefits to its users; Otherwise, there is a risk that such technology will never be adopted on a broader scale.

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# 7 Appendices

**Appendix A**

Berge, S. H., Hagenzieker, M., Farah, H., & De Winter, J. (2022). Do cyclists need HMIs in future automated traffic? An interview study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *84*, 33–52. https://doi.org/10.1016/j.trf.2021.11.013

**Appendix B**

Berge, S. H., De Winter, J., & Hagenzieker, M. (2023a). Support systems for cyclists in automated traffic: A review and future outlook. *Applied Ergonomics*, *111*, 104043. https://doi.org/10.1016/j.apergo.2023.104043

**Appendix C**

Berge, S. H., De Winter, J., & Hagenzieker, M. (2023b). User interfaces for cyclists in future automated traffic. *Companion Proceedings of the 28th International Conference on Intelligent User Interfaces*, Sydney, Australia, 91–94. https://doi.org/10.1145/3581754.3584140

**Appendix D**

Tabone, W., Lee, Y. M., Merat, N., Happee, R., & De Winter, J. C. F. (2021b). Towards future pedestrian-vehicle interactions: Introducing theoretically-supported AR prototypes. *Proceedings of the 13th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications,* Leeds, UK, 209–218. https://doi.org/10.1145/3409118.3475149

**Appendix E**

Tabone, W., Happee, R., García, J., Lee, Y. M., Lupetti, L., Merat, N., & De Winter J. C. F. (2023a). Augmented reality interfaces for pedestrian-vehicle interactions: An online study. *Transportation Research Part F: Traffic Psychology and Behaviour, 94*, 170–189. https://doi.org/10.1016/j.trf.2023.02.005

# 7.1 Appendix A. Do cyclists need HMIs in future automated traffic? An interview study

Berge, S. H., Hagenzieker, M., Farah, H., & De Winter, J. (2022). Do cyclists need HMIs in future automated traffic? An interview study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *84*, 33–52. https://doi.org/10.1016/j.trf.2021.11.013

**Abstract**

Cyclists are expected to interact with automated vehicles (AVs) in future traffic, yet we know little about the nature of this interaction and the safety implications of AVs on cyclists. On-bike human-machine interfaces (HMIs) and connecting cyclists to AVs and the road infrastructure may have the potential to enhance the safety of cyclists. This study aimed to identify cyclists' needs in today's and future traffic and explore on-bike HMI functionality and the implications of equipping cyclists with devices to communicate with AVs. Semi-structured interviews were conducted with 15 cyclists in Norway and 15 cyclists in the Netherlands. Thematic analysis was used to identify and contextualise the factors of cyclist-AV interaction and on-bike HMIs. From the analysis, seven themes were identified: Interaction, Bicycles, Culture, Infrastructure, Legislation, AVs, and HMI. These themes are diverse and overlap with factors grouped in sub-themes. The results indicated that the cyclists prefer segregated future infrastructure, and in mixed urban traffic, they need confirmation of detection by AVs. External on-vehicle or on-bike HMIs might be solutions to fulfil the cyclists' need for recognition. However, the analysis suggested that cyclists are hesitant about being equipped with devices to communicate with AVs: Responsibility for safety should lie with AV technology rather than with cyclists. A device requirement might become a barrier to cycling, as bicycles are traditionally cheap and simple, and additional costs might deter people from choosing cycling as a transport mode. Future studies should investigate user acceptance of on-bike HMIs among cyclists on a larger scale to test the findings' generalisability, and explore other, perhaps more viable solutions than on-bike HMIs for enhancing AV-cyclist interaction.

**Introduction**

Automated vehicles are expected to reduce the frequency of road accidents by removing the human factor from driving (Fagnant & Kockelman, 2015; Kröger, 2020). However, urban road automation is likely to be a prolonged transformative process (Rupprecht et al., 2018), and human road users can be expected to interact with vehicles of varying degrees of automation for decades to come (Litman, 2020; Owens et al., 2018).

Active transport like walking and cycling is beneficial to public health (Raser et al., 2018) and promises substantial reductions in $CO_2$ emissions (McDonald et al., 2015). While AVs are assumed to produce fewer emissions than conventional vehicles (Milakis et al., 2017), active transport remains more sustainable (Creger et al., 2019). Trends indicate that cycling is on the rise in urban areas (EPINION, 2019; Harms & Kansen, 2018; OECD/ITF, 2013; Pucher & Buehler, 2017), and it is likely that cyclists will be interacting with AVs in future traffic.

Cyclists are vulnerable road users (VRUs) (Holländer et al., 2021), and a motorised vehicle colliding with a cyclist is likely to result in significant injury to the cyclist (Schepers et al., 2015). The way cyclists interact with human drivers cannot automatically be transferred to the context of AVs, as cyclists might base their behaviour and interaction strategies on incorrect expectations of AV behaviour (Vissers et al., 2017). To ensure cyclists' safety in future traffic, exploring solutions for enhancing AV-cyclist communication becomes vital.

Dey et al. (2020) suggested that present solutions for enhancing AV-VRU communication can be categorised in two broad terms: (1) technical, such as network and communication systems, and (2) human factors oriented, focusing on the ergonomics and interaction aspects of the interface between AVs and VRUs.

Among the technical solutions for enhancing AV-cyclist interaction, there are bicycle-to-vehicle connectivity and VRU beacon systems (Silla et al., 2017). As transport is increasingly becoming a part of the Internet of Things (Behrendt, 2019), several researchers have argued that connectivity between automated vehicles and VRUs is essential to use vehicle automation to its full advantage (Farah et al., 2018; Owens et al., 2018; Sanchez et al., 2016). Cyclists could be connected to AVs and the road infrastructure through their bicycles (Jenkins et al., 2017; Meinken et al., 2007; Piramuthu, 2017; Scholliers et al., 2017; Shin et al., 2013), or through wearables such as smartphones (Anaya et al., 2014; Engel et al., 2013; Liebner et al., 2013; Scholliers et al., 2017; Wu et al., 2014) and helmets (Hernandez-Jayo et al., 2016). However, little is known about the consequences of equipping cyclists with devices to communicate with AVs in terms of reliance, liability, and responsibility of the AVs and the cyclists (OECD/ITF, 2019; Owens et al., 2018).

Solutions for enhancing AV-cyclist interaction from a human factors perspective mainly revolve around external on-vehicle human-machine interfaces (eHMIs). eHMIs substitute the lack of explicit human-to-human communication cues with driverless AVs by providing additional cues on vehicle displays, lights, or projections on the road. The eHMI research has focused primarily on physical interface elements like placement, colour, and textual versus non-textual messages (Bazilinskyy et al., 2019; Dey et al., 2020). Out of the eHMI concepts considered by Dey et al. (2020), 91% targeted pedestrians. Cyclists were, however, included as a multiple target user in 23% of the concepts. Cyclist behaviour differs from pedestrians in speed, glancing behaviour and movement patterns (Hagenzieker et al., 2020; Trefzger et al., 2018). This points towards the necessity of considering these differences in the eHMI design process for cyclists and pedestrians. Similar viewpoints were expressed by Hou et al. (2020), as their findings for eHMIs for cyclists differed from pedestrians.

A cyclist-specific solution for enhancing communication between AVs and cyclists could be combining the technical and human factors approaches by adding interfaces to the bicycle and connecting cyclists to a network of automated vehicles and infrastructure. Previous research on on-bike HMIs in conventional traffic has examined warning systems (Engbers et al., 2018; Jenkins et al., 2017; Prati et al., 2018), lane-keeping assistance systems (Matviienko et al., 2019), turn-indicators (Dancu et al., 2015), and navigation systems (Dancu et al., 2015; Pielot et al., 2012). For instance, Engbers et al. (2018) tested a front- and rear-view assistant system for cyclists and found that the front-view assistant resulted in less lateral distance to the approaching oncoming cyclist. In Prati et al. (2018), cyclists were more likely to decrease their speed if warned by an on-bike system. Other studies have investigated augmentation concepts like Augmented Reality (AR) glasses (Ginters, 2019; Von Sawitzky et al., 2020) and head-up displays (HUDs) (Dancu et al., 2015; Hou et al., 2020; Matviienko et al., 2019) for cyclists. However, the potential of on-bike HMIs to enhance AV-cyclist interaction remains largely unstudied.

Investigating the factors that constitute cyclist interaction today might offer insight into cyclists' needs for AV interaction in the future. Utilising semi-structured interviews invites end-users to reflect on a topic (Gulliksen et al., 2003; Willig, 2008). In addition, by taking a qualitative and constructivist approach to the AV-cyclist interaction and on-bike HMIs, we aim to provide an in-depth description and understanding of the dynamics of these novel topics, and lay a basis for further hypotheses development and testing.

The objective of the present study is to fill the knowledge gap of on-bike HMIs for AV-cyclist interaction by exploring the factors that constitute cyclist interaction in traffic, both in current environments and in future scenarios with AVs. Moreover, we investigate whether on-bike HMIs are desired by cyclists and potential design strategies of on-bike HMIs to enhance the interaction between AVs and cyclists.

## Method

We conducted semi-structured online interviews with 15 cyclists in Norway and 15 cyclists in the Netherlands. The interviews were performed individually either in Norwegian or English by the first author via Microsoft Teams or Zoom from August to November 2020 and had an average duration of 50 minutes. The interviews started with a short introduction of the project and demographic questions, followed by open-ended questions sectioned into three topics. Table 1 shows the interview topics and selected questions from the interview guide. See Appendix A.1 for the complete interview guide.

Before participation, the interviewees received and signed an information sheet and consent form digitally through Adobe Sign. Participation was anonymous and voluntary. The study was approved by the Human Research Ethics Committee of TU Delft. Adhering to open science principles, the participants agreed to open access storage of anonymised written transcripts from the interviews.

### Sample and recruitment

Aiming to gather a range of experiences among European cyclists, Norway was selected as a country with low shares of cyclists, and the Netherlands as a country with high shares of cyclists (Buehler & Pucher, 2012). By interviewing cyclists in two countries with different shares of cyclists and cycling culture, this approach allowed us to explore how cultural differences may affect cyclist interaction and to what extent these differences play a role in the future of cycling.

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The sample was recruited by invitations linking to a recruitment website shared on social media in the authors' personal and professional networks, LinkedIn, Facebook cycling interest groups[1], and Twitter[2]. Three of the interviewees were referred by other participants. In total, 66 potential participants were identified. The participants were contacted consecutively by e-mail with a request for an interview. The only prerequisite required was cycling experience in Norway or the Netherlands. A sample of 15 cyclists was selected from each country. Note that in thematic analysis, a sample size of 30 is regarded as sufficient, as 'thematic saturation' can be achieved with substantially smaller sample sizes (Fugard & Potts, 2015; Guest et al., 2006).

**Table 1**

*Interview topics and a selection of questions from the interview guide*

| Topic | Question |
|---|---|
| **Current traffic interaction** | *I would like to know about your experience with cycling …*<br>Could you start by describing a typical cycling trip?<br>How would you describe the interaction with motorised vehicles?<br>Do you encounter any challenges while cycling? Please elaborate. |
| **The future of cycling** | *Imagine a future where cars are fully automated, and there is no longer a human driver behind the wheel …*<br>How will this impact you as a cyclist?<br>How do you think *[challenge(s) already mentioned by the participant]* will change when cars are automated and driverless?<br>As a cyclist, what kind of information would you need from an automated vehicle? |
| **Bicycles and technology** | *Imagine the future of cycling, with new and exciting technological progress. I want you to think of your perfect bicycle (it does not have to be realistic) …*<br>What would it look like? |

[1] Syklistforeningen i Oslo and Dutch Cycling Embassy
[2] SWOV Institute for Road Safety Research

What kind of features would it have?

*Imagine a system or device that helps you interact with automated vehicles …*
How should this device be designed?
How should the device communicate with the cyclist?

*If you could receive information about other road users such as automated vehicles through a device or a system on your bike (like the one you just imagined) …*
What are the benefits of such a system?
What kind of information about cyclists would be useful for the automated vehicle?
What are the disadvantages of such a system?

Table 2 provides an overview of the interview participants. The sample of 30 participants consisted of 11 females and 19 males.

The participants were evenly distributed across the age groups, with an average age of 43 years (*SD* = 16, *R* = 53). However, the age distribution differed between the two countries. All participants in the youngest age group were from the Netherlands, while most participants 62 years or older were Norwegian. Most of the participants (73%) cycled daily. The number of participants owning more than two bicycles was even between the two countries. A larger share of Norwegians (47%) owned an e-bike than participants in the Netherlands (13%). None of the Norwegians owned a city bike. Lastly, 70% of the early adopters of technology was interviewed in the Netherlands. Note that although we did not ask specifically about education and background, some participants had professional knowledge of AVs and human factors.

**Table 2**

*Demographics of the interview participants*

| | *n* | Total | Norway | The Netherlands |
|---|---|---|---|---|
| **Gender** | | | | |
| Female | 11 | 37% | 5 | 6 |
| Male | 19 | 63% | 10 | 9 |
| **Age** | | | | |
| 18-28 years | 6 | 20% | 0 | 6 |
| 29-39 years | 8 | 27% | 5 | 3 |
| 40-50 years | 7 | 23% | 5 | 2 |
| 51-61 years | 4 | 13% | 1 | 3 |
| > 61 years | 5 | 17% | 4 | 1 |
| **Cycling frequency** | | | | |
| Daily | 22 | 73% | 11 | 11 |
| Weekly | 7 | 23% | 3 | 4 |
| Monthly | 1 | 3% | 1 | 0 |
| **Employment** | | | | |
| Employed | 22 | 73% | 12 | 10 |
| Retired | 4 | 13% | 3 | 1 |
| Student | 3 | 10% | 0 | 3 |
| Unemployed | 1 | 3% | 0 | 1 |
| **No. of bikes** | | | | |
| 0 | 1 | 3% | 0 | 1 |
| 1 | 11 | 37% | 6 | 5 |
| > 1 | 18 | 60% | 9 | 9 |
| **Type of bike** | | | | |
| City bike | 11 | 37% | 0 | 11 |
| Electric | 9 | 30% | 7 | 2 |
| Hybrid | 13 | 43% | 10 | 3 |
| Road bike | 6 | 20% | 3 | 3 |
| Other | 25 | 83% | 11 | 14 |

| | | | | |
|---|---|---|---|---|
| **Approach to technology** | | | | |
| Early adopter | 10 | 33% | 3 | 7 |
| Average | 17 | 57% | 11 | 6 |
| Last to try | 3 | 10% | 1 | 2 |
| **Total** | 30 | 100% | 15 | 15 |

### Analysis

Thematic analysis adapted from Braun and Clarke (2006) was chosen as the methodological approach. Thematic analysis is a flexible and systematic approach for synthesising, linking, analysing and reporting patterns in interview data (Braun & Clarke, 2006) and has been shown valuable in previous transport research (Alyavina et al., 2020; Gössling et al., 2016; Liu et al., 2020; Pettigrew et al., 2020). Table 3 presents the six steps of our thematic analysis process.

**Table 3**

*Six-step process of thematic analysis*

| Phase | Description |
|---|---|
| **1** | Familiarising with data |
| **2** | Generating initial coding |
| **3** | Searching for themes |
| **4** | Reviewing themes |
| **5** | Defining and naming themes |
| **6** | Reporting the findings |

Audio from the interviews was recorded with Audacity and transcribed clean verbatim by a professional transcription company, removing repetitions and filler words as they were deemed of no relevance to the nature of the analysis. The transcripts were compared with the audio files to ensure their authenticity by the researcher who performed the interviews, and minor corrections were made to the transcripts. While the transcripts were transcribed in Norwegian and English, respectively, the thematic analysis was performed in English. Atlas.ti 9 was used to categorise, code, and analyse the interview data. The analysis was data-driven and emergent. The first author performed the coding process, based on the transcripts' semantic content, using raw quotes as codes. The codes were sorted into thematic categories based on repetition, similarities, and differences (Ryan & Bernard, 2003). Within each thematic category, the codes were further differentiated and sorted into sub-themes. The analysis was iterative, where codes and their allocation to each overarching theme were reassessed and merged during the initial phases. The emergent nature of the analysis necessitated using a single coder (Smith & McGannon, 2018). During the synthesis of the themes in phases 3 and 4, however, the authors discussed and reassessed the sub-theme allocation to the overarching themes.

As two or more codes could be allocated to the same data segment, there is some overlap (code co-occurrence) between the themes. Code co-occurrence can provide useful information on understanding the thematic domains beyond simple frequencies (Namey et al., 2008). Code co-occurrence is common in thematic analysis as the themes are not disjointed from the data, but rather a result of similarities and connections within and across the dataset (Braun & Clarke, 2006).

## Results

### Overview of results

Seven overarching themes and 47 sub-themes that constitute cyclist interaction today and in future scenarios with AVs were identified in the analysis: Interaction, Bicycles, Culture, Infrastructure, Legislation, AVs, and HMI. Table 4 shows an overview of the seven themes and their respective sub-themes.

There are some code co-occurrences across the themes. As seen in Figure 1, Interaction had most code co-occurrences with the other themes. The overlaps of Interaction were most evident with Infrastructure (44 co-occurrent codes), Culture, and AVs (28 co-occurrent codes each), implying that these themes are closely associated. Similar claims can be made for AVs and HMI (35 co-occurrent codes), and Bicycles and HMI (30 co-occurrent codes).

**Table 4**

*Overview of the main themes and sub-themes*

| Theme | Sub-theme | Category within sub-theme |
|---|---|---|
| Interaction (30) | Cyclist behaviour (30) | Eye-contact (24) |
| | | Motion cues (17) |
| | | Hand gestures (12) |
| | Challenges (29) | |
| | Other road users (28) | Drivers (27) |
| | | Mopedists (5) |
| | | Pedestrians (4) |
| | Cycling (22) | |
| | Perceptions (19) | |
| | Safety (19) | |
| | Informal rules (6) | |
| Bicycles (30) | Features (30) | Electrification (21) |
| | | Simplicity (14) |
| | | Connectivity (8) |
| | | Tailored (8) |
| | Utility (29) | |
| | Theft (6) | |
| Culture (30) | The Netherlands (18) | |
| | Norway (14) | |
| Infrastructure (30) | Separated (29) | Safety (22) |
| | Challenges (26) | |
| | Future (16) | |
| | Traffic lights and signals (13) | |
| | Smart (4) | |
| | Parking (3) | |
| Automated vehicles (30) | Expectations and AV capabilities (30) | |
| | Cyclist needs (24) | |
| | Challenges (24) | |
| | eHMI (18) | |

| | | |
|---|---|---|
| | Future applications of AVs (6) | |
| Human-machine interface (30) | Functionality (30) | |
| | Perceptions and attitudes (30) | |
| | Design strategies (27) | Display (21) |
| | | Audio (12) |
| | | Haptics (10) |
| | | Lights (8) |
| Legislation (30) | Planning and regulation (21) | |
| | Rule-breaking (14) | Red lights (11) |
| | | Enforcement (4) |
| | Standardisation (9) | |
| | Privacy (9) | |

*Note.* The numbers indicate the frequency of interviews each sub-theme occurred in.

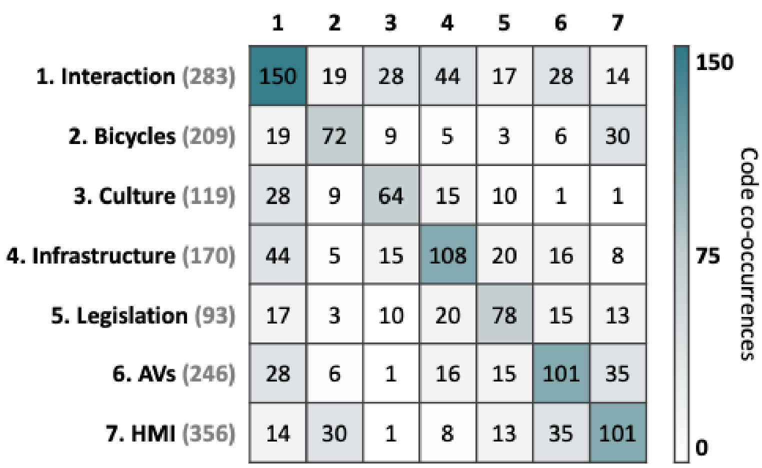


***Figure 1.*** *Code co-occurrence of the main themes. The numbers on the diagonal indicate the total number of code co-occurrences for that theme. The numbers displayed after each theme indicate the total number of coded quotations within each theme.*

In the following sections, the themes are presented with a selection of quotes from the participants, describing the thematic analysis's narrative direction.

**Interaction**

The theme Interaction encompasses perceptions of cycling, cyclist behaviour and informal rules, safety, interaction with other road users, and the challenges cyclists face related to interaction.

Cyclist interaction entails a certain degree of unpredictability and anarchy. Cyclists are described by the participants as having a high degree of freedom to move, even in congested traffic. Cycling in urban areas requires a high mental workload, and it may be challenging to predict other road users' intentions. In a group, however, cyclists can follow the crowd and pay less attention to motorised traffic. There is a group dynamic that seems to work well:

> *"It has something to do with the understanding that there is an interaction between many actors in a particular cityscape. Cyclists have the advantage that they can react flexibly." (NO3)*
>
> *"One of the paths I follow from my house to go to the train station is the busiest cycling road in the Netherlands. (…) It's like some thousands of bikes. To me, it's quite impressive that people can manage. It means that the system kind of works. People know how to cycle properly." (NL24)*

Most of the interviewees described themselves as considerate and well-behaved, expressing gratitude and smiling to other road users, but it was also acknowledged that they could act carelessly and selfishly. Cyclists use a mix of eye contact, hand gestures, and motion cues to interact with other road users. They are likely to establish eye contact with drivers at intersections, crossings, and in ambiguous situations.

> *"I do use eye contact sometimes, for example, when I'm at a crossroads and the driver kind of slows down to let me pass or even, you know, uses his hand gestures to tell me to pass, I would usually look at them and like, wave and say thank you." (NL21)*
>
> *"If a car approaches me, most of the time, I try to look at the driver to see if he sees me." (NL29)*

Eye contact can be particularly important when the cyclist is breaking the formal or informal rules of cycling. However, some interviewees said they tend to rely more on motion cues like change in speed and velocity to interpret other road users' intent than eye contact.

> *"Sometimes I wait to get an indication that they are going to slow down or they're going to let me pass - they know I'm there. Often that's if they slow down or they*

*maybe move to the left a little, so to give me a little way, and then I know that they're aware of me, and then I'm fine." (NL20)*

*"Even if you do not see each other's eyes, I see how the car drives and the driver sees my posture and how I move." (NO12)*

*"I have to see that the car stops, that it slows down, I have to be sure of that." (NO2)*

Hand gestures are used to signal intention and are often combined with alignment on the road and adjustment of speed to interact and negotiate with other road users.

Perceptions of cyclists and cycling varied across the interviewees. Cycling was perceived as mostly smooth and cooperative. However, some of the interviewees mentioned that they are fearful of drivers, of not being seen, and of losing balance and falling. In urban areas without cycling infrastructure, the cyclists often cycle defensively and at lower speeds to avoid critical situations with cars and heavier vehicles.

*"I have a rather defensive style of cycling. I never cycle so fast that I expose myself to, at least not consciously, any dangerous situation." (NO1)*

The consensus among the cyclists interviewed in the Netherlands was that cycling is safe and easy. Protective gear and equipment are seen as not needed because cyclists are cared for in traffic:

*"In Netherlands, cyclists are meant to be cared about. I mean, the other users should take care of cyclists; they shouldn't take care of themselves. That's why they don't force you to wear helmets." (NL19)*

In regard to interaction with other road users apart from fellow cyclists, three types of road users were recurringly mentioned during the interviews: drivers, mopeds, and pedestrians. The interviewees perceived drivers as attentive, considerate, and aware of cyclists. For the most part, interaction with drivers is effortless. However, some drivers seem to be annoyed, drive aggressively, and apparently do not appreciate sharing the road with cyclists, sometimes to the extent where they are perceived to try to hinder cyclists in traffic deliberately. In addition, some drivers come too close, and are not aware of their vehicle size, misjudging the space needed for overtaking. Norwegian cyclists, in particular, mentioned that they sometimes feel disdained and not welcome by other motorised road users.

*"When you look at motorists, you can get the impression that "it's just a cyclist, so we don't have to comply with the obligation to give way" (…). There is both*

*uncertainty about whether they see me, or whether they simply don't care." (NO11)*

In the Netherlands, it is assumed that drivers are more considerate because they are often cyclists themselves.

*"In other countries, you are either a cyclist or a driver. Here, drivers also cycle themselves. Maybe most of the time they cycle, but sometimes they drive or the other way around. So, they have experience of both, being a cyclist and driver. When they are driving, they understand the feeling of the cyclist in front of them." (NL19)*

Likewise, a Norwegian interviewee said he changed his view of cyclists from negative to positive after he started cycling regularly.

*"In my experience, there are a lot of drivers who prevent cyclists by deliberately placing themselves all the way to the curb so you cannot... "no way in hell you are getting in front of me", sort of. I have been a motorist for many years. I do not have a car anymore, but I was probably that type of driver. Now, I get these moments of realisation: I thought cyclists were in the way." (NO13)*

Traffic is, however, considered inherently dangerous, and with cyclists often being the losing party in a traffic accident, perceived safety was reported as higher when there is less interaction with other road users such as drivers. Some cyclists said they plan their routes to avoid mixed traffic and prefer taking the less busy and quieter roads.

*"When I cycle with cars and other heavier vehicles, I cycle as if everything is a potential danger to my life. I ride my bike as if everything is a death threat." (NO4)*

*"As a vulnerable road user, I try to be careful not to be hit by cars. I always think there is a risk when I bike on the road. Mostly I try to ride on bike and pedestrian paths." (NO3)*

*"I will highly avoid cycling next to cars like I know some roads (…) are kind of mixed, so you have to be really close to cars. But I feel quite unsafe if I don't have my own cycle path. (…) I will maybe do a reroute myself to just make sure I don't have cars really next to me because you never know." (NL24)*

Cyclists experience a wide range of challenges related to interaction. Unpredictable behaviour by other road users, such as rule-breaking, sudden braking or backing up, being cut off or experiencing tailgating or takeovers, was reported as a recurrent challenge. Parked cars and cars stopping and starting in bicycle lanes could also be challenging. Traffic with high complexity, combined with high speed at points of interaction, such as crossings and intersections, could be a challenge as well. Among the Dutch interviewees, interaction with mopeds and other cyclists were recurring challenges, especially when there are cyclist congestion or busy cycling paths, risk-taking cyclists and elderly e-bikers that might be unstable or react slow.

### Bicycles

The theme of Bicycles encompasses bicycles as a mode of transport, desired features of today's and the future's bicycle, as well as bicycle theft.

Bicycles serve as a means of transport for commuting, errands, leisure activities, and recreation. In urban areas, in particular, cycling is an alternative to driving and saves travel time. Bicycles cover most everyday needs for transport, and with innovations such as e-bikes, cargo, and utility bikes, cyclists can transport children and goods on their bikes at longer distances. The cyclists interviewed saw cycling as a benefit to public health: Cycling is cheap, involves physical activity, and is beneficial to the environment.

> *"The more people who manage to use the bike for the bulk of their traffic or transportation needs, the better it is for city space utilization, noise levels, and traffic safety. In addition, it benefits public health. In every conceivable way, cycling is good." (NO4)*

The perfect future bike could take many forms and shapes, and the participants suggested features such as self-stability, sensors, automated braking and gearing systems, improved traction, improved lights and signalling systems, and anti-theft and locking systems. The interviewees acknowledged that bicycles have versatile functionality and said they prefer a bicycle tailored to their individual needs. Half of the interviewees did, however, point out that the strength of the bicycle is its simplicity. The perfect future bicycle was often described as inexpensive and simple, with slightly improved features, such as better gears and brakes.

> *"I think the basic model, as the bike looks today, is how it will continue to look like. (…) Cars have had an enormous technical development, but bicycles have only been perfected using technology we already have. There is nothing about my bike I would want differently. It's perfect." (NO6)*
>
> *"I definitely think that the perfect bike today is already the bike that exists and is being used. That's what's so liberating about cycling in general. It's simply the joy of transporting yourself. This freedom you have, it does not need the help of [additional] technology." (NO11)*

Electrification was one of the most reoccurring sub-themes of bicycles in the interviews. While physical activity is an essential factor for many cyclists, it was acknowledged that electrification might be the future of cycling. E-bikes have the potential to increase personal mobility and make cycling more accessible to the public, including older persons. Electrification was reported useful for longer distances, and for cyclists who value travel time and comfort. On the other side, e-bikes are heavy and have a limited battery capacity. If the future bike is electric, some cyclists appreciate the option of turning the e-functionality off:

> *"Well, ideally I would like to have the choice if the bike is electric or not, but I would like to still have the choice to exercise because cycling serves this purpose too for me. I like to keep myself healthy by cycling, but if I'm too tired or I want some boost, it would be nice to get some extra assistance." (NL24)*

In a future where traffic has a high degree of automation, the interviewees were open to adding connectivity to their bikes, either through a simple sensor integrated into the bike, or a wearable, or a more elaborate cycling computer system used for navigation and communication with other road users and infrastructure. Some cyclists were, however, hesitant about adding new technology to bicycles. They argued that such systems will be excluding by no longer making bicycles affordable. Expensive bikes are also more prone to theft, some cyclists are wary of investing in extra equipment and features for their bicycles.

> *"Bikes getting lost is a thing in the Netherlands. Bikes are stolen. So, I would imagine having such technology already in the bike, isn't good (…) because when the bike is lost you lose a lot of money." (NL17)*
>
> *"Everyone has had a lot of bikes, but everyone has also had a lot of bikes stolen. I think everyone I know has had a bike stolen and I think a bike like that would be really expensive with modern technology." (NL18)*

**Culture**

As the cyclists were interviewed about cycling in Norway and the Netherlands, respectively, the theme Culture clusters around cycling culture in these two countries. Additionally, some of the participants had cycling experience from both, and several other countries, mostly in Europe.

***Norway***

The interviewees portrayed Norwegian road infrastructure as tailored to cars since the 1970s. Since then, cyclists have stereotypically been described as a nuisance to drivers. Cycling is permitted on sidewalks, and cyclists are in many instances forced to share the sidewalk with pedestrians as there is no viable alternative. If cyclists are using sidewalks, they typically lower their speed and cycle more carefully. It is, however, preferred to share the road with cars rather than cycle on sidewalks with pedestrians.

Cycling on the road can be a dangerous activity, where wearing protective gear and equipment is a must. There is a sense of anarchy among many cyclists, and rule-breaking seldom has legal consequences. For instance, it is common for cyclists to slow down and roll through an intersection, exploiting gaps in traffic, even if there is a red light. While waiting at a red light in mixed traffic, cyclists often start cycling before the light turns green, assumingly to make themselves more visible to drivers. Moreover, several of the Norwegian interviewees said cyclists have no clear role in traffic. This ambiguity enables cyclists to act as a vehicle in one moment and as a pedestrian in the next. Nevertheless, the lack of a clear role also adds frustration and confusion among cyclists and other road users:

> *"I think it prevents many from cycling. They often experience unpleasant situations. (…) When I cycle in the city and I'm in a hurry, I use the sidewalk, cross at pedestrian crossings, and I cycle on the road, whatever seems best in the moment. You always have to solve problems where there are no good solutions. I understand that this is frustrating for a lot of road users. I really do. It's the infrastructure that's lacking." (NO15)*

Cycling innovation has previously revolved around creating more lightweight and racing bicycles, tailored to sports activity rather than everyday transport. Norwegian cyclists described the past cycling culture in Norway as egocentric and aggressive. With increasing shares of cyclists and added diversity with e-bikes, cargo, and utility bikes, the interviewees said that the culture is changing, and that cycling is becoming increasingly available to the population. Particularly in urban areas, government officials and interest groups are working towards cycling as a viable mode of transport, focusing on more consistently designed cycling infrastructure and increasing access to cycling through shared city bikes- and bicycle subscription services.

> *"One thing that happened is that there are many more cargo bikes. (…) It's more like the Dutch, shall we say, or the Danes. The proportion of racing cyclists is declining. Because they will now ride on e-bikes and cargo bikes. There are people with a basket on the handlebars, sitting upright and so on. I think that makes the traffic culture among cyclists a little more relaxed." (NO12)*

### *The Netherlands*

The cyclists interviewed in the Netherlands saw cycling as a way of life and a big part of Dutch culture. Cycling is a natural part of childhood – bicycles and cyclists are everywhere, and cycling is the number one transport mode.

> *"Everybody cycles. Almost everybody has at least one bike, and a lot of people cycle at least once a week, I would say, but I also know [for] a lot of people, especially living in an urban area, it's the quickest way to get from point A to point B by cycling." (NL16)*
>
> *"I would describe it more like a way of life, like in the Netherlands, like you get your keys, your phone, your credit card and your bike and you go. It's a must-have." (NL24)*

Several participants pointed out that the Netherlands has been working towards a cycling culture since the 1970s. This has resulted in a network of continuous cycling infrastructure, including consistently designed cycling roads, traffic signs and signals for cyclists.

> *"I think it started in the 1970. Because a lot of accidents with cars were happening, like a lot of young children, also died of car accidents. And then there was this movement of people who really didn't like cars because both those accidents and also the environment and then the government started to invest in the cycling structure and infrastructure, and it really paid off." (NL22)*

Combined with naturally flat terrain, cyclists can cycle for hours without stopping. Moreover, cyclists often have priority in urban areas, ensuring cycling as the fastest transport mode for short distances.

The interviewees portrayed Dutch drivers as patient and considerate. On the downside, cyclists who are used to be given priority may exhibit risky behaviour such as disrespecting traffic lights or misjudging a situation, leading to near-miss encounters with other road users:

> *"I guess because it's so normal to go by bike, a lot of people and also myself, I guess we think we are the bosses on the road. And sometimes people don't wait or ignore the red lights or quickly go before a bus or a car." (NL18)*

Sports and recreational cyclists tend to invest in more expensive bicycles tailored to their interests. The average Dutch bike, however, was portrayed by the interviewees as simple and cheap.

**Infrastructure**

Infrastructure as a theme describes how infrastructure affects cycling, which challenges cyclists experience related to infrastructure, and how infrastructure might look like in the future of automation.

Separated infrastructure was one of the most reoccurring topics during the interviews. Cyclists prefer using bicycle roads and lanes over sharing the road with other road users:

> *"A dedicated space for bikes is paramount in my opinion. This makes me feel absolutely safe." (NL21)*
>
> *"It feels much safer with separate lanes. You are the losing party. You are a vulnerable road user, and if you are out on the road when something happens, you are essentially doomed." (NO1)*

However, a few interviewees noted that separation might lead to a higher speed of road users than in shared traffic; shared spaces are more chaotic and may slow down traffic, potentially increasing safety but reducing comfort in the process. Although preferred by most of the interviewees, infrastructure does not have to be completely separated; many are comfortable with a bicycle lane if the lane has sufficient width for overtaking or is separated from the road by a low curb or slight elevation.

> *"There must be wider cycle paths. And I appreciate bike paths that are much more separated from the road than they are today. It should not just be a red field with a white marking on the side [often used to indicate cycle lanes on roads in Norway], but that they are placed on a separate road." (NO2)*
>
> *"It would have been very nice with bicycles lanes and bicycles lanes elevated from car traffic on some of the roads (…). It's almost like a sidewalk [for cyclists], I think. And then there is often a small, sloped curb towards the pedestrians so there is a clear separation." (NO9)*

Cyclists experience various challenges related to infrastructure. Particularly among the Norwegian cyclists, inconsistently or poorly designed cycling infrastructure was reported as challenging: Bicycle lanes suddenly ending at an intersection, narrow lanes, or lack of cycling infrastructure altogether, forcing the cyclists to choose between sharing the road drivers or the sidewalk with pedestrians.

> *"In Norway, it's like "here is a bike lane, and here comes the intersection". Snap, the bike lane is gone. You just have to figure it out yourself. Suddenly, the bike*

> *lane appears on the other side. It's like "what happened in the middle there"? You are at the mercy of drivers." (NO7)*

Crossings, roundabouts, and intersections can be a challenge for cyclists in both countries, often due to low visibility and heavy traffic with road users coming from several directions. The cyclists tended to find signalised intersections less challenging than un-signalised intersections because traffic lights provide clear information.

> *"I try to position myself, so I can see the traffic lights and that I'm able to see ahead in the intersection, where the bike lane often disappears. I make sure to position myself behind the first car, so that I can see if the driver is using the turn signal to go right when I am going straight." (NO10)*

In a future where vehicles have a high degree of automation, most of the interviewed cyclists were sceptical about sharing the road and call for fully separated infrastructure to avoid interaction.

> *"Cyclists (…) are self-regulating and perhaps the closest humans can get to a flock of birds. It would require a lot before automated vehicles to function in coexistence with us. I believe if we go for automated vehicles and this is the future of our transport system, it will require separate pathways and a large degree of separation." (NO4)*

It was acknowledged that mixed traffic may be unavoidable and complete separation of cyclists and AVs may not be realistic:

> *"In general, it's safe to assume that (…) as a cyclist you would [still] have places where you would have to interact with automated vehicles at some point. It's impossible to completely avoid that unless you just have bridges and tunnels everywhere. That's not realistic." (NL17)*

However, a few of the interviewees were optimistic about sharing the road with AVs. They argued that complete separation may delay the trust process between cyclists and AVs. A few of them also pointed out that AVs' implementation in the Netherlands might be more straightforward than in Norway, as there is already a larger amount of separated infrastructure available in the Netherlands.

Some of the interviewed cyclists mentioned smart infrastructure's potential, for instance, to inform cyclists about weather conditions, street pollution or for providing route advice. Smart infrastructure could also detect cyclists and inform AVs about the cyclists' position. Other features suggested during the interviews were the ability to detect cyclists and change traffic lights to accommodate them, either by changing the light or by showing a countdown to the next green light on a sign or as a feature of an on-bike HMI.

**Legislation**

This theme describes how legislation is intertwined with cycling, the challenges cyclists encounter in traffic, and the implications legislation could have for cycling in a future of automation.

Several of the cyclists interviewed said that even though they strive to follow the traffic laws, rules are broken regularly. Running red lights was described as the most common rule to break. The chances of being caught are slim, as enforcement of traffic laws for cyclists was reported as rare. The fines are also expectedly lower than for drivers:

> *"I think that the fines are higher when driving my car through a red light, but also the police does not have enough people to check up on the cyclists who are going through the red lights." (NL16)*

Some of the interviewees argued that the legislative focus should be on regulating the road user with the most significant damage potential, i.e., motorised vehicles. They claimed that investing in bicycling infrastructure would set precedence, and by prioritising vulnerable road users in legislation and law enforcement, cyclists would be more welcome in traffic.

> *"[We need] more bike paths, more bike traffic lights, more of specific things for cyclists to make you feel like you belong in traffic. Now we are sort of stuck between a rock and a hard place. Drivers do not want us, and pedestrians do not want us." (NO7)*

In urban areas where vulnerable road users share the road with motorised vehicles, the interviewees suggested speed limits to be lowered, and priority given to cyclists at intersections. Moreover, regulating the speed would ensure road users using the same lane or road are on equal terms.

Legislation promoting standardisation among AV manufacturers was mentioned as important by several of the interviewees. In particular, standardisation is essential in designing intent indicators such as eHMIs and potential on-bike HMIs to correspond with colours, symbols, and signs road users are already familiar with in the current traffic environment. International agreements on standardisation of such indicators could cause less confusion and increase

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safety in a future where road users, to a greater extent, might depend on information from eHMIs, HMIs, and smart infrastructure.

> *”I think the issue here is just standardisation. Everyone can come up with like two hundred different concepts, but which are you going to choose.” (NL23)*
>
> *“If different manufacturers use different signals, or there is signal type that is otherwise used in traffic. Then it can get a little messy.” (NO8)*

With the trend of increasing connectivity in today’s society, some of the interviewees had privacy concerns about sharing location data with connected automated vehicles, infrastructure and other vulnerable road users. Any device used to detect or share data from cyclists should comply with privacy regulations.

> *”This would also trigger a big discussion about personal data, of course. I don't want people to know where I'm going, and this kind of stuff. So, I'm also not very happy or I'm reluctant, you know, sharing all of my personal thought just like that (…). But I would expect that there would be some rules about that and a certain amount of anonymity. In that case, I would say that it has quite a lot of positives.” (NL21)*

The interviewees suggested that data sharing should be anonymised, and that cyclists should only be detectable within a given radius. On the other hand, a few participants pointed out that most of us already are providing sensitive data to various tech companies and governments from devices such as wearables and smartphones. Assumingly, data sharing might be inevitable, and opting out may no longer be possible:

> *”How things are going at the moment, we are kind of doomed on privacy.” (NL24)*

### Automated vehicles

The theme of Automated vehicles consists of cyclists’ expectations and AV capabilities, the challenges they will encounter in a future of AVs, as well as what needs cyclists have to safely interact in traffic with AVs.

Some of the interviewees argued the transition period from semi-automated vehicles to fully AVs will be longer than expected. Although they recognised that disruptive technologies force people to reconsider their current systems, some were sceptical if fully automated vehicles are the future. They argued that a change of focus to active transport like walking and cycling would be more desirable:

> *"If the car industry and tech bros define the mobility of the future, then you get something that is not egalitarian and that solves a very minority of its problems at the expense of everyone else. Because it taps funding from public transport and facilitation of vulnerable road users. (…) I do not think it is impossible to implement. But I think implementation comes at a social cost that is too high." (NO4)*

However, in a future where motorised vehicles are fully automated, AVs are expected to react faster and more rational, make fewer mistakes and be more predictable in traffic compared to humans. AVs would not overtake as often and be consistent in the use of turn signals, resulting in smoother interactions.

> *"You do not quite know what human drivers will do. If a car is automated, you kind of know how it will drive. Maybe it is better at using intent indicators. It would be easier to deal with." (NO8)*
>
> *"I think the technology of the future will be sufficient, that as a cyclist you do not have to think so much about it. The cars are good at detecting cyclists. In theory, there should not be any dangerous situations. It is possible that errors occur. But I think that it will be safer than having a [human] driver or steering wheel." (NO5)*

Some of the cyclists noted that they expect the ambiguity of today's traffic to continue in the future. AV algorithms reflect human input and may be shaped by the attitudes and prejudices of programmers. If AVs are programmed to be normative, this will imply a change in traffic interaction as current cycling interaction follows informal rules and non-verbal cues. The interviewees claimed AVs should mimic human behaviour, replicate subtle cues, and adapt to sudden movements.

The consensus among the participants was that it is the AVs' responsibility to ensure other road users' safety. It was assumed that AV programming would be considerate and prioritise the safety of vulnerable road users. Some of the interviewees did, however, voice concern about safety during the transition period and fear there will be a decrease in car accidents, but an increase among vehicles and cyclists. One interviewee noted that automation adds a layer of uncertainty in traffic: Most humans have an inherent motivation not to hurt themselves and others, while automation does not. This unknown factor may add to the complexity of traffic interaction.

> *"As a vulnerable road user in traffic, automating other road users just adds more uncertainty. People who drive a car mostly have a desire to make traffic flow*

*smoothly and not harm other people. That’s very straightforward and easy to relate to” (NO10)*

On the other hand, AVs programmed to be conservative might lead to risk-taking and frustration, and traffic safety might be affected by AVs’ exploitation:

*”I can imagine some people exploiting the automated vehicle, knowing that it sees me and it’s going to stop for me, so I'm just going to keep on biking, I don't care.” (NL17)*

*”If it continues with that level of conservative behaviour of safety [as today], that could lead to frustration of other road users and lead to risk-taking. In my view, I think it should behave as realistic as possible (…), not too aggressive and not too cautious.” (NL25)*

In the end, there might be a trade-off between prioritising the safety of vulnerable road users and traffic efficiency:

*“It boils down to the debate of the car being programmed to save vulnerable road users at all costs, whether you can really trust that. (...) If the car is programmed to be completely safe, then it wouldn't move at all.” (NL23)*

The cyclists did have very limited, if any, experience cycling with AVs at the time of the interviews. There was an expectation that AVs would be connected and share information about the environment with other road users and infrastructure. The interviewees assumed that future AVs would be capable of receiving and transmitting information about the position, speed, and trajectory of other road users such as cyclists. Some cyclists suggested that the AV could adapt its driving style to the road user group, for instance, by driving slower or more conservatively in areas with cycling children.

The cyclists expressed scepticism about whether they would be comfortable or trust AVs in mixed traffic. They were concerned about how AVs would interpret rule-breaking behaviour and understand informal rules. A few cyclists questioned if AV intelligence will be advanced enough to adapt to cyclists’ versatility and unpredictability and whether unexpected behaviour such as frequent stopping by conservative AVs would affect safety and traffic flow.

Some cyclists prefer more distance between cyclists and AVs than with human drivers. Being informed about AVs’ capabilities and limitations or receive training with AVs might substitute this need, some cyclists suggested. The interviewees assumed that cycling with AVs will be safer and more pleasant than today once the technology is sufficient and trust is established.

One of the most reoccurring topics among the cyclists interviewed was the need to be seen in traffic, and acknowledgement that the AV detects the cyclist. With fully automated vehicles, the factor of eye contact between the driver and the cyclist will be lacking. Moreover, the eye contact gained with the passenger in the vehicle might add to more confusion. The interviewees preferred that the AV signalises both detection and vehicle intent explicitly. While some interviewees said that the turn indicators of today's vehicles are sufficient, the majority called for additional on-vehicle eHMIs for AVs:

> *"The major problem that I face, and my fellow cyclists and pedestrians face, is that you don't know what the car is going to do. (…) I think there needs to be some sort of tangible information that is conveyed to the bicyclist that lets him know if he should go or stop, whatever it is. But then it needs to be a very tangible thing from the end of the car, not from the end of the bicycle." (NL23)*
>
> *"It would be nice to see that the car has identified me and is going to stop (…) a light or the same way to have a hand interaction with the driver to say: thanks." (NL24)*

The interviewees portrayed on-vehicle eHMIs as a useful way for AVs to display info in the initial stages of deployment. eHMIs offer an objective indicator of intention and are assumed to increase traffic flow. Described as particularly applicable in zones with much human-human interaction, the main challenge of eHMIs arises when conveying information to a group of road users. It might be preferred in such cases that a general message, such as vehicle status, is displayed.

> *"If automated vehicles also have displays that give instructions to the cyclists; that you may go first. I think then it becomes so important to know who that information is directed towards. If there's two cyclists, or three cyclists, not from one direction, but in opposing directions, but they see the same automated vehicle, how does that automated vehicle then customise personalised information for each of these cyclists that it's interacting with?" (NL17)*

A few cyclists pointed out that AVs should not be explicitly marked as fully automated, as this might make other road users try to exploit it.

Regarding design strategies for on-vehicle HMIs, the interviewees' preferences varied. Some would prefer the AV indicating intention or a message on display, others by a light strip or a light, with different colours indicating detection of the cyclist or the AV's intention. Some said that they prefer an eHMI as audio over a display, but the consensus was that audio might be hard to detect or cause distraction in traffic.

> *"It could be something as simple as a sound, auditory display, or maybe some displays, light flashes, indicators. There's a plenty of options." (NL23)*

**Human-machine interface**

The dimension of HMI encompasses cyclists' perceptions and attitudes towards on-bike HMIs, along with HMI design strategies and desired HMI functionality. One of the most common sub-themes of HMI is the potential of an HMI to increase cyclist safety. A device could add more predictability, reduce human error, help AVs understand cyclists' intention, and make the interaction more efficient and comfortable. Some cyclists did not see many disadvantages with a cyclist HMI and believed it might reduce mental workload, especially in urban areas where busy traffic requires constant attention.

> *"I think it helps in reducing human error. Sometimes I may see something from the corner of my eye. In the junction I cross, it doesn't only have an intersection this way, but also it cuts from the left, sometimes I miss the guy cutting from the left. So, having that information would be helpful to increase spatial awareness." (NL23)*

Connectivity (bicycle-to-vehicle communication) was also a reoccurring topic. Being mutually aware of other road users' positions and intentions could benefit cyclists' situational awareness and reduce uncertainty in the traffic environment.

> *"I think from a safety point view, communication would be nice. (…) I think the advantage of communication is that the car can detect all the time the changes in the speed profile and acceleration, so it can detect easier if there is a potential for an accident." (NL25)*

Among the interviewees, the consensus was that a device should not be mandatory. Some of the cyclists claimed a device would be of no advantage to the cyclist and only benefit the AV.

> *"The challenge is that [the HMI] will be one more thing to deal with, in a situation where you are already the vulnerable road user and the losing part. [It] should not exist." (NO10)*
>
> *"I would be really annoyed if I had to buy that so other people can drive automated vehicles." (NL20)*

If a device is needed to communicate safely in traffic, some interviewees claimed that it would become a barrier to the convenience of cycling: Devices break and need maintenance, or the cyclist might forget the device at home. There is also the matter of cost, which would affect the accessibility for all sorts of cyclists.

> *"I believe that having as little electronics on the bike as possible and make [bikes] easily accessible to the vast majority is better. The responsibility should be placed on the scary, heavy machines and those who manufacture these, not with the vulnerable road user." (NO15)*

The consensus was that the responsibility of safety lies with AVs: AV technology should be sufficiently able to detect cyclists before AVs are released in traffic. If AVs start relying on data collected from VRUs' devices, some of the interviewees feared that this might decrease safety, as the AV could misinterpret the absence of data from non-users.

> *"It's problematic to plan for such a system (…). Because then, in a way, there is an expectation that the vast majority must have it, or that everyone has it." (NO12)*

Several of the cyclists interviewed stressed that the simplicity of the bicycle is its advantage, and that they do not want an additional device to be safer in traffic:

> *"The bike is so technologically free from all gadgets; that's what gives it an advantage. Anything that has new regulations about how a cyclist should behave, or have equipment, I am definitely opposed to. This will make it more difficult for cyclists. (…) It will make it easier and better for the automated vehicle, and that's the wrong way to look at it. Turn it around. It is not the cyclists or the pedestrians who should have to adapt to the automated vehicles." (NO11)*

While a device could increase situational awareness, an HMI might also be distracting and make the cyclists unfocused. Additional information from a device could increase complexity in traffic. There is also the matter of trust. Placing too much trust in a device could cause less awareness.

> *"You start relying too much on technology and also that you tend to become lazy, in the way of sensing things. (…) Adding more of that technology can also give you a false safety, which causes you to do other things than being alert." (NL29)*
> *"So unfocused that you (…) become a traffic hazard. You get so preoccupied with signals from the computer, vibration, light, everything." (NO1)*

The most common HMI design strategy among the interviewed cyclists was an on-bike device. A detachable device mounted on the handlebars could be utilised across bicycles. On the other hand, an integrated, less conspicuous device or sensor system might deter theft. It could also have the potential to be used to track the bicycle if it gets stolen. Whether the device should be integrated or detachable depends on the functionality. Some cyclists noted that they do not like carrying extra accessories and that the device might be easily misplaced if it is detachable. Several of the cyclists envisioned an HMI as a wearable, by using an application on their smartphone or smartwatch, or as AR-glasses.

Design strategies identified in the analysis were divided into four main categories: audio, display, haptics, and lights. Most importantly, an HMI should be designed user-friendly and intuitive. Weather resistance and robustness are also key features. A device using audio was not preferred by most cyclists. The device could, however, have voice recognition and the possibility of voice commands.

The most commonly mentioned design strategy was a display or a screen. The display must be visible in sunlight and display vital information. The visual information should be simplistic, easy to read, and use colours and icons that road users are already familiar with.

> *"The visual part is very important. (...) I wouldn't put too much information on the screen, like not cluttered information, not things that are difficult to read because you're on the bike and especially if you drive with 20 kilometres per hour, you need to pay attention to the street." (NL21)*

Changing display modes according to the purpose of the trip would also be desirable for some cyclists. For instance, the cyclist may require different cycling information in urban areas compared to rural areas.

A display could be combined with haptic feedback from the handlebars and seat. However, some cyclists prefer no display; instead, they opt for haptic feedback combined with a light or an LED light strip providing additional information. Haptic feedback would ensure full visual attention on the road while cycling. One interviewee noted that there might be too much vibration from the road for haptics to be feasible. A simplistic type of HMI envisioned by the interviewees was lights on the handlebars signalling detection by the AV. Lights could also be used to signal the intention of the cyclist, substituting hand gestures.

The cyclists envisioned a broad spectrum of HMI functionality. The main objective of an on-bike HMI is to enhance human communication. If connected to AVs, the device becomes the agent representing the cyclist. However, the device should provide additional information, not make decisions:

> *"It could just be for information acquisition, but not the deciding factor in decision making for the AV and the cyclist. Just get more information, that helps with reducing the uncertainty of the driving environment." (NL17)*

It would be an advantage if both cyclists and pedestrians could utilise the device. The most common display type of functionality envisioned was a radar-like interface showing the location, trajectory, or intent of other road users such as AVs.

> *"It's almost like a radar, I think. [The other road users] see which direction I'm riding, and the instrument shows those who are crossing in my direction – they could be visually presented on the screen. An arrow showing direction." (NO3)*

A similar approach could be used for an AR glasses interface. The device could notify the cyclist if another road user is close to crossing the cyclist's trajectory. To not interfere with the cycling experience, the cyclists preferred to be notified by the device on rare occasions:

> *"Ideally, it will be nice to combine augmented reality. So, I can wear some smart glasses and I don't have to look on a screen to get information from my bike if needed. I just enjoy the nature and I look at the road (…). But then I can see my own speed or I am signalled to be careful if a car is coming." (NL24)*

A feature often desired by cyclists was also whether a car is approaching from behind or emerging from side/entryways with low visibility.

The interviewees envisioned the device's key functionality as connectivity: The device is most likely connected to AVs and infrastructure. The device could provide each bicycle with a unique ID and broadcast info like the cyclist's speed and position to AVs and infrastructure. With a display type of interface, the device could exchange this information between the bike and the AV. With connectivity, the device could show the remaining time until a green light ahead or help the cyclist arrive at an intersection at a green light by adjusting the bicycle's speed or changing the traffic light itself.

An on-bike HMI could also function as a cycling computer showing speed, elevation and heart rate of the cyclist. As an integrated navigation system, the device could advise travel routes according to characteristics, such as the most scenic, fastest, or less congested cycling route. The device has the potential to collect user data from bicycles. The cyclist could receive analytics and advice on their cycling and traffic behaviour based on smartness, travel, and personal historical data. Data collected could also be used in research and development, create maps of cities, and provide user data on other road users. The privacy issues related to connectivity and exchanging information in the theme Legislation overlaps with the theme of HMI.

## Discussion

The thematic analysis resulted in seven themes constituting cyclists' experiences and challenges in today's traffic and how these might change in the future with AVs: Interaction, Bicycles, Culture, Infrastructure, Legislation, AVs, and HMIs. The following sections discuss the implications of the findings for cycling today and future interactions of cyclists with AVs, followed by a discussion on whether on-bike HMIs and connectivity are necessary or useful, or if a better solution would be to focus on detection by AVs and infrastructure rather than connected bicycles.

### Cycling today

From the analysis, experiences with and perceptions of cycling are described across several themes, mainly Interaction, Bicycles, Culture, Infrastructure, and Legislation. As a mode of transport, the theme of Bicycles shows how bicycles are versatile and cover most of the everyday needs for transport. While there are varied reasons why cyclists choose to cycle, some of our interviewees depicted cycling as *good* in every conceivable way. Compared to personal motorised vehicles, cycling is assumed to be better for the environment and beneficial to public health, contributing to a more sustainable transport system. These viewpoints have been addressed in previous research as well, emphasising the environmental effects (McDonald et al., 2015) and health benefits (Boschetti et al., 2014; Pucher & Dijkstra, 2003; Raser et al., 2018) of active transport and the fact that cycling is environmentally, socially and economically sustainable (Pucher & Buehler, 2017).

The theme Interaction describes cyclists' perceptions of cycling and how cyclist interaction is guided by eye contact, hand gestures, and motion cues corresponding to formal and informal rules. These aspects of interaction are reflected in previous research (Bjørnskau, 2017; Lundgren et al., 2017; Vissers et al., 2017; Walker, 2005).

More cyclists interviewed in the Netherlands indicated that they generally feel safe while cycling than participants from Norway. The analysis implies that the disparities in perceived safety might be related to differences in the themes Culture and Infrastructure between the two countries. Norwegian cyclists reported that they must wear protective gear and equipment to cycle in traffic. The same was not the case among the Dutch interviewees; a few noted that helmet usage is not encouraged in the Netherlands. In recent years, though, the sport-centred Norwegian cycling culture has been portrayed as changing to resemble the diversity of Dutch cycling culture, fuelled by a political climate promoting active transport, increased shares of cyclists, and bicycle infrastructure.

The need for designated cycling infrastructure was a prevalent sub-theme in the analysis. Bicycle infrastructure in the two countries still differs significantly. Dutch cities have invested heavily in cycling facilities since the 1970s (Pucher & Dijkstra, 2000). These investments have ensured a more consistently designed network of cycling infrastructure separating cyclists from motorised traffic. This is not the case in Norway. Note that inconsistently designed cycling infrastructure where bike lanes suddenly end or impede cyclists' traffic flow is not strictly a Norwegian phenomenon. A British interview study on cycling expressed similar findings (Christmas et al., 2010).

As suggested by our interview participants, investing in cycling infrastructure could set precedence and show that cyclists belong in traffic. Several of the interviewed Norwegian cyclists noted that they do not need fully separated cycling infrastructure to feel safe in today's traffic – they are satisfied with an integrated bicycle lane, preferably separated by slight elevation and sufficient width for takeovers. Previous literature is inconclusive whether completely separated cycling infrastructure is safer than bicycle lanes (Cripton et al., 2015; Melhuus et al., 2015). Schepers et al. (2011) indicated that bicycle lanes have 54% more cycling accidents in intersections than bicycle paths. Nevertheless, the effect of bicycle lanes versus mixed traffic on accidents is evident; a meta-analysis of the effect of bicycle lanes on cycling accidents showed that there is a decrease of about 45% in accidents with a separate lane compared to cycling in mixed traffic (Høye et al., 2015). These findings give some validity to the viewpoints of the interviewees in our study: Completely separated infrastructure increases safety and could explain why the interviewees in the Netherlands generally felt safer than interviewees in Norway. In turn, bicycle lanes are safer than cycling in mixed traffic and, if invested in, would probably increase the perceived safety of Norwegian cyclists as well.

The differences in infrastructure and cycling culture in the Netherlands and Norway might affect how cyclists perceive interaction with other road users. While most of our interviewees reported interaction with others as smooth, more cyclists in Norway mentioned drivers as problematic compared to the Dutch participants: They reported that some drivers seem annoyed, drive aggressively, and do not appreciate sharing the road with cyclists. As Norwegian cyclists often do not have a clear place or role in traffic, they can make split-second decisions according to the situation, including cycling on sidewalks and pedestrian crossings. This unpredictability can be one of the main contributors to conflicts between cyclists and motorised vehicles (Bjørnskau et al., 2012). However, in another Norwegian study, drivers reported that the sudden role changes were not a significant issue, but rather cyclists often running red lights (Fyhri et al., 2012).

### Future interaction: Expectations and cyclist needs

The theme of Infrastructure shows that our interviewees had a clear preference for completely segregated infrastructure in future traffic with AVs. Segregation of cyclists and AVs has been noted as ideal in other interview studies (Botello et al., 2019). However, our interviewees did argue that their scepticism towards sharing facilities with AVs might change as they become more experienced with AVs. This finding is in line with Blau et al. (2018), where cyclists were more likely to prefer protected facilities over sharing the road with AVs.

The theme of AVs depicts how our cyclists expect future AVs to embody equal or better capabilities than human drivers. AVs are assumed to be capable of replicating and understanding the implicit, subtle cues of human road user interaction. Human motorists tend to deviate from traffic rules by yielding to cyclists regardless of priority (Bjørnskau, 2017; Van Haperen et al., 2018), which indicates that AVs following familiar, non-normative interaction patterns might be necessary when interacting with cyclists. The challenge, however, is that the informal communication cues of cyclists can be subtle and unambiguous and might be difficult to anticipate or decipher by AVs (Kooij et al., 2019; Vissers et al., 2017).

In the theme of Interaction, the cyclists described eye contact as a part of how cyclists negotiate in today's traffic. Some interviewees expressed concern that eye contact would be lacking when there is no longer a human driver present in the AVs. As a behavioural cue, eye contact of the driver may encourage cyclists to continue pedalling (Bazilinskyy et al., 2021).

However, some of the interviewees claimed that they do not use eye contact at all but instead rely on vehicles' motion cues. Risto et al. (2017) identified movement gestures as the vehicles' primary mode of expressing intent. Indeed, in future AV-cyclist interaction, interpreting AVs' motion cues and movement patterns might suffice (Habibovic et al., 2016; Lee et al., 2020; Moore et al., 2019; Sripada et al., 2021).

Our analysis indicated that cyclists prefer AVs to communicate recognition explicitly. Similar findings are shown in Merat et al. (2018), where cyclists and pedestrians reported that they would prefer to receive communication about AVs' status and behaviour, particularly about detecting VRUs. Proposed solutions by the interviewees in the present study included eHMIs or vehicle-to-bicycle technology, which is in line with the current development of eHMIs to enhance road user interaction (De Clercq et al., 2019; Habibovic et al., 2018; Lundgren et al., 2017; Mahadevan et al., 2018; Merat et al., 2018; Rouchitsas & Alm, 2019). However, another issue brought up in a few of our interviews was how eHMIs would communicate recognition when there is more than one recipient. A solution could be an eHMI conveying the AVs' current state rather than instructing VRUs what to do (Tabone et al., 2021a).

The dynamic and versatile nature of cycling points toward a need for new types of eHMIs, for example, eHMIs that can be perceived omnidirectionally, as suggested by Eisma et al. (2019), or directional eHMIs that can address specific road users, as suggested by Dietrich et al. (2018).

### On-bike HMIs: Potential and design strategies

Electrification was one of the most recurring bicycle features mentioned in the interviews. While our interviewees said they enjoy the physical activity involved in cycling, they argued that the future of cycling is likely to be electric. Market trends confirm this notion: E-bike use is on the rise, and shares of e-bikes in the Netherlands are expected to increase from 19% to 37% by 2025 (KiM, 2020).

Previous literature suggests that on-bike HMIs can accommodate cyclists' needs for detection and communicate that the AV has recognised the cyclist (Schieben et al., 2019; Tabone et al., 2021). The theme of HMI describes how the interviewees proposed that an on-bike device might increase safety. An ideal device would result in more predictable interactions, reduce human error, and help AVs understand cyclists' intentions. Connectivity would be a key functionality of on-bike HMIs—being mutually aware of other road users' positions and intentions could benefit the cyclists' situation awareness and reduce uncertainty in the traffic environment.

Some of the cyclists we interviewed were interested in using an on-bike HMI to communicate with AVs if the utility value is beyond guaranteeing their safety. For instance, the device could function as a navigation system or a cyclo-computer. As noted by several of our interviewees, a detachable HMI might be more feasible than a device integrated into the frame or handlebars. Still, with cyclist accessories such as helmets, bags, and e-bike batteries, a few interviewees noted that carrying extra devices is a hassle to be avoided. The utility value of bicycles, costs, and potential theft imply that the most apparent solution as to HMI design strategies is to use devices already available to cyclists, such as their smartphones, cyclo-computers or other wearables. A wearable HMI design fits well with previous research on VRU connectivity, where most solutions involve using smartphones or wearables (Dasanayaka et al., 2020; Scholliers et al., 2017).

Positive aspects aside, the majority of the cyclists in our interview study were hesitant about on-bike HMIs. A major dilemma is that a device would have to be mandatory and universal as the absence of data will not inform the AV of VRUs' presence, potentially putting these road users in increased danger. Most of the interviewed cyclists, however, said that a device should *not* be mandatory for communication with AVs. Our interviewees disapproved of a device merely connecting AVs and infrastructure by broadcasting the cyclist's location or ID tag. They argued that there should not be a need for on-bike HMI and connectivity between VRUs and AVs with sufficient development of AV technology before its employment on a large scale in traffic.

Another concern voiced in the interviews was that an on-bike HMI requirement might become a barrier to cycling. The interviewees reasoned that an on-bike device might reduce the accessibility of cycling, as cycling is traditionally a cheap and simple mode of transport. One could argue that simplicity is not a universal desire among cyclists: The average price of a Dutch bicycle is among the highest in Europe[3]. Moreover, 60% of the interviewees said they

[3] According to Statista (2020)

own more than one bicycle and choose their type of bicycle according to the purpose of the trip. Even so, additional bicycle costs are undesired, as theft is common. On average, half a million Dutch report bicycle theft worth €600 million yearly (Kuppens et al., 2020).

In summary, the consensus among our participants was that the primary responsibility of safety lies with the AV. Being dependent on a device that might malfunction, be misplaced or stolen was not desired. There were also concerns about how AVs interpret the absence of data from non-users and about road user privacy. Similar arguments were made by academic, industry, and government experts in an interview study on AVs and planning for active transport, where they expressed concern about a VRU device requirement for recognition by AVs: While a device might increase safety, a requirement might not be egalitarian and could pose privacy issues (Botello et al., 2019).

The ethical aspect of safety and responsibility of AVs versus VRUs is reflected in previous literature proposing connectivity among all road users (OECD/ITF, 2019; Owens et al., 2018). Worst case scenario, we could end up with a second-class citizen society, where only people who can afford these devices can safely leave their homes in urban areas with AVs. This issue draws parallels to the ethical issues debated in the light of the COVID-19 pandemic, i.e., whether the population will be needing a vaccine pass to access certain services or be allowed to travel freely (Voo et al., 2021).

Even though our interview participants were hesitant about on-bike HMIs to enhance communication with AVs, this does not necessarily mean that on-bike HMIs should be rejected immediately. The public does not always welcome traffic safety measures. For instance, most drivers recognised that vehicle safety belts effectively reduce or prevent driver injuries, but seat belt usage was not prevalent when first implemented. Similarly, while the Dutch safety belt mandate increased seat belt usage from 20% to 50% in 1975 (Hagenzieker, 1992), it took another 35 years before seat belt use became nearly universal (SWOV, 2012).

Acceptance of new technology to enhance road user safety might increase with more experience and knowledge (Nordhoff et al., 2020), and this might also be the case with on-bike HMIs. With e-bike use on the rise (KiM, 2020) and increased connectivity and smart travel in the future transport system (Behrendt, 2019), it is plausible that at least some future bikes will be connected via (low-cost) Wi-Fi. By placing the responsibility of safety on the AVs, cycling connectivity may become an option rather than a requirement. Various simple, inexpensive, and optional on-bike HMIs can be envisioned as a starting point, such as a vibrating handlebar or integration with existing cyclo-computers.

**Future studies**

A possible limitation of the present study, originating in the qualitative nature of the research, is a lack of generalisability. Whether the viewpoints depicted in our study can be generalised to the general public should be explored on a larger scale in future studies, along with potential other solutions than on-bike HMIs for enhancing AV-cyclist interaction.

Future studies should further investigate to what extent additional, explicit behavioural cues of AVs, such as eHMIs, are necessary to ensure safe and desired interaction between cyclists and AVs. For instance, exploring whether on-bike HMIs are necessary or useful in a naturalistic setting might bring insight into their feasibility as a traffic safety measure. Moreover, exploring other solutions that do not require connected cyclists via additional devices is essential, such as improved detection sensors in AVs, on-vehicle eHMIs, and smart infrastructure systems.

## Conclusion

Our analysis showed that cyclists' primary need in AV-cyclist interaction is sufficient detection by AVs. Moreover, cyclists prefer that the AVs communicate recognition explicitly. The findings strengthen the notion that on-bike HMIs are potential solutions for enhancing interaction between cyclists and AVs. Previous studies on enhancing AV-cyclist interaction tend to focus on the technical feasibility of such devices and their effect on safety, without considering the actual end-users. Our analysis yielded that the interviewees particularly favoured HMI functionality, informing them about other road users' location, and road user connectivity.

The analysis also uncovered that cyclists are hesitant about on-bike HMIs, mainly in terms of unclear utility value and the ethical aspect of imposing the responsibility of safety on the more vulnerable road user. Moreover, a device requirement might become a barrier to cycling, as increased costs are undesired and theft is common. Even if we are utilising ubiquitous devices in the future, we should be careful about adding restrictions or requirements that may discourage the population from choosing active transport, as cycling and walking is beneficial to public health and the environment. Future studies should investigate user acceptance of on-bike HMIs among VRUs on a larger scale to test the findings' generalisability and explore other, perhaps more viable, solutions for enhancing AV-cyclist interaction.

### CRediT authorship contribution statement

**Siri Hegna Berge.** Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualisation, Writing – original draft. **Marjan Hagenzieker:** Conceptualisation, Funding acquisition, Supervision, Validation. **Haneen Farah:** Supervision, Writing – review & editing. **Joost de Winter:** Conceptualisation, Funding acquisition, Supervision, Validation, Writing – review & editing.

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### Research data

A REFI-QDA Standard project file with anonymised interview transcripts, analysis, document groups, code groups, and codes, along with text files containing the same information are available at the 4TU.ResearchData repository at https://doi.org/10.4121/c.5559372

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# APPENDIX A.1: INTERVIEW GUIDE

*[All notes in italic are cues or explanations and not necessarily conveyed to the participant]*

**Topic: Background (5 min)**

First, I thought we would start off with some background questions.

1. Where do you live?
2. How old are you?
3. What do you do for a living?
4. How often do you go cycling? *(frequency, distance)* If at all, where? *(urban or rural).* Winter?
5. Do you own a bike? *(shared rental, regular or electric etc.)*

   *If yes:* What kind?

   *If no:* Do you use rental or shared bikes?
6. When it comes to using new technology, would you consider yourself …
   a. An early adopter?
   b. Among the last to try
   c. Somewhere in between?

**Topic: Current traffic interaction (12 min)**

I would like to know about your experience with cycling …

7. Could you start by describing a typical (cycling) trip?
8. How would you describe the interaction with motorised vehicles?
9. Do you encounter any challenges while cycling? Please elaborate.

   *Probe for unsafe situations, workload, situational awareness when interacting with motorised vehicles.*
10. As a cyclist, what do you think would make you feel safer in traffic?

    *(Improved infrastructure, bike lanes, bike paths, better/enhanced bikes)*

We are doing interviews in different countries and would like to see if there are any differences in cycling culture …

11. How would you describe the cycling culture in [country]?

    *Traffic safety culture definition: "Common norms for desired or normal behaviour in traffic, shared expectations of other road users and common values/priorities (e.g., safety, accessibility, courtesy)".*

**Topic: The future of cycling (12 min)**

Imagine the future, where cars are fully automated, and there is no longer a human driver behind the wheel *(there might not even be a wheel)*.

12. How will this impact you as a cyclist?

    *For instance, some of the interaction between road users are based on behavioural cues like facial expressions, hand gestures and/or eye contact*.
13. *Follow-up:* What will change?

14. How do you think *(situations from question 9)* will change when cars are automated and driverless?

In the future, where cars are automated and there's no driver to interact with...

15. As a cyclist, what kind of information would you need from an automated vehicle?
    *Cues if stuck: eHMIs: (Projected) light or sound signals indicating intended behaviour, text-based signs on the car ("stop", "turning right" etc.), a sign indicating fully AV*.

**Topic: Bicycles and technology (25 min)**

For my next question, I want you to continue thinking of the future. Imagine the future of cycling, with new and exciting technological progress.

16. I want you to think of your perfect bicycle *(does not have to be realistic).*
    a. What would it look like?
    b. What kind of features would it have? *(Enhancements, jetpacks, electric, non-electric, connected, apps, anything goes)*
    c. What kind of technology?

In the future, where cars are automated and driverless:

17. Imagine a system or device that helps you interact with automated vehicles.
    a. How should this device be designed?
        *i. On-bike (attached or detachable)*
        *ii. Integrated in bike (in the frame or handlebars)*
        *iii. As a wearable (phone app, AR glasses, etc.)*
    b. How should the device communicate with the cyclist?
        *i. Audio*
        *ii. Light*
        *iii. Vibration/haptics (handlebars or seat)*
        *iv. Display screen or cyclometer*
    c. Would you be interested in using such a device? Why/why not?

18. If you could receive information about other road users such as automated vehicles through a device or system on your bike *(like the one you just imagined)* …
    a. What are the benefits of such a system?
    b. What kind of traffic information would be useful to receive?
    c. What kind of information about cyclists would be useful for the automated vehicle?
    *Cues: Connected vs detected, map trajectory of cyclist to avoid conflicts etc.*
    d. What are the disadvantages of such a system?
    *Cues: Increased mental workload, trust, overreliance*

## 7.2 Appendix B. Support systems for cyclists in automated traffic: A review and future outlook

Berge, S. H., De Winter, J., & Hagenzieker, M. (2023a). Support systems for cyclists in automated traffic: A review and future outlook. *Applied Ergonomics*, *111*, 104043. https://doi.org/10.1016/j.apergo.2023.104043

**Abstract**

Interaction with vulnerable road users in complex urban traffic environments poses a significant challenge for automated vehicles. Solutions to facilitate safe and acceptable interactions in future automated traffic include equipping automated vehicles and vulnerable road users, such as cyclists, with awareness or notification systems, as well as connecting road users to a network of motorised vehicles and infrastructure. This paper provides a synthesis of the current literature on communication technologies, systems, and devices available to cyclists, including technologies present in the environment and on motorised interaction partners such as vehicles, and discusses the outlook for technology-driven solutions in future automated traffic. The objective is to identify, classify, and count the technologies, systems, and devices, extrapolate the potential of these systems to aid cyclists in traffic with automated vehicles, and stimulate discourse on the implications of connected vulnerable road users. We analysed and coded 92 support systems using a taxonomy of 13 variables based on the physical, communicational, and functional attributes of the systems. The discussion frames these systems into four categories: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems, and highlights the implications of the visual, auditory, motion-based, and wireless modes of communication of the devices. The most common system was cyclist wearables (39%), closely followed by on-bike devices (38%) and vehicle systems (33%). Most systems communicated visually (77%). We suggest that interfaces on motorised vehicles accommodate cyclists with visibility all around the car and incorporate two-way communication. The type of system and the effect of communication modality on performance and safety needs further research, preferably in complex and representative test scenarios with automated vehicles. Finally, our study highlights the ethical implications of connected road users and suggests that the future outlook of transport systems may benefit from a more inclusive and less car-centred approach, shifting the burden of safety away from vulnerable road users and promoting more cyclist-friendly solutions.

## Introduction

Before the large-scale deployment of highly automated vehicles (AVs), AVs must understand the social aspect involved in road user interaction. Specifically, interaction with vulnerable road users (VRUs) in complex urban traffic environments remains a significant challenge for AVs (Rasouli & Tsotsos, 2020; Schieben et al., 2019). One proposed solution for supporting VRUs in future automated traffic is equipping AVs and VRUs with human-machine interfaces (HMIs) that display notification messages and warnings (Berge et al., 2022a). Another solution, substituting the lack of explicit human-to-human communication by driverless vehicles, is external on-vehicle HMIs (eHMIs), providing communication cues to other road users through displays, lights, or projections on the road. eHMIs have been widely researched, including the effect of the physical shape and appearance of the interfaces, such as placement, colour, and the use of text, symbols, or lights (Bazilinskyy et al., 2019; Dey et al., 2020).

Research on AV-VRU interaction focuses primarily on the effects of eHMIs on the crossing behaviours of pedestrians (Dey et al., 2020; Rasouli & Tsotsos, 2020), on designing the interaction of Avs( (Schieben et al., 2019) and on AV acceptance (Merat et al., 2017). When cyclists are included in eHMI studies, they are rarely the main subject of study: None of the eHMI concepts identified by Dey et al. (2020) solely targeted cyclists, and only a few empirical studies focus specifically on cyclist interaction with AVs (Bazilinskyy et al., 2021; Berge et al., 2022a; Hagenzieker et al., 2020; Hou et al., 2020; Kaß et al., 2020; Rodríguez Palmeiro et al., 2018; Utriainen & Pöllänen, 2021; Nuñez Velasco et al., 2021; Vlakveld et al., 2020). Cyclists are vulnerable road users (Holländer et al., 2021), but differ from pedestrians in eye-gazing behaviour. Trefzger et al. (2018) found that cyclists are more preoccupied with looking on the road and gaze less frequently at vehicles than pedestrians. Cyclists also differ in speed and movement patterns compared to pedestrians: While pedestrians usually interact with vehicles at crossings, cyclists regularly share the road and travel parallel to vehicles, experiencing passing, merging, and overtaking situations (Berge et al., 2023). To ensure the safety of cyclists in automated traffic, targeting them as a specific road user group in research is vital. Currently, there is no overview of technologies and solutions for cyclists to improve their interaction with AVs.

With transport systems increasingly becoming part of the Internet of Things (IoT) (Behrendt, 2019), it has been suggested that interconnectivity between infrastructure, AVs, conventional vehicles, and VRUs is essential for the successful full-scale deployment of AVs (Farah et al., 2018; Sanchez et al., 2016). Interconnectivity could increase visibility among road users, making them mutually aware of each other's locations and trajectories, which in turn could be a significant safety improvement (Owens et al., 2018), resulting in a reduction in conflicts and better traffic flow (Papadoulis et al., 2019). At the same time, the rising security and privacy issues accompanying VRU connectivity tend to be overlooked and understudied (Hasan & Hasan, 2022). Although some researchers have questioned whether VRUs should depend on additional devices for safety in traffic with AVs (Berge et al., 2022a; Tabone et al., 2021), the discussion in academic and media circles regarding the ethical considerations surrounding connectivity for VRUs remains limited. In light of the proliferation of IoT and technological advances, it is plausible to expect that most new devices will have some form of connectivity in the near future. Therefore, we argue that a technological approach to support systems for cyclists merits further investigation in research, to establish a foundation for future studies and to promote ethical discourse.

The present study provides a synthesis of existing literature and a comprehensive overview of the state-of-the-art support systems for cyclists to encourage the discussion of technological devices and connectivity for VRUs such as cyclists in future automated traffic environments. The objectives of the study are three-fold:

1. To identify, classify, and quantify the various communication technologies, systems, and devices that have the potential to aid cyclists in automated traffic.
2. To align the support systems with knowledge about human factors related to cycling and to discuss the systems' potential in the context of AVs.
3. To provide a reflection on the prospect of AV-cyclist interaction and recommendations for future research.

The overall goal is to enhance the understanding of AV-cyclist interaction, promote discourse and research by identifying gaps in current literature, and discuss strategies for optimising cycling in future traffic environments with AVs.

## Method

This paper presents an exploratory synthesis and descriptive analysis of systems designed for cyclists and bicycles with the potential to affect cyclist interaction in automated traffic systems. We collected concept descriptions of the technologies, systems, and devices from the literature and taxonomically coded and analysed them descriptively. For simplification purposes, we refer to the descriptions of the identified technologies, systems, and devices as ‘concepts’ throughout the analysis.

**Selection of literature**

We performed literature searches in Scopus and Google Scholar to collect relevant academic articles. In addition, we used Google to identify informal or commercial concepts from the industry. The literature searches were dynamic as the field of support systems for cyclists in the context of AVs is new and emergent. When reviewing a topic with limited academic literature, the inclusion of grey literature and commercial publications can provide valuable insights and perspectives that may not be found in academic literature alone (Paez, 2017). Commercial concepts can offer practical, real-world examples of support systems for cyclists that have not been studied by academia but may still help understand the systems’ application and impact on cyclists in the context of AVs. As the field currently lacks a standardised nomenclature, we performed keyword searches combining words across four categories:

1. Target road user: cyclist, vulnerable road user, VRU.
2. Location: bike, bicycle, car, vehicle, infrastructure.
3. Function: interface, interaction, communication, detection, connect*.
4. Automation: autonomous, automated, self-driving, driverless.

The criterion for selecting the study sample was set to transport-related concepts capable of transferring messages or information among road users through technology, or the ability to be developed or adapted for use in the context of vehicles with automation capabilities beyond SAE level 2 (Shi et al., 2020). The publication had to indicate at least one cyclist or bicycle as the target user of the concept. For the searches in the scientific databases, the titles, and abstracts of the first 100 results were assessed for inclusion. When a relevant article was located, a search with the *related articles* function of Google Scholar was performed.

**Sample**

We identified 62 publications that fit the inclusion criteria. Out of the 62 publications, 40 of the articles were from academia, with 13 journal articles, 25 conference papers, one book section, and one poster. The remaining 22 publications were from industry, with 18 commercial or industry articles and four patents. Several of the publications contained descriptions of more than one concept description, adding up to 92 descriptions of concepts in total. Most of the concepts originated from Europe: Germany (20), the Netherlands (17), Italy (11), Sweden (9), France (3), the United Kingdom (2), Latvia (1), and Spain (1). Moreover, 12 concepts were published in the United States, followed by Canada with 9 concepts. Two concepts originated in Australia and Japan, and one concept from Colombia, Chile, Israel, and Taiwan, respectively. The oldest concepts identified were published in 2007, and the most recent in late December of 2021. See Appendix B.1 for a full list of the identified publications.

**Analysis and coding of concepts**

The study sample was analysed systematically using a taxonomical coding system outlined in section 2.4. The taxonomy was developed in an iterative process. First, we established the dimensions and definitions based on the classification taxonomy of eHMIs by Dey et al. (2020). The publications were analysed, and the identified concepts were initially coded based on their physical and functional characteristics in line with Dey et al. (2020). Throughout the initial coding, the suitability of each dimension was consecutively evaluated and modified per concept by creating cyclist- or bicycle-appropriate sub-categories and removing the original sub-categories that did not sufficiently describe our study sample. In cases where the original eHMI taxonomy dimensions did not depict all appropriate aspects of the identified concepts, the dimensions were merged or removed entirely, and new variables were created. For instance, variable *9. Functionality* is inspired by and covers in part the dimensions *Message of Communication in Right-of-Way Negotiation* and *Covered states* (Dey et al., 2020). The taxonomy was further refined through discussions within our research group.

The full classification taxonomy was applied to each of the 92 identified concepts. The physical and functional characteristics of the concepts were coded based on the descriptions or information available in the publications, varying from text and illustrations, to photos, animations, and videos demonstrating the concept in use. Certain concepts had multiple features, e.g., a concept could have HMI placements as an on-bike device and a cyclist wearable and utilise more than one modality of communication. Each of these features was recorded with separate values divided by commas within the applicable sub-categories. The variables pertaining to usability and realism in real-world traffic, such as *11. Complexity of implementation,* required interpretation during coding and relied on the coder's knowledge and understanding of the feasibility of the technology available today. The data from the 92 concepts were analysed descriptively using frequency counts and pivot tables in Microsoft Excel.

**Taxonomy definitions**

The taxonomy separates the concepts into four categories according to interface placement: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems. The concepts were further differentiated according to their physical characteristics, intended functionality, modality of communication, communication strategies, and evaluation method based on a refined version of the classification taxonomy of eHMIs proposed by Dey et al. (2020).

In total, there are 13 taxonomical categories used for coding the concepts: terminology, target road user, HMI placement, number of interfaces, number of messages, modality of communication, communication strategy, connectivity, functionality, type of concept, the complexity of implementation, support for people with special needs, and finally, concept evaluation. Table 1 shows an overview of the variables and their definitions. The variables directly adapted from Dey et al. (2020) are noted in the table. A full description and rationale of the variables can be found in Appendix B.2.

**Table 1**

*Taxonomy definitions*

| | Variable | Definition |
|---|---|---|
| 1 | Terminology | The words used to describe a concept. |
| 2 | Target road user | The type of road user targeted by a concept. |
| 3 | HMI placement | The location of the interface or location of the message conveyed to its intended recipient. |
| 3.1 | Cyclist wearables | The interface is located on the cyclist. |
| 3.2 | On-bike devices | The interface is located on the bicycle. |
| 3.3 | Vehicle systems | The interface is located on or within the motorised vehicle. |

| | | |
|---|---|---|
| 3.4 | Infrastructural systems | The interface is located on infrastructure. |
| 4 | Number of interfaces | The number of modalities capable of communicating a piece of information between the system and the human road user(s). |
| 5 | Number of messages | The number of messages communicated through an interface. Adapted from Dey et al. (2020). |
| 6 | Modality of communication | The way communication is achieved by a concept. |
| 6.1 | Visual | The concept communicates through visual perception and sight. |
| 6.1.1 | Colour | The colour of visual modalities. |
| 6.2 | Auditory | The concept communicates through the sense of hearing. |
| 6.3 | Motion | The concept communicates through the action or process of moving or being moved. |
| 6.4 | Wireless | The message is delivered through a signal transmission on a frequency spectrum. |
| 7 | Communication strategy | The way the system addresses road users when communicating its message. Adapted from Dey et al. (2020). |
| 7.1 | Unicast | The system communicates and delivers its messages targeted to a single road user. |
| 7.2 | Broadcast | The system broadcasts its messages to non-targeted road users. |
| 7.3 | Multicast | The system targets and delivers its message to multiple road users at the same time. |
| 8 | Connectivity | The concept has the capacity for interconnection by signal transmission between systems or users. |
| 9 | Functionality | The intended functionality or purpose of the message(s) communicated to its recipient(s). |
| 9.1 | Information systems | Systems informing road users about a particular arrangement or sequence of events. |
| 9.2 | Warning systems | Systems intending to convey messages of caution or urgency to their users. |
| 9.3 | Support systems | Systems conveying messages with a behavioural component of the cyclist or bicycle to its user, such as information about a cyclist's current or future behaviour. |
| 10 | Type of product | The concept stage of development (i.e., whether it is conceptual, a prototype, or an end product). |

| | | |
|---|---|---|
| 11 | Complexity of implementation | The complexity of implementing a concept in real traffic scenarios. Adapted from Dey et al. (2020). |
| 11.1 | Ready to use | Technology is ready to use today. |
| 11.2 | New technology required | The concept requires new technology but does not depend on widespread implementation or infrastructural changes to function. |
| 11.3 | New technology and large-scale changes required | The concept requires new technology but depends on widespread implementation or infrastructural changes to function. |
| 11.4 | Highly aspirational | The concept uses technology that is not yet developed or available. |
| 12 | Support for people with special needs | The concept accommodates the special needs of visually, auditory, or cognitively impaired persons through multimodal communication. Adapted from Dey et al. (2020). |
| 13 | Evaluation of concept | The concept has been evaluated in a scientific publication. Adapted from Dey et al. (2020). |

## Results

This section presents the results from the descriptive analysis of the coding and categorisation of the 92 communicative technologies and concepts identified in the literature search. See Appendix A for the full list of publications from the literature search.

### Terminology

We investigated the terminology used in the 62 articles. 55% of the articles used the word *system* to describe their technology, while about one in five referred to their concept as an *interface* or *HMI.* Other reoccurring terms were *communication* (13%), *warning* (11%), *safety* (6%), and *smart* (6%).

### Target road user

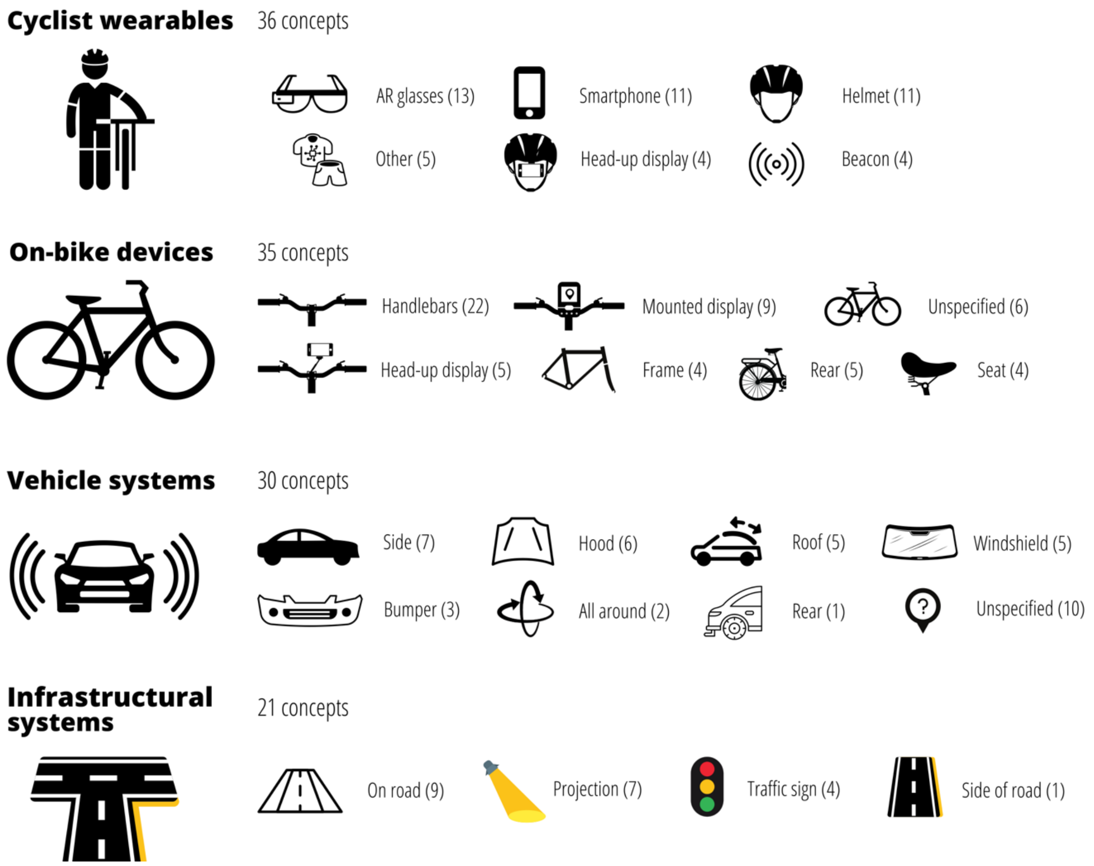
As inherent to the study's search strategy, cyclists were the target road user in all 92 concepts; however, cyclists were the sole target road user in 63% of the concepts. This means that the remaining 37% (34 of the concepts) were multi-agent systems involving the communication of messages to cyclists, pedestrians, or drivers/vehicles. Seven of the multi-agent concepts targeted cyclists and drivers/vehicles, 14 concepts targeted cyclists and pedestrians, and 13 concepts targeted all three groups of road users.

**HMI placement**

The most common placement of the system or interface was cyclist wearables (39% of all concepts), closely followed by on-bike devices (38% of all concepts) and vehicle systems (33% of all concepts). About one in four concepts had placements on infrastructure or projections on infrastructure. One out of three concepts was categorised as having more than one placement. For instance, De Angelis et al. (2019b) describe a multi-agent system with a display mounted on the bicycle's handlebars and a display placed on infrastructure. Another example by Matviienko et al. (2018, 2019a, 2019b) portrays a wearable system with interfaces embedded in the cyclist's helmet and on the bicycle's handlebars. Figure 1 shows an overview of the HMI placement of the concepts categorised as cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems.

**Figure 1**

*An overview of the 92 concepts categorised according to their placement on the cyclist (wearables), bicycle, vehicle, or infrastructure.*




*Note.* As a concept could be a multi-agent system, a concept can be categorised into more than one category.

**Number of interfaces and messages**

Table 2 shows the number of interfaces and messages identified in the analysis. The analysis showed 41 concepts (45%) with one interface conveying messages to a recipient. The other half of the concepts used more than one interface for communication: two (25 concepts, 27%), three (10 concepts, 11%), four (8 concepts, 9%), and more than four (4 concepts, 4%). It was not possible to count the exact number of interfaces for four concepts, which were marked as unclear.

**Table 2**

*Number of interfaces and messages of concepts*

| | Number of interfaces | Number of messages |
|---|---|---|
| **One** | 41 | 45 |
| **Two** | 25 | 16 |
| **Three** | 10 | 13 |

| | | |
|---|---|---|
| **Four** | 8 | 2 |
| **More than four** | 4 | 1 |
| **Unclear** | 4 | 15 |

*Note.* n = 92.

Regarding the number of distinct messages delivered by the interfaces, half of the concepts delivered only one message. Of the remaining concepts, 16 concepts (17%) delivered two messages, 13 concepts (14%) delivered three messages, two concepts (2%) delivered four messages, and only one concept delivered more than four messages. We could not count the number of messages for 15 concepts, which were marked as unclear.

**Modality of communication**

The most common communication modality was visual with abstract/light (54% of visual concepts). For instance, a concept coded as visual and abstract/light could describe a light blinking on the bicycle's handlebars or an abstract shape that does not resemble text, symbols, or anything anthropomorphic projected on the ground. As seen in Figure 2, four out of five concepts communicated their message visually. For visual interfaces, red (19%), green (18%), and yellow (13%) were the most common colours used (see Figure 3).

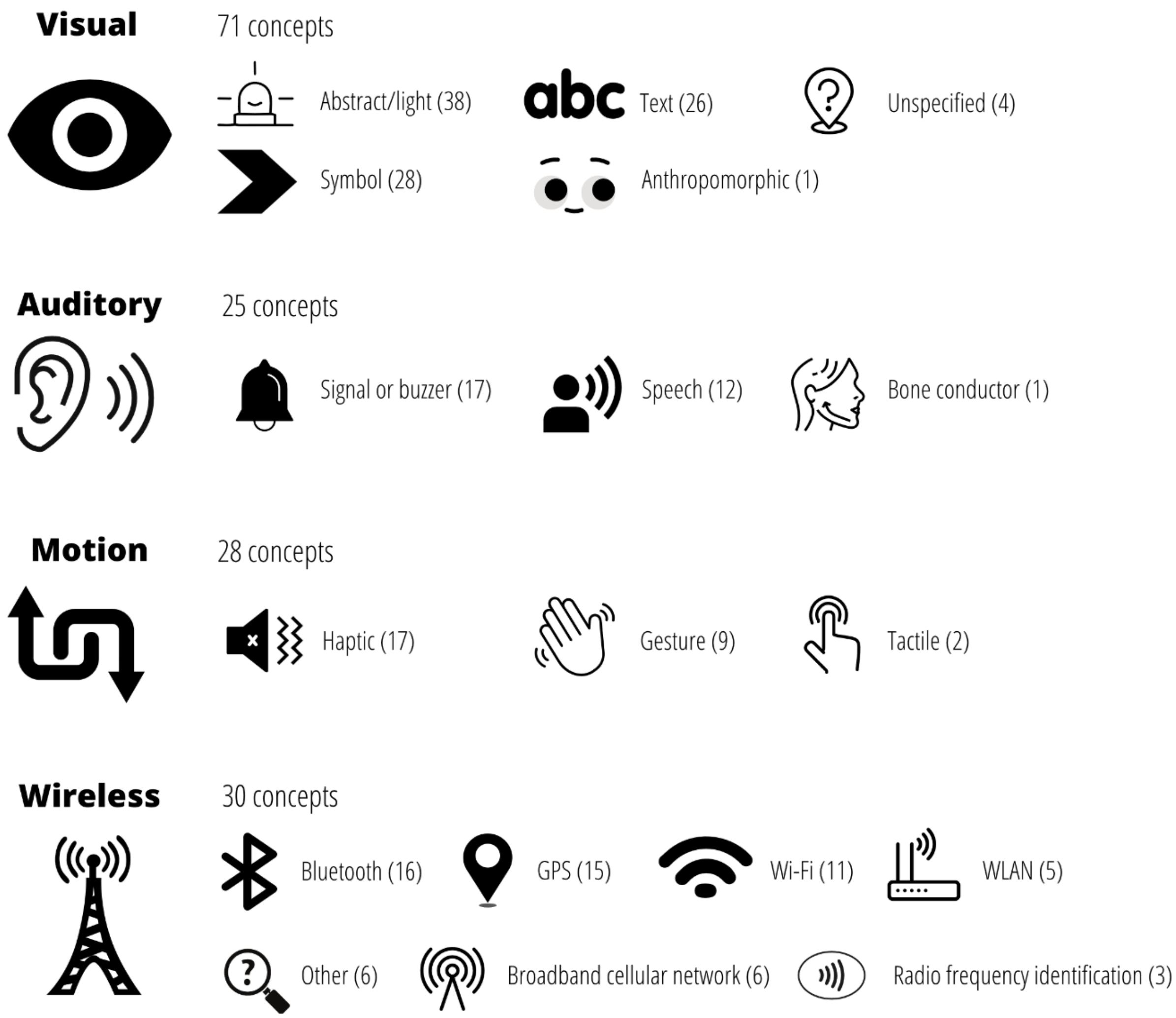
Approximately one in three concepts used auditory and motion-based communication modalities. The most common way of auditory communication was a signal or buzzer (17 concepts, 68% of auditory concepts), typically as an alert or warning to the cyclist. In about two out of three motion-based concepts, the communication modality was haptic feedback, such as vibrating handlebars. Nine concepts used gestures, typically to control AR glasses.

There is potential for road user connectivity in 41% of the concepts: 38 of 92 concepts described a connectivity feature or technology with the potential of connecting multiple agents to transmit messages. As seen in Figure 2, concepts specifying wireless communication utilised technology such as Bluetooth (53%), GPS (50%), and Wi-Fi (37%). Six concepts had wireless as their only communication mode and were typically cooperative communication systems or vehicle-to-everything systems.

Table 3 shows the results from the pivot table analysis of the concepts' HMI placement and modality of communication. Almost all concepts with interfaces on infrastructure used a visual mode of communication. Visual mode of communication was the most common modality for on-bike devices (77%, 27 out of 35 concepts) and vehicle systems (77%, 23 out of 30 concepts). Wireless and visual were the most common modes of communication for cyclist wearables (64%, 23 out of 36 concepts, respectively). When opting for a motion-based mode of communication, the interface of choice was mainly on bicycles (78%, 18 out of 23 concepts).

**Figure 2**

*An overview of the modalities of communication identified in the concepts*



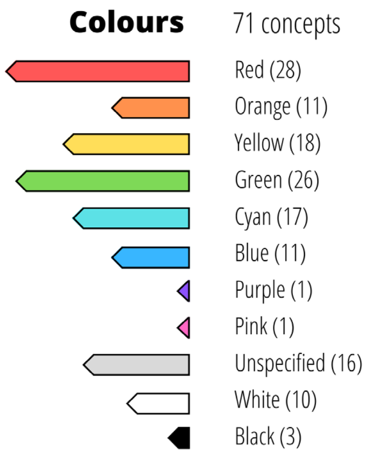
*Note.* n = 92. As a concept could communicate through more than one interface, a concept could be categorised into more than one category. Four concepts coded as having an unspecified mode of communication are not represented in the figure.

**Communication strategy**

We investigated whether the concepts used targeted or non-targeted communication strategies and whether they address single or multiple road users. Table 4 shows that half of the concepts targeted a single road user (47 out of 92 concepts), while 41% (38 out of 92 concepts) broadcasted their messages, and 23% (21 out of 92 concepts) targeted their communication to multiple users. The majority of cyclist wearables and on-bike devices delivered messages to a targeted, single road user. About two out of three vehicle systems broadcasted their messages to multiple road users in a non-targeted manner.

**Figure 3**

*The colours used in the 71 visual concepts*




*Note.* A concept could be coded with more than one colour.

**Table 3**

*Pivot table of HMI placement and modality of communication*

| HMI placement | Modality of communication |
|---|---|

| | **Visual** 71 concepts | **Auditory** 25 concepts | **Motion** 28 concepts | **Wireless** 30 concepts |
|---|---|---|---|---|
| **Cyclist wearables** \| 36 concepts | 23 | 16 | 13 | 23 |
| **On-bike devices** \| 35 concepts | 27 | 12 | 18 | 11 |
| **Vehicle systems** \| 30 concepts | 23 | 5 | 4 | 13 |
| **Infrastructural systems** \| 21 concepts | 20 | 1 | 4 | 5 |

*Note.* n = 92. Note that four infrastructural systems are classified as using motion and one as using auditory as the mode of communication due to concepts with more than one interface. The coding system did not distinguish the modality of different interfaces within the same concept.

**Table 4**

Pivot table of HMI placement and communication strategy

| | **Communication strategy** | | |
|---|---|---|---|
| **HMI placement** | **Unicast** 47 concepts | **Broadcast** 38 concepts | **Multicast** 21 concepts |
| **Cyclist wearables** \| 36 concepts | 30 | 2 | 6 |
| **On-bike devices** \| 35 concepts | 25 | 11 | 11 |
| **Vehicle systems** \| 30 concepts | 4 | 19 | 10 |
| **Infrastructural systems** \| 21 concepts | 6 | 12 | 4 |

*Note.* n = 92. The coding system did not distinguish the communication strategy of different HMI placements within the same concept, i.e., a concept could be coded with more than one placement and communication strategy.

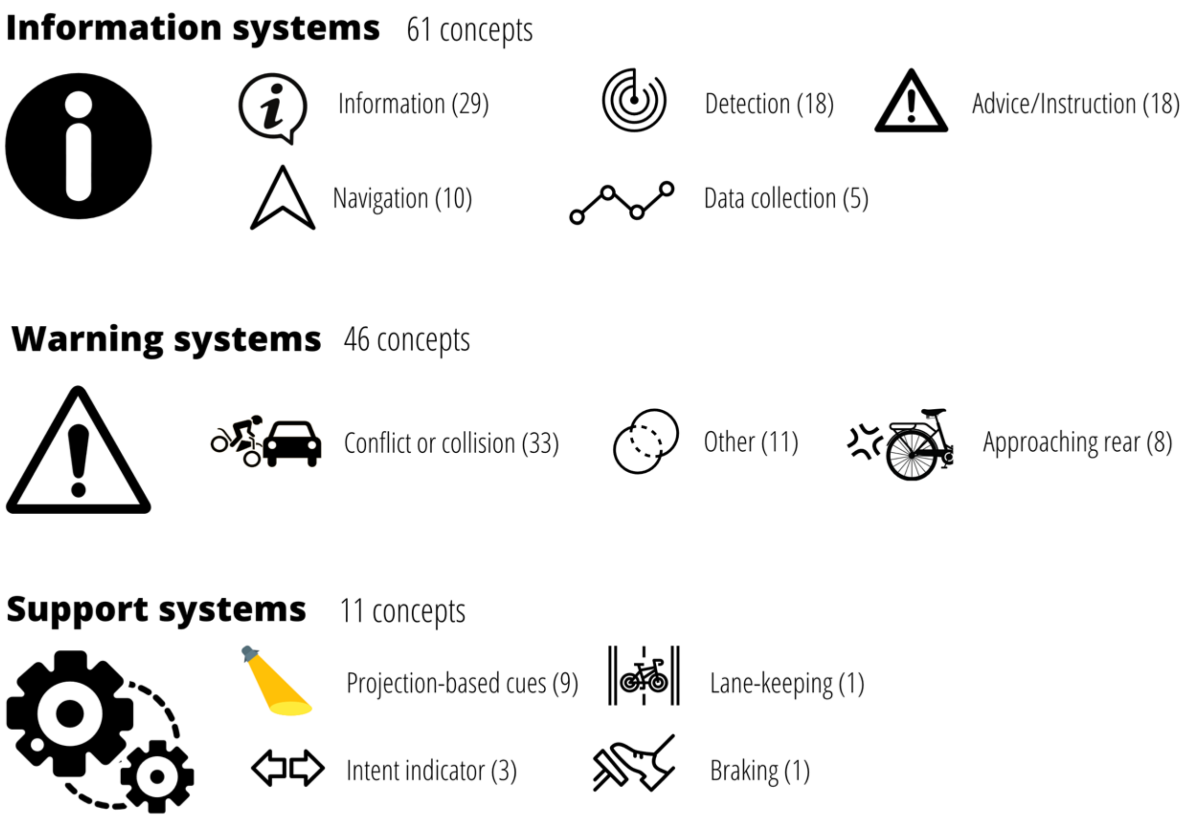
### Functionality

The 92 concepts were categorised into three groups of systems based on their functionality: information systems, warning systems, and support systems. A system could be classified as having more than one function and therefore coded within more than one system sub-group. Figure 4 shows an overview of the functionality of the concepts.

As seen in Figure 4, two-thirds of the concepts were coded as information systems. However, the most common functionality among the concepts was a warning system communicating an alert of an imminent or potential conflict or collision (36% of all concepts). For instance, the smart bicycle helmet concepts by Von Sawitzky et al. (2021) warned the cyclist of the potential door opening of parked cars on the side of the road, while Matviienko et al.'s (2018) helmet and bicycle warning concept for children warned the user of a potential left or right collision at junctions, as well as vehicles appearing from behind obstacles. Eight of the concepts (17% of the 46 warning system concepts) were warning systems about other road users approaching from the rear. Engbers et al.'s (2018) front and rear-view assistant concept for older cyclists was coded as both conflict or collision and approaching from the rear, as the concept involved a bicycle equipped with a radar detecting road users from the front of the bicycle, as well as a camera detecting road users approaching the cyclist from behind.

**Figure 4**

*Overview of the coding results for functionality*




*Note.* n = 92. As a concept could have more than one function, a concept can be categorised into more than one category.

One out of four concepts was categorised as a warning system and the sub-category *other*, see Figure 4. These concepts describe systems that warned the user of an unspecified event without indicating that the event is a collision or conflict.

Only 11 of the concepts had the functionality of a support system, and nine of these systems were concepts that projected signals onto infrastructure. For instance, in a concept by Hou et al. (2020), a vehicle projected a cyclist symbol coloured red or green next to the cyclist, indicating whether the cyclist can change lanes, while in Dancu et al. (2015), cues for navigation or the intended trajectory of the cyclist were projected onto the road.

Table 5 shows the results of the pivot table analysis of HMI placement and functionality. Almost all vehicle systems (97%, 29 out of 30 concepts) and infrastructural systems (85%, 18 out of 21 concepts) had functionality coded as an information system. The main functionality of information systems concepts is to inform the user or other agents in the system of an entity, object, or event. For instance, the six-vehicle system concepts by Dey et al. (2018) all aimed to inform VRUs about the vehicle's current or future behaviour. De Angelis et al. (2019b)'s concepts involved different types of interfaces placed on infrastructure, showing countdown timers for a green light.

**Table 5**

*Pivot table of HMI placement and functionality*

| **HMI placement** | **Functionality**<br>**Information system**<br>61 concepts | <br>**Warning system**<br>46 concepts | <br>**Support system**<br>11 concepts |
|---|---|---|---|
| **Cyclist wearables \|** 36 concepts | 23 | 20 | 4 |
| **On-bike devices \|** 35 concepts | 13 | 25 | 5 |
| **Vehicle systems \|** 30 concepts | 29 | 11 | 2 |
| **Infrastructural systems \|** 21 concepts | 18 | 7 | 6 |

*Note.* n = 92. The coding system did not distinguish the functionality of different HMI placements within the same concept, i.e., a concept could be coded with more than one placement and functionality.

Most of the on-bike devices (71%, 25 out of 35 concepts) were warning systems. In an on-bike concept by Oczko et al. (2020), the cyclist is warned by haptics in the handlebars and through speakers if the system estimates a collision or close-miss encounter with a vehicle.

**Type of concept**

Of the 92 concepts, 43% were conceptual, e.g., created digitally for research purposes or as an aspirational patent. Close to one in five concepts were end products ready for commercial use, and the remaining 39% of the concepts were prototypes.

**Complexity of implementation**

The results from the descriptive analysis show that almost half of the concepts (see Table 6, 38 out of 92 concepts) require new technology that depends on large-scale deployment or infrastructure changes to function in future roads with automated vehicles. About one in five concepts require new technology without large-scale deployment or changes, and 34% (31 out of 92 concepts) can use technology today. Only 4% of the concepts are highly aspirational, awaiting the development of novel technology. As seen in Table 6, more concepts using wireless communication require large-scale deployment or changes to work (63%, 19 out of 30 wireless concepts).

**Table 6**

*Pivot table of the modality of communication and complexity of implementation*

| Complexity of implementation | Modality of communication: **Visual** 71 concepts | **Auditory** 25 concepts | **Motion** 28 concepts | **Wireless** 30 concepts |
|---|---|---|---|---|
| **Ready to use \|** 31 concepts | 28 | 5 | 10 | 8 |
| **New technology required \|** 19 concepts | 15 | 6 | 8 | 2 |
| **New technology and large-scale changes required \|** 38 concepts | 26 | 13 | 9 | 19 |
| **Highly aspirational \|** 4 concepts | 2 | 1 | 1 | 1 |

*Note.* n = 92. The coding system did not distinguish the modality of different interfaces within the same concept, and more than one modality of communication could be applicable to each concept. For instance, four concepts were coded with highly aspirational complexity of implementation, where one of the concepts had two modalities of communication.

### Support for people with special needs

More than half of the concepts had multimodal ways of communication. However, based on the results from the mode of communication category, we considered only 23% (21 out of the 92 concepts) to have support for people with special needs.

### Evaluation of concepts

Out of the 92 concepts, 50 were evaluated in a scientific publication. About half of the concepts were evaluated quantitatively, while 38% used mixed methods involving objective data as well as qualitative data like interviews or observations. Table 7 provides an overview of the results from the descriptive analysis of eight coded categories for the evaluation of the concepts.

**Table 7**

*The method, type of data collection, scenario setup, task of cyclist, time of day, weather conditions, cycling infrastructure, and road condition used in the evaluation of the concepts*

| **Method** | | **Data collection** | | **Direction of movement** | | **Task** | |
|---|---|---|---|---|---|---|---|
| Naturalistic | 14 | Automatic recording | 29 | Same/parallel | 12 | Adjust speed | 9 |
| Controlled outdoor | 5 | Eye-tracking | 2 | Perpendicular | 16 | Cycle normally | 17 |
| Simulator (screen) | 11 | Questionnaire | 41 | Opposite | 6 | Anticipate behaviour | 14 |
| Simulator (VR headset) | 11 | Interview | 13 | No interaction | 13 | Other | 3 |
| Video/animation | 12 | Observation | 2 | Unspecified | 25 | Unspecified | 13 |
| Photo | 2 | Video recording | 1 | | | | |
| **Time of day** | | **Weather conditions** | | **Cycling infrastructure** | | **Road condition** | |
| Daylight conditions | 25 | Direct sunlight | 2 | Mixed traffic | 22 | Clean road | 32 |
| Evening conditions | 1 | Indirect sunlight | 28 | Bike lane | 3 | Water on road | 0 |
| Night-time conditions | 1 | Rain or snow | 0 | Separated bike path | 13 | Snow on road | 0 |
| Unspecified | 24 | Unspecified | 24 | Unspecified | 18 | Unspecified | 17 |

*Note.* n = 50. An evaluation could involve the use of more than one method, type of data collection, setup, and task.

Most concepts were evaluated in a simulated, virtual, or digital environment, with a total of 72% of the concepts evaluated in one of these environments. In half of the evaluations, the type of scenario was not specified. 26% of the scenarios identified had no interaction with other road users. Out of the scenarios with interaction, the most common scenario was a vehicle approaching the cyclist from a perpendicular direction. When specified, almost all concepts were evaluated in daylight, most in indirect sunlight with clean roads, meaning there was no rain or ice on the road (see Table 7). It was most common to test concepts in non-segregated traffic; there was no bike lane in 44% of the concepts. About one in four evaluations had scenarios with a separate bike path.

Table 8 shows that the scenarios used for prototype evaluation were relatively simple; only 6% involved more road users than the cyclist and a vehicle, and 12% involved two vehicles or more throughout the entire scenario. Interestingly, 12% of the evaluations did not involve a cyclist. These concepts were evaluated using photos of infrastructure and the bicycle's handlebars, with no cyclists or vehicles present, such as the concepts by De Angelis et al. (2019b).

**Table 8**

*The number of simultaneous road users and vehicles per trial*

| | **Number of simultaneous road users per trial** | **Number of vehicles per trial** |
|---|---|---|
| **0** | 12% | 14% |
| **1** | 8% | 28% |
| **2** | 28% | 6% |
| **>2** | 6% | 6% |
| **Unspecified** | 40% | 40% |

*Note.* n = 50.

Regarding the sample sizes of the evaluated concepts, the samples ranged from five to 2389 participants, with an average of 310 participants. Not all evaluations were performed on cyclists due to the nature of the data collection methods, e.g., studies using crowdsourcing surveys to collect data. The average age of the participants in the studies was 31 years old. Two studies were carried out on children with a median age of nine and ten, while three included elderly cyclists with an average age of 70.

## Discussion

This study synthesises the current literature on communicative technologies, systems, and devices available to support cyclists. The overall goal is to pinpoint knowledge gaps in the literature and develop strategies for optimising cycling in future traffic environments with AVs. The following sections are divided into three: We first discuss the type of cyclist support systems categorised according to HMI placement: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems. The next section addresses the different modalities of communication and their potential for cyclists, before finally, a section providing a broader reflection on the prospects of future AV-cyclist interaction presented as knowledge gaps in the literature and recommendations for future research on cyclist support systems.

### Type of systems

#### *Cyclist wearables*

From the 92 concepts, the most common systems were cyclist wearables and on-bike devices. Cyclist wearables are usually lightweight and can be utilised across bicycles. One in three cyclist wearable concepts was embedded in a helmet. HindSight, for instance, is a concept in which a camera on the cyclist’s helmet notifies the cyclist of approaching road users outside the cyclist’s field of view (Schoop et al., 2018). Moreover, thirteen of the cyclist wearable concepts in this study used AR to communicate with the cyclist, and five of these concepts were already commercially available AR glasses (Cosmo Connected, 2022; Everysight LTD, 2022; Garmin, 2022a; Julbo, 2022; Solos Smartglasses, 2018). AR technology enhances the real-world environment by adding a virtual layer of computer-generated perceptual information in real-time (Milgram & Kishino, 1994). Among the academic conceptual concepts, Von Sawitzky et al.’s (2020b) augmentation concepts create a digital overlay of a smart bicycle path indicating whether the gap allows for safe crossing, while a later concept warns the cyclist of a potential vehicle door opening ahead (Von Sawitzky et al., 2021).

Wearable obstacle detection systems like HindSight (Schoop et al., 2018) and academic AR concepts (Von Sawitzky et al., 2021; Von Sawitzky et al., 2020b) depend on several data sources (e.g., vision data and motion data) and cannot detect a hazard on their own (Hasan & Hasan, 2022). This means that they would have to be a part of a multi-agent system to function in real-life traffic. The accuracy of wearable obstacle detection systems also relies on correct positioning and calibration (Hasan & Hasan, 2022). Trusting a wearable system for safe interaction with AVs may pose another challenge: The device might malfunction, be stolen, or simply not be worn by the user. For example, self-reported helmet use among cyclists varies from 2% in the Netherlands to 80% in Norway (Haworth et al., 2015). If the system is integrated into devices already available to most VRUs, such as a smartphone or other types of wearables that may become ubiquitous in the future (e.g., AR glasses or chip implants), universal usage might be less of an issue.

***On-bike devices***

An HMI placement on the handlebars was the most common among our on-bike devices. The handlebars are likely a favourable place out of practicality and convenience, as they are located in the centre of a cyclist's focal view between traffic and the road. A range of commercial on-bike products like cyclocomputers placed on the handlebars already exist. Often paired with wearables such as AR glasses, smartwatches, and fitness trackers, on-bike devices are popular among sports cyclists. Today, these types of devices are typically performance-based, providing cyclists with real-time heart rate, speed, and cadence data. In the future, they have the potential to be programmed to aid cyclists with automated vehicles.

***Vehicle systems***

Almost all concepts categorised as vehicle systems (97%, 29 out of 30 concepts) were information systems. Most of these were eHMIs targeting pedestrians and cyclists, and only seven concepts were omnidirectional — two were visible from all around the motorised vehicle, and five were placed on the vehicle's roof. Cyclists differ from pedestrians in terms of movement patterns, speed, and eye-gazing behaviour (Trefzger et al., 2018). For cyclists, it is likely vital that the interfaces are omnidirectional to accommodate the differences in movement patterns and that the message can be observed at high speeds. When anticipating their needs in future automated traffic, interviewed cyclists' main concerns were visibility and confirmation of detection by the automated vehicle (Berge et al., 2022a). Some of the concepts identified in our study have the potential to cover these needs. For instance, CommDisk, a 360° rooftop-mounted eHMI providing omnidirectional two-way communication (Verstegen et al., 2021), and The Tracker, a band of light surrounding the vehicle illuminating a small segment in the spatial proximity of the detected VRU (Dey et al., 2018), both show promise in accommodating the topography and needs of cyclists.

***Infrastructural systems***

Out of the 92 concepts identified in our study, 21 were infrastructural systems that communicated with the system's user through interfaces on the road surface, projections, or traffic signs. Eighteen of the infrastructural systems were coded as information systems, aiming to inform the user about a particular arrangement or sequence of events. The main function of these systems was to detect elements or entities in the cyclist's environment or advise or instruct the cyclist on desired behaviour through normative messages. Traditionally, traffic lights, signs, and markings regulate road users' normative behaviour. In a survey on the effect of text, colour, and perspective of eHMIs, egocentric interfaces instructing the user to "walk" or "stop" were regarded as clearer than allocentric displays informing the user of the vehicle's intended behaviour (e.g., the vehicle displaying it "will stop" or "will not stop") (Bazilinskyy et al., 2019). Communicating through designs and interfaces familiar to users, such as traffic signs or road markings, may relieve cognitive load and shorten the learning process and is in line with the design principles of consistency (see Constantine & Lockwood, 1999; Norman, 2013). When designing a system to support cyclists in automated traffic, it would be recommended to rely on the modes of communication and messages the cyclists are familiar with. Nevertheless, incorporating messages about AV behaviour into normative infrastructural systems may have legal implications from a liability point of view: Advising an action from VRUs based on AVs' behaviour may be particularly challenging when the AV encounters multiple cyclists or pedestrians as there can be confusion as to which road user the AV is addressing (Bazilinskyy et al., 2019; Tabone et al., 2021).

**Modality of communication**

***Visual communication***

From the analysis, the concepts' most common modality of communication was visual (77% of all concepts). The majority of the visual communication used abstract types of light, while approximately one in three concepts used text. Lights and light signals are typical modes of visual communication in traffic. The most common colours used by the concepts (red, green, and yellow) resonate with the colours used in traffic today. In our study, most of the infrastructural systems concepts also use a visual mode of communication, such as different types of countdown timers for a green light (De Angelis et al., 2019), an interactive crossing system that responds dynamically to road users by lighting up large displays on the ground to increase awareness (Umbrellium, 2017), and a light system alerting vehicles of nearby cyclists crossing the road (Heijmans, 2022). Infrastructural concepts using visual communication modes included systems communicating through projections on the road surface. Broadcasting visual messages by projecting them on the road enables the system to reach multiple road users simultaneously. On the downside, projection-based and infrastructural systems are vulnerable to weather. In particular, fog, ice, and snow might obstruct the line of sight and reduce efficiency.

The majority of the cyclist wearables communicated visually. AR glasses communicating visually offer unicast and individualised messages to the user, alleviating the uncertainty as to which road user is addressed when a message is broadcast by an on-vehicle eHMI. The functionality of academic AR prototype concepts could potentially be integrated into commercially available AR glasses and be utilised to improve the interaction of cyclists and vehicles, both conventional and automated. Although no differences in perceived safety or mental workload were noticed, augmented warning messages caused cyclists to increase their distance from a potential hazard earlier than swerving when a hazard occurred (Von Sawitzky et al., 2021). Similar augmentation concepts for supporting pedestrians' crossing behaviour in automated traffic have been suggested (Hesenius et al., 2018; Tabone et al., 2021, 2022).

Close to half of the on-bike concepts in our study involved a type of visual display on the bicycle's handlebars. Using an on-bike display to communicate messages from AVs could be a potential solution for cyclists: Transmitting and receiving signals from other road users and being mutually aware of each other's location and trajectory in traffic, e.g., via a radar display, is a functionality desired for an on-bike system (Berge et al., 2022a). However, adding tasks or demands by prompting cyclists with cues or messages about AVs through an on-bike display might negatively impact cyclists' performance and increase their mental workload. Although other modalities of communication may increase mental workload as well, visual cues could be particularly distracting because they prompt cyclists to place their attention elsewhere than on the road. For instance, the use of a touch screen negatively affected cycling behaviour and resulted in worse visual detection performance (De Waard et al., 2014). In another study, the use of mobile phones while cycling negatively affected cycling performance, and visuotactile tasks such as texting were more distracting than listening to music (Jiang et al., 2021).

Cyclists' mental workload can also be higher in complex compared to simple traffic situations, despite cyclists compensating with a reduction in speed (Vlakveld et al., 2015). In that sense, visual or visuotactile support systems might be more appropriate for use in rural environments with fewer other road users than in complex, urban traffic environments. The effect of a visual and visuotactile mode of communication on cyclist distraction and mental workload in traffic with AVs should be explored further in future research.

***Auditory communication***

Auditory communication was the least popular way of transmitting messages among the concepts in our study, with 25 out of 92 concepts using sound. Auditory messages were mostly delivered as a signal or buzzing sound (68% of auditory concepts). It is questionable whether audio is a feasible option for cyclists in a busy traffic environment with multiple sources of sound and noise, reducing detection accuracy (Hasan & Hasan, 2022). This concern resonates with an interview study on cyclist HMIs, where some of the cyclists pointed out that they prefer on-vehicle eHMIs with audio over a visual display, but a device using audio was generally not preferred by most cyclists. The consensus was that audio might be hard to detect or cause distraction in traffic (Berge et al., 2022a). If a concept can deliver targeted messages to the user without interfering with or disturbing other road users, an auditory feature may be feasible. In our study, most cyclist wearables used a unicast communication strategy, meaning that they offered targeted communication. The efficiency and feasibility of auditory devices for cyclists could be a focus of future research; however, as auditory-based systems elicit limited information about the hazard or nature of obstacles (Hasan & Hasan, 2022), a device using auditory communication will likely have to be multimodal.

***Motion-based communication***

Half of the on-bike concepts in our study use motion-based communication, mostly through the use of vibro-haptic feedback in the handlebars or bicycle seat. While visuotactile communication methods like touch screens may not be a feasible cyclist support system, combining visual cues with haptic feedback may be a solution for complex situations with a high mental workload: Visuo-haptic, multimodal communication was found to be more effective for multiple tasks in high workload conditions (Burke et al., 2006). Eight of the concepts identified in our study were categorised as warning systems for alerting the cyclist of another road user approaching from behind, and half of these concepts used motion-based communication to alert the cyclist. Engbers et al. (2016) found that haptic feedback had a higher acceptance rate than visual warnings. The system received similar positive feedback in a later study, where haptics was described as intuitive and easy to distinguish from vibrations caused by the cycling itself (Engbers et al., 2018). Using haptics to warn about other road users approaching from the rear may benefit situational awareness, particularly in rural areas where other road users do not frequently approach from behind. In urban environments with a higher sensory input, however, cyclists may find a passive system that does not notify the user less strenuous: In a study on passive versus active on-bike warning systems, the participants preferred a passive system alerting the vehicle rather than the cyclist over a system eliciting audio-visual or haptic warnings (De Angelis et al., 2019a).

Nine of the concepts in our study used gestures as a mode of communication. Most of these concepts are AR glasses, in which the cyclist controls the device by swiping a touchpad embedded in one of the spectacle rods. Other systems use head movements as a way of communication, e.g., an eHMI concept attempting two-way communication by blinking if the VRU nods at the sensor (Verstegen et al., 2021), and a smart helmet sensing head tilt to enable turn indicators (Jones et al., 2007). The advantage of such systems is that they allow the cyclist to maintain eye contact with the road and other road users instead of looking at a display.

***Wireless communication***

Future transport systems will likely depend on interconnectivity, and there is much potential in utilising digital infrastructural systems to aid road users in becoming a part of IoT. Today's infrastructure is often equipped with sensors, e.g., road infrastructure and junctions are fitted with low-power transponders that are detectable by vehicle sensors, in preparation for the intelligent transport systems of tomorrow. There are also traffic cameras and roadside units collecting traffic data, which can provide essential information about other road users and the environment that may be missed by automated vehicle sensors (Rebsamen et al., 2012).

AVs' main challenge in urban traffic today is the interaction with pedestrians and cyclists. Equipping and connecting all road users with sensors may seem like a plausible solution to this challenge. Fifteen of the concepts in our study used GPS, which enables obstacle detection without relying on line-of-sight (Hasan & Hasan, 2022). In terms of functionality, two-thirds of the concepts analysed in this study were categorised as cyclist wearables, and on-bike devices were warning systems detecting a nearby entity and alerting the cyclist of a potential conflict. Moreover, almost all vehicle systems (97%) aim to inform the cyclist about the vehicle's current or future behaviour. Combining these concepts by utilising the wireless mode of communication by connecting the cyclist or bicycle to a network of AVs and infrastructure might enhance visibility and sufficiently acknowledge the cyclists.

**Knowledge gaps and recommendations for future research**

***On-vehicle eHMIs targeting cyclists***

With conventional vehicles equipped with intelligent transport systems like detection, lane-keeping, and braking systems, and automated vehicles with their lidar and radar sensors and continuously developed algorithms, the necessity of on-vehicle cyclist support systems like eHMIs can be questioned. In their position paper, De Winter and Dodou (2022) conclude that road users seem to want and accept eHMIs, as eHMIs can add to implicit communication and fill the void of social interaction with driverless vehicles in terms of eye contact. Moreover, eHMIs have the potential to communicate multifaceted messages, indicating the vehicle's functional state, both in terms of sensors and whether the automated system is active (De Winter & Dodou, 2022). In sum, vehicle systems such as eHMIs seem to be a welcomed addition that could potentially enhance VRU interaction with AVs.

The next step is likely to be the standardisation of eHMIs across car manufacturers. In that case, it is vital to consider cyclists in the design and evaluation process, as the needs of cyclists and how they affect the interaction with AVs are understudied topics to date. We suggest that eHMIs for cyclists should be designed with visibility all around the vehicle and with messages observable at the higher speeds of cyclists compared to pedestrians.

Incorporating two-way communication, allowing the cyclist to receive confirmation of detection by AVs, is also likely a desirable feature of a cyclist support system. The exact configurations and attributes of a cyclist-oriented eHMI still require additional research.

***The effect of modality on performance and safety***

More than half of the concepts analysed in this study were evaluated by previous research. The evaluation method and measurement variables varied from study to study, ranging from preference and acceptance to usability and bicycle speed and trajectory adjustments.

It is not possible to draw conclusions about the effects or usability of the systems based on these evaluations, particularly as few of the concepts were evaluated in the context of AVs. Moreover, most of these concepts were evaluated in simulated, virtual, or digital environments. However, simulators and virtual reality are common methods in user studies in automotive research, providing a safe, controllable, and immersive test environment for the participants (Hock et al., 2018). Real-world experiments also raise legal and ethical concerns pertaining to automation. Although simulations do not entail all details of real-world traffic environments, virtual reality has been found to be useful for investigating pedestrians' behaviour when interacting with AVs (Nuñez Velasco et al., 2019). Considering that the field of AV-cyclist interaction is still in early stages, performing research in virtual environments is a reasonable approach.

We propose that investigating the effect of visual versus auditory and motion-based modes of communication on cycling performance, safety, situational awareness, and mental workload are important directions for future research. In particular, augmentation concepts and head-up displays for cyclists, although already commercially available as AR glasses, remain largely unexplored by academia.

***Increased complexity and representative test scenarios***

Most of the concepts were evaluated using relatively simplistic scenarios. If there was an interaction between a cyclist and another road user in the evaluation, the most common scenario was a vehicle approaching the cyclist from the left or right side in broad daylight on clean, dry roads. Future research on cyclist interaction with AVs could benefit from more complex and realistic scenarios to increase the ecological validity and generalisability of the findings, including scenarios with more than one cyclist and vehicle, and cluttered urban environments with varied weather and lighting conditions. Moreover, the development of standardised test scenarios for AV-cyclist interaction would be a welcomed addition to the literature base.

***The implications of connected VRUs and inclusive transport systems***

The number of devices connected to the internet has increased significantly in recent years (Lombardi et al., 2021), and with the transport system increasingly becoming part of the IoT (Behrendt, 2019), connected bicycles and cyclists are likely the future of cycling. The assumption is that equipping bicycles or the cyclists themselves with sensors will ensure that smart infrastructure and AVs are aware of the cyclists' location, increasing their safety. One of the key challenges with this solution is that only the connected cyclists will be detected if AV programming depends on data from these sensors. Human road users without sensors, whether for economic or privacy reasons, may be at increased risk due to the absence of data. The ethical implications of equipping VRUs with beacon systems are rarely considered in research, and issues pertaining to user privacy and security arising from VRU safety systems are typically retroactively addressed (Hasan & Hasan, 2022). Shifting the burden of safety to the cyclists by requiring them to invest in or wear additional devices to be safe from AVs is one of the main reasons cyclists are hesitant about using HMIs in automated traffic (Berge et al., 2022a).

Silla et al. (2017) investigated the effect of intelligent transport systems on preventing cyclist injuries and fatalities. With a 100% penetration rate, *pedestrian and cyclist detection systems* paired with *emergency braking* and bike-to-vehicle communication had the highest positive effect on cyclist-vehicle accidents, while VRU beacon systems had the lowest effect. Without a near-perfect prevalence of connected bicycles, the vehicle-based systems (detection system and emergency braking) showed the highest reduction in fatalities and injuries. The effect of on-vehicle eHMIs was not considered in this study. While more research is required, the findings still suggest the necessity of high penetration rates of cyclist support systems to increase the safety of cyclists in future traffic and indicate that vehicle systems, such as improved sensors and programming, possibly paired with on-vehicle eHMIs, may perform better in terms of safety if connected VRUs is not universal.

Historically, the drive for new mobility paradigms in transport has been auto-oriented, oppressing active modes of transport for the benefit of motorised vehicles (Gaio & Cugurullo, 2022). Considering that cyclist wearables or on-bike devices may be stolen, malfunction, or be misplaced, we hypothesise that the sensors connecting human road users will likely have to be embedded in the human body to ensure everyone's safety. Members of transhumanist and biohacking communities have demonstrated the potential of implantable technologies such as neodymium magnets, radio-frequency identification chips, and sensors for human enhancement (Yetisen, 2018). In the future, such implants may become ubiquitous. While the Internet-of-People may be a possible way forward, the privacy and safety implications of prospective mass surveillance are of major concern. It is highly debatable whether connected road users through implants is an acceptable solution to the AVs' challenges of interacting with VRUs in complex, urban environments.

The acceptance of road user connectivity should be explored in future research. While interviewed cyclists expressed uncertainty about systems that provide information about critical safety situations in connected traffic (Berge et al., 2022a), the participants in a study conducted by Von Sawitzky et al. (2021) indicated a willingness to use such systems. Additional knowledge of current situations in the traffic environment may improve cyclists' situational awareness. For instance, a system that alerts cyclists about critical situations through modalities that do not interfere with visual attention or mental workload may prevent accidents and increase cyclist safety. Situational awareness-enhancement systems may prove to be feasible solutions during the transition period between conventional and automated vehicles and should be further investigated. In terms of the burden of safety, these systems will not shift the burden onto cyclists as long as the use of such systems are voluntary and not a requirement of safe AVs in future traffic.

In the forthcoming years, a critical direction for AV-cyclist interaction will be the development of eHMI technology tailored to the specific needs of cyclists. In the context of road user connectivity, allocentric on-vehicle eHMIs – interfaces informing VRUs about the AVs' intended behaviour – will not require additional sensors or VRU beacon systems. However, we also suggest that exploring other solutions, essentially shifting the car-centred and technology-driven perspective towards a more inclusive and multimodal transport future, might be equally important to investigate. As suggested by Gaio and Cugurullo (2022), future advancements in mobility should prioritise mobility justice and mode choice rather than primarily promoting a single transport mode such as AVs. Policy-driven initiatives that promote active transport and more inclusive urban environments, such as reducing the speed of AVs in urban areas, reallocating urban road infrastructure to active transport, and separating AVs from VRUs to a greater extent, may be a viable direction forward.

**Limitations**

While this paper provides a comprehensive overview of the communicative technologies and solutions identified for cyclists, we cannot claim it is a complete and fully systematic review. The literature searches showed that the research field on communicative solutions for cyclist interaction with AVs is relatively new and emergent, and there is presently no widespread agreed-upon terminology to describe these concepts. The lack of nomenclature in the field warrants an explorative approach to the literature review rather than a systematic approach. Thus, we do not provide detailed information about the search strings used to identify publications, but rather the categories of keywords combined in the searches. Moreover, only some of the coding taxonomy variables used to categorise the concepts were based on previous research (Dey et al., 2020). Our coding taxonomy has not been formally validated nor tested for internal reliability. In light of these limitations, the results from the analysis should be interpreted and considered as indicative of trends rather than definitive conclusions.

Most of the concepts identified in our study have not been tested or evaluated with AVs. Interpreting the need for and necessity of the systems based on the results from evaluations with or without other road users is challenging. However, in the new and emerging field of AV-cyclist interaction, we argue that the inclusion of concepts not primarily designed for vehicle interaction is beneficial if the concept technology is deemed to have the potential to be adapted for use with vehicles. In our study, we define potential as the ability of the technology or device to be developed or adapted for use in the context of vehicles with automation capabilities beyond SAE level 2. For instance, the Bicycle Light Communication System by Westerhuis et al. (2021) is intended to support cyclists in traffic with other cyclists by displaying their speed, braking, and turning intentions. Although the concept was tested and evaluated in the context of cyclists, the information emitted by the light communication system could be interpreted by AV sensors and used to calculate cyclists' behaviour and trajectories. Other concepts, such as the on-bike warning system by Erdei et al. (2021), were evaluated in the context of testing signal perception and the effects of communication modalities among cyclists. The authors argued that warning systems could increase cycling safety by informing the user of imminent critical situations related to other road users or high-risk cycling conditions, but they did not specify the exact functionality of their warning system. Still, such proof-of-concept studies show the potential for further development of cyclist support systems in the context of conventional motorised vehicles and AVs. The inclusion of concepts that have not been tested nor evaluated with AVs in the present study provides a broader overview of the technologies available to cyclists. A broader overview contributes to uncovering more knowledge gaps in the literature and may be beneficial to future research, testing, and development of concepts for supporting cyclists in future automated traffic.

## Conclusion

The findings from this study provide a synthesis of the present literature on AV-cyclist interaction and an overview of the state-of-the-art cyclist support systems. We aligned this overview with knowledge about cyclists and their behaviour from a human factors perspective and explored whether the solutions meet cyclists' needs in future automated traffic. Focusing on technology-driven solutions, we propose that the future of cyclist support systems may be a passive beacon or chip system that connects cyclists with vehicles, other road users, and infrastructure. This system could be paired with on-vehicle eHMIs that are visible from all around the vehicle and incorporate two-way communication if deemed feasible. However, drawing conclusions based on the evaluations of the concepts identified in this study or recommending a particular type of system is not feasible before the concepts are tested and evaluated in the context of AVs or vehicles. Testing the type of system and the effect of communication modality on performance and safety in more complex and representative scenarios involving AVs would be beneficial. Investigating the effect of visual versus auditory and motion-based modes of communication on cycling performance, safety, situational awareness, and mental workload are important directions for future research. In particular, augmentation concepts and head-up displays for cyclists, although already commercially available as AR glasses, remain largely unexplored by academia. Finally, our study promotes ethical discourse by highlighting the ethical implications of connected road users and suggests that the transportation system may benefit from a more inclusive and less car-centred approach, shifting the burden of safety away from VRUs and promoting more cyclist-friendly solutions.

## CRediT authorship contribution statement

**Siri Hegna Berge:** Conceptualisation, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualisation, Writing – original draft. **Joost de Winter:** Conceptualisation, Funding acquisition, Supervision, Validation, Writing – review & editing. **Marjan Hagenzieker:** Conceptualisation, Funding acquisition, Supervision, Validation, Writing – review & editing.

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## Research data

A document containing the sample and coding of the concepts is available at the 4TU.ResearchData repository at https://doi.org/10.4121/c.6202309.

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# APPENDIX B.1. LIST OF INCLUDED PUBLICATIONS

| | **Reference** | **Publication type** | **Location** |
|---|---|---|---|
| 1 | Benderius et al. (2018) | Journal article | Sweden |
| 2 | Boreal Bikes GmbH (2021) | Commercial/industry publication | Germany |
| 3 | Céspedes et al. (2016) | Conference paper | Chile, Colombia |
| 4 | Cohda Wireless (2017) | Commercial/industry publication | Australia |
| 5 | Colas (2017) | Commercial/industry publication | France |
| 6 | Cosmo Connected (2022) | Commercial/industry publication | France |
| 7 | Dancu et al. (2015) | Conference paper | Sweden |
| 8 | De Angelis et al. (2019a) | Conference paper | Italy |
| 9 | De Angelis et al. (2019b) | Journal article | Italy |
| 10 | Delft University of Technology (2021) | Commercial/industry publication | Netherlands |
| 11 | Dey et al. (2018) | Conference paper | Netherlands |
| 12 | Engbers et al. (2018) | Journal article | Netherlands |
| 13 | Engbers et al. (2016) | Journal article | Netherlands |
| 14 | Engel et al. (2013) | Conference paper | Germany |
| 15 | Englund et al. (2019) | Conference paper | Sweden |
| 16 | Erdei et al. (2020) | Journal article | Germany |

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|---|---|---|---|
| 17 | Erdei et al. (2021) | Journal article | Germany |
| 18 | Everysight LTD (2022) | Commercial/industry publication | Israel |
| 19 | Ford Motor Company & Virginia Tech Transportation Institute (2017) | Commercial/industry publication | USA |
| 20 | Garmin (2022a) | Commercial/industry publication | USA |
| 21 | Garmin (2022b) | Commercial/industry publication | USA |
| 22 | General Motors (2012) | Commercial/industry publication | USA |
| 23 | Ginters (2019) | Conference paper | Latvia |
| 24 | Grimm et al. (2009) | Patent | USA |
| 25 | Hagenzieker et al. (2020) | Journal article | Netherlands |
| 26 | Harrison (2011) | Patent | Australia |
| 27 | Heijmans (2022) | Commercial/industry publication | Netherlands |
| 28 | Hernandez-Jayo et al. (2016) | Poster | Spain |
| 29 | Hou et al., (2020) | Conference paper | Canada |
| 30 | Jenkins et al. (2017) | Conference paper | USA |
| 31 | Jones et al. (2007) | Conference paper | USA |
| 32 | Julbo (2022) | Commercial/industry publication | France |
| 33 | Kaß et al. (2020) | Conference paper | Germany |
| 34 | Kiefer & Behrendt (2016) | Journal article | UK |
| 35 | Liebner et al. (2013) | Conference paper | Germany |
| 36 | Lindström et al. (2019) | Conference paper | Sweden |
| 37 | Matthiesen et al. (2018) | Patent | USA |
| 38 | Matviienko et al. (2018) | Conference paper | Germany |
| 39 | Matviienko et al. (2019a) | Conference paper | Germany |
| 40 | Matviienko et al. (2019b) | Conference paper | Germany |
| 41 | Nissan Motor Corporation (2015) | Commercial/industry publication | Japan |
| 42 | Oczko et al. (2020) | Conference paper | Germany |
| 43 | Prati et al. (2018) | Journal article | Italy |
| 44 | Rashdan et al. (2020) | Conference paper | Germany |
| 45 | Raßhofer et al. (2007) | Book section | Germany |
| 46 | Schaffer et al. (2012) | Journal article | Germany |
| 47 | Schoop et al. (2018) | Conference paper | USA |
| 48 | Shin et al. (2013) | Conference paper | Taiwan |
| 49 | Solos Smartglasses (2018) | Commercial/industry publication | USA |
| 50 | SWARCO (2022) | Commercial/industry publication | Denmark |
| 51 | Terranet (2021) | Commercial/industry publication | Sweden |

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| 52 | Tome Software (2019) | Commercial/industry publication | USA |
| 53 | Toyota Motor Engineering & Manufacturing North America Inc. (2016) | Patent | USA |
| 54 | Umbrellium (2017) | Commercial/industry publication | UK |
| 55 | Verstegen et al. (2021) | Conference paper | Netherlands |
| 56 | Vlakveld et al. (2020) | Journal article | Netherlands |
| 57 | Von Sawitzky et al. (2020a) | Conference paper | Germany |
| 58 | Von Sawitzky et al. (2021) | Journal article | Germany |
| 59 | Von Sawitzky et al. (2020b) | Conference paper | Germany |
| 60 | Westerhuis et al. (2021) | Journal article | Netherlands |
| 61 | Yoshida et al. (2015) | Conference paper | Japan |
| 62 | Van Brummelen et al. (2016) | Conference paper | Canada |

**Appendix B.2.** Taxonomy definitions

### 1. Terminology

In this category, we map the words used to describe a concept. The terminology was deduced from the title, abstract, or keywords of the academic articles. For commercial concepts, the terminology was chosen from the words used to describe their product.

### 2. Target road user

This dimension pertains to the type of road user targeted by a concept. Cyclists are the main road user group of interest in this study; however, a concept could target more than one type of road users. Other relevant road users targeted are pedestrians and the vehicles themselves, including the driver or onboard passenger.

### 3. HMI placement

This category describes the location of the interface conveyed messages to its intended recipient. If a concept offers multimodal communication, all locations of the interfaces are categorised, meaning that a concept could have more than one placement. The placement of the concepts was further divided into four subcategories: cyclist wearables, on-bike devices, vehicle systems, and infrastructural systems.

**3.1 Cyclist wearables.** A concept is categorised as a cyclist wearable if the communication device is located on the cyclist. A cyclist wearable is subcategorised as a helmet, smartphone, AR-glasses, a head-up display mounted on the helmet, a beacon or tag that was not specified as a smartphone, or as other, which included backpacks and belts.

**3.2 On-bike devices.** To be categorised as an on-bike device, the system or interface of communication is located on the bicycle**.** More specifically, concepts categorised as on-bike devices had HMI placements such as on the handlebars, a mounted display between the handlebars, a head-up display extended from the handlebars, and systems placed on the frame, seat, and rear of the bicycle. The category ‘unspecified’ includes concepts mentioning placement on the bicycle but without pinpointing the exact location.

**3.3 Vehicle systems.** In this category, the communication device is located on or within the motorised vehicle, either on the bumper, hood, rear, roof, side, windshield, or all around the vehicle. Concepts described as being on or in the vehicle without specifying the exact placement were coded as unspecified.

**3.4 Infrastructural systems.** Within this category, the interface with the message of communication is located on infrastructure, e.g., a traffic sign, on the road, or on the side of the road. Devices using projections were also categorised as infrastructural systems, as the message of communication is communicated on an infrastructural surface like the road.

**4. Number of interfaces**

We counted the number of interfaces identified within a concept in this category. An *interface* can be defined as a relation between two distinct entities selectively allowing communication of information from one entity to the other. In other words, an interface allows a user to interact with a device, program, or machine. The number of interfaces is distinguished by the number of modalities capable of communicating information between a machine and a human road user. For instance, a concept alerting the cyclist through vibrating handlebars and a signal from a speaker would be counted as two interfaces: one on the handlebars and one through the speaker.

**5. Number of messages**

This category describes the number of different messages communicated through an interface. An interface can transmit multiple messages, but only one message at a time. As in Dey et al. (2020), the number of messages is coded as one message if the same message is communicated through multiple interfaces independently or simultaneously (e.g., a light on the handlebars of the bicycle paired with haptic feedback in the seat, both conveying the same message). If an interface conveys a message as a continuous process (e.g., projected lights around a bicycle, changing colours indicating the proximity of other road users or entities in the environment), it is also coded as one message.

**6. Modality of communication**

Modality of communication describes how communication is achieved by a concept and is classified as visual, auditory, motion, or wireless means of communication. Multimodal concepts are categorised by all forms of communication, meaning a concept could be categorised within more than one sub-category.

**6.1 Visual.** This category pertains to retrieved concepts that communicate through visual perception and sight. Visual modalities are coded according to the following sub-categories:

- **Anthropomorphic:** The concept communicates visually using a human form or attributes, like a waving hand.
- **Abstract/light:** Abstract visual shapes or light-based modalities communicating intuitively through an open-to-interpretation interface without the specific use of text, symbols, or anthropomorphic shapes, e.g., a blinking light on the bicycle's handlebars.
- **Symbol:** The use of recognisable and commonly used symbols like a stop sign, zebra crossing lines, arrows, or other types of symbols used to communicate.
- **Text:** The explicit use of text or numbers on an interface, e.g., advice or instructions such as "go", "stop", or "safe to pass", or information-based text displaying distance or speed, or a countdown timer with numerical text.
- **Unspecified:** Visual means of communication that are not specified.

Another sub-category of visual modalities of communication is the **colour (6.1.1)** used in these concepts, identified as black, blue, cyan, green, orange, pink, purple/violet, red, white, yellow, and unspecified.

**6.2 Auditory.** Concepts communicating through the sense of hearing are categorised as auditory. The following sub-categorised are used to describe auditory modalities:

- **Speech:** Communication is expressed as articulate sounds, e.g., a voice instructing the cyclist to "turn left now" or a cyclist using voice-based commands to control a system.
- **Signal or buzzer:** The use of a non-speech-related audio signal or buzzing noise.
- **Bone-conductor:** Audio transmitted by sound waves vibrating bone. While bone conduction could be considered a motion-based modality of communication, we have chosen to place it as a sub-category of auditory modalities as it is difficult for the user to distinguish between sound conducted through bone compared to via air.

**6.3 Motion.** Concepts communicating through the action or process of moving or being moved would be categorised as using motion as their modality of communication. Furthermore, motion is sub-categorised into three categories:

- **Haptic:** The technology actively applies force, vibration, or motion to communicate with the user, e.g., vibrating handlebars or bicycle seat.
- **Tactile**: The message of communication is tangible; delivered through touch, e.g., the cyclist communicates a message to a system by pressing a button.
- **Gesture:** Gesture-based communication, such as a display with a waving humanoid or a cyclist using hand or head movements to communicate with a system.

**6.4 Wireless.** Concepts categorised as wireless deliver their message of communication through signal transmission on a frequency spectrum. Wireless is categorised according to the technology utilised to transmit the message:

- **GPS:** Global Positioning System, a satellite-based radio navigation system.
- **Bluetooth:** Short-range wireless technology standard for exchanging data between fixed and mobile devices.
- **Wi-Fi:** Wireless fidelity trademarked; wireless network protocols based on the IEEE 802.11 family of standards.
- **WLAN:** Wireless local area network, without specifying they are based on the IEEE 802.11 standard.
- **Broadband cellular network:** 3G, 4G, and 5G.
- **Radio frequency identification:** Radio waves to identify a tagged object passively.

- **Other:** Global Navigation Satellite System (without specifying the system uses GPS), real-time locating systems (RTLS), dedicated short-range communications (DSRC), and Global System for Mobile Communications (GSM).

### 7. Communication strategy

This category defines how the system addresses road users when communicating messages. It describes whether the communication is targeted or non-targeted and whether the message is intended for single or multiple users (adapted from Dey et al., 2020). The concepts are categorised into three categories, where a concept can communicate in more than one way.

- **Unicast:** The system communicates and delivers its messages targeted to a single road user, e.g., vibrating bicycle handlebars.
- **Broadcast:** The system broadcasts its messages to non-targeted road users, e.g., a light on the rear of the bicycle indicating whether the cyclist is speeding up or braking.
- **Multicast:** The system targets and delivers its messages to multiple road users at the same time, e.g., a projection of a cyclist symbol on the road, indicating whether it is safe to change lanes.

### 8. Connectivity

*Connectivity* is a dimension that classifies whether the concept has the capacity for interconnection by signal transmission between systems or users.

### 9. Functionality

This dimension classifies the intended functionality of the message(s) communicated through the device or system, as described by the authors of each original article. Functionality is the intended message communicated to its recipient or the *purpose* of the messages communicated. The dimension of functionality is further categorised into three sub-categories: information systems, warning systems, and support systems. A concept could have more than one functionality and be categorised into more than one sub-category.

**9.1 Information systems.** Concepts categorised within information systems aim to inform the user about a particular arrangement or sequence of events, such as details about objects' or other road users' location or behaviour. Within information systems, we have defined the following sub-categories of functionality:

- **Navigation:** The system provides the user with navigational cues.
- **Information:** The system provides information about the vehicle, the cyclist, or the bicycle's state, e.g., whether the vehicle is stopping or going, if the cyclist is receiving a call, or the current speed of the bicycle.
- **Advice/Instruction:** Normative messages conveying desired behaviour of the recipient or other commands contingent on the recipients' actions, e.g., displays with the messages "go" or "do not cross".
- **Detection:** The concept detects elements or entities in its environment without the intention of warning the recipient of an immediate conflict or danger.
- **Data collection:** The concept collects and sends data about its users or entities in the environment, e.g., bicycle speed, location, and user data.

**9.2 Warning systems.** Concepts within this sub-category intend to convey messages of caution or urgency to its users. While a warning system is essentially an information system, the difference lies in the function of the message: The purpose is to prepare the user of a conflict so they can act accordingly to mitigate or avoid it. Warning systems are further differentiated into three sub-categories:

- **Conflict/collision:** The system warns the user of an imminent conflict or collision.
- **Approaching rear:** The system warns the user of an entity approaching from behind, e.g., a vehicle approaching the rear of a bicycle.
- **Other:** The system alerts the user of an unspecified event of urgency.

**9.3 Support systems.** Similar to information systems, concepts coded as a support system have functionality conveying messages about an arrangement or sequence of events. The difference between information and support systems is in the nature of the message: support systems convey messages with a behavioural component of the cyclist's current or future behaviour, such as braking or turning. The functionality of support systems is categorised in the following sub-categories:

- **Braking system:** The system communicates to other road users that the bicycle is actively reducing its speed, i.e., indicating that the cyclist is braking.

- **Projection-based cues:** These concepts project messages indicating the current or potential behaviour of the cyclist, e.g., symbols, lights, or other visual elements on the ground or field of view indicating the potential trajectory of the cyclist or bicycle.
- **Intent indicator:** A functionality similar to projection-based cues; however, the intent indicator conveys messages of the active intent of the cyclist, such as a turn indicator located on the bicycle.
- **Lane-keeping system:** The system informs the user to stay within a pre-defined area while cycling, e.g., a head-up display or a screen outlining the boundaries of the road.

**10. Type of product**

In this category, the concepts were coded according to their current state of development, whether they were conceptual, a prototype, or an end product.

**11. Complexity of implementation**

This dimension describes the complexity of implementing a concept in real-world traffic scenarios. Some concepts can be aspirational and practically unrealistic to implement in today's traffic environments without technological advances, full-scale adoption by other road users, or extensive infrastructure changes. The concepts are coded within four sub-categories adapted from Dey et al. (2020, pp. 13):

- **Ready to use:** Technology is ready to use today.
- **New technology required:** Requires new technology but does not depend on large-scale deployment or infrastructure changes to function.
- **New technology and large-scale changes required:** Requires new technology but depends on large-scale deployment or infrastructure changes to function.
- **Highly aspirational:** Uses technology that is not yet developed or available.

**12. Support for people with special needs**

Adapted from Dey et al. (2020), this category describes whether the concept accommodates the special needs of visually, auditory, or cognitively impaired persons via multimodal communication.

**13. Evaluation of concept**

Evaluation of concept is a category describing whether the technology, device, or system has been evaluated in a scientific publication. If an evaluation has not been conducted, the concept is coded as unknown, in line with the evaluation of concept dimension by Dey et al. (2020). If a concept has been evaluated, it is further classified into the following 13 sub-categories:

- **Method of data collection:** Automatic recording, eye-tracking device, questionnaire, interview, observation, or video recording.
- **Methodology:** Qualitative, quantitative, or mixed methods.
- **Method of evaluation:** Naturalistic, controlled outdoor, simulator (screen-based), simulator (VR headset-based), video or animation, or photo.
- **Direction of movement:** The behaviour and/or direction of the cyclist and other road users (if applicable) during the data collection, e.g., whether the cyclist is cycling straight ahead, turning left or right, and the direction of the other road user (opposite, perpendicular, or same/parallel trajectory relative to the cyclist).
- **Task:** The task of the cyclist during the evaluation of the concept.
- **Time of day:** Daylight conditions, evening conditions, night-time conditions, or unspecified.
- **Weather conditions:** Direct sunlight, indirect sunlight, rain, snow, or unspecified.
- **Road condition:** Clean roads, water on the road, snow on the road, or unspecified.
- **Cycling infrastructure:** Mixed traffic with no bike lane, mixed traffic with a bike lane, separated bike path, or unspecified.
- **Number of simultaneous road users per trial.**
- **Number of vehicles per trial.**
- **Sample size:** Number or unknown.
- **Sample age:** Median or mean age of the sample, or unknown.

## 7.3 Appendix C. User interface for Cyclists in Future Automated Traffic

Berge, S. H., De Winter, J., & Hagenzieker, M. (2023b). User interfaces for cyclists in future automated traffic. *Companion Proceedings of the 28th International Conference on Intelligent User Interfaces*, Sydney, Australia, 91–94.
https://doi.org/10.1145/3581754.3584140

### Abstract

In future traffic, intelligent user interfaces may aid cyclists in interpreting the behaviour of automated vehicles. Cyclists can be equipped with obstacle-detecting sensors, and an interface could display relevant information or use audible alerts to warn or inform cyclists of other road users' intent and potential hazards. Researching intelligent user interfaces for cyclists is vital for understanding how users can efficiently and safely interact with automated vehicles. This work-in-progress paper presents two studies for developing and testing user interfaces for cyclists in future automated traffic. In the first study, we reanalysed interview data from 30 cyclists, resulting in two interface concepts: the app CycleSafe and an omnidirectional on-vehicle interface capable of communicating cyclist recognition. In the second study, we outline an envisioned experiment to test these two concepts in a naturalistic environment with cyclists and a vehicle emulating automation. We hypothesise that cyclists prefer receiving warning signals over no warnings, prefer early over late warnings, and that auditory signals and visual on-vehicle interfaces will perform better than visual on-bike interfaces.

### Introduction

Integrating automated vehicles (AVs) into the transport system raises concerns about the potential impact on vulnerable road users such as cyclists. As cycling is an increasingly popular mode of transport [12], it is crucial to understand how AVs and cyclists interact to ensure the cyclists' safety and continued inclusion in the transport system.

Human-machine interfaces (HMIs) allow users to interact with a device, program, or machine. The electrification of bicycles and the introduction of intelligent HMIs can potentially revolutionise the cycling industry and enhance the overall cycling experience, including cyclists' interaction with AVs. Regarding safety, bicycles can be equipped with self-balancing technology [17,18] and sensors detecting obstacles or conflicts [7]. An intelligent HMI for cyclists could include a display showing cyclists relevant information or warning signals of potential collisions or other hazards [10,11,14,15]. With the advent of intelligent interfaces and connected transport systems, researching HMIs for cyclists is essential for understanding how users can efficiently and safely interact with these technologies.

This paper outlines a work in progress of two studies exploring the potential of using cyclist-oriented HMIs to improve the safety of cyclists in future traffic with AVs. The overall objectives of the studies are to develop HMI concepts and investigate when and how warnings should be presented to cyclists. In the first study, we analysed interviews with 30 cyclists to explore the type of information cyclists want from AVs and the design strategies applicable to cyclist-oriented HMIs. The second study outlines a naturalistic experiment investigating the effects of visual and auditory warning signals for cyclists interacting with a vehicle in ambiguous situations.

## First study: User Interface Development

### Method

In this study, we applied an exploratory approach by analysing qualitative data from 30 cyclists from Norway and the Netherlands [3] collected in a previous interview study [1]. The semi-structured interviews were conducted online. The sample consisted of 19 males and 11 females with an average age of 43 years (*SD* = 16). Most participants (73%) cycled daily, and one-third identified themselves as early adopters of technology.

We performed an inductive thematic analysis by Braun and Clarke [4] on data from the following questions:

- What kind of information would you need from an AV?

- Imagine a device that helps you interact with AVs: How should this device be designed? How should the device communicate with cyclists?
- If you could receive information about AVs through a device on your bike: What kind of traffic information would be useful? What kind of information about cyclists would be useful for the AV?

Combining the results from the thematic analysis with previous literature, we created mock-up designs of two HMIs. See supplementary data for the complete analysis and a selection of quotes.

## Results

The interface concepts were developed to accommodate cyclists' needs and characteristics extracted from the thematic analysis. The analysis uncovered that cyclists' primary need in traffic with AVs is to be seen. Cyclists also prefer explicit communication of detection from the AV. However, the most frequently mentioned features of a cyclist-oriented HMI were a system detecting other road users – including vehicles and other cyclists – and conveying information about their trajectories and intentions to the cyclist while also providing an option for real-time recommendations about navigation, speed, and traffic information. The communication modality of choice varied among the interviewees, but a visual interface was the most recurring modality in the analysis. The first interface concept, CycleSafe, aspires to meet these criteria. CycleSafe is a mobile application that utilises bicycle, vehicle, and infrastructure sensors combined with mapping technology to detect the presence and location of other road users and display this information on the screen. It also includes an alert system for critical or urgent situations, such as an imminent conflict with a vehicle, e.g., an approaching vehicle, a vehicle in the cyclist's blind spot, or a vehicle attempting to overtake the cyclist, as well as features like speed tracking and turn-by-turn navigation.

Cyclists have higher speeds than pedestrians and interact with vehicles longitudinally and in crossing and merging situations [2]. Accommodating cyclists' behavioural characteristics and desire for explicit communication, we developed the second concept: An omnidirectional external HMI (eHMI) placed on the vehicle (see Figure 1). The interviewed cyclists suggested that on-vehicle interfaces should be designed as an objective indicator of AV behaviour, as display, light, or LED lightbar, with different colours indicating the detection of the cyclist or the automated vehicle's intention. Taking cyclists' movement patterns into consideration, our proposed eHMI concept uses an LED light strip visible from all around the vehicle, to indicate whether the car is in automated driving mode. The light strip also changes colours from yellow to orange and red to indicate the proximity of the cyclist to the vehicle. As cyan is easily visible, perceptible to colour-deficient individuals, and not yet used in traffic signs [5,16], the light strip is cyan when automated driving is active.

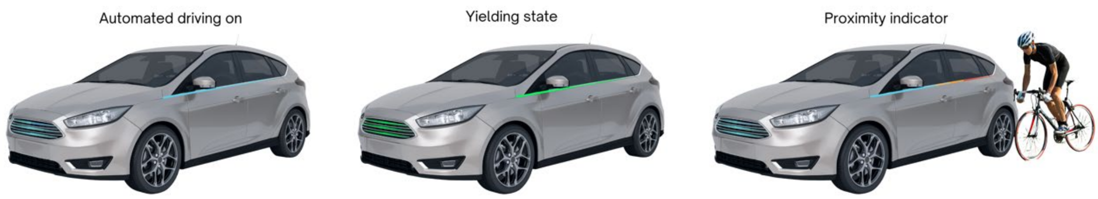


*Figure 1. The eHMI interface concept*

## Discussion

This study aimed to improve cyclist-AV interaction by identifying cyclists' information needs and developing HMI concepts. Two concepts were developed: CycleSafe, an app-based smartphone concept, and an eHMI concept using an omnidirectional design and lights changing colours to indicate the cyclists' proximity to the vehicle. The analysis showed that cyclists prefer visual HMIs, although previous research indicates that audio is an efficient modality [9,13] and that haptics is a slightly more preferred modality [6]. In sum, it is essential to continue further research on the effects of different HMI communication modalities on cyclists.

## Second study: Real-life testing

In this study, we outline an envisioned experiment for empirical testing of the two HMI concepts: a warning system feature of CycleSafe and the omnidirectional eHMI. Focusing on the effect of HMIs' communication modalities, this proposed experiment investigates whether cyclists benefit from receiving a warning signal and compare the efficiency of auditory and visual warning modalities. We derived the following research questions:

- Do cyclists benefit from and accept a warning about an approaching vehicle compared to no warning?
- Should the warning be presented in a visual or auditory modality or on the vehicle itself?
- Should the warning be presented early, i.e., anticipatory: before implicit communication manifests, or late?
- How does vehicle automation affect the efficiency of HMIs?

## Method

The experimental task is envisioned at a staged intersection without occlusion, where the cyclist crosses the intersection with a vehicle approaching from the right side in a 90-degree perpendicular direction. The cyclist will be instructed to cross the intersection if the car comes to a complete stop or stop if the vehicle implies taking the right-of-way. The driver will be instructed to initiate yielding or non-yielding by slowing down and stopping approximately 7 meters before the intersection or slowing down and crawling approximately 5 meters further to indicate the vehicle is not yielding. To the participant, the situation may appear ambiguous. The driver will not make head turns or eye contact with the cyclist, resembling the behaviour of a distracted driver or passenger of an AV with SAE level 3 or 4. The cyclist will receive an early or late warning through an on-bike smartphone with CycleSafe (see Figure 2) or the on-vehicle eHMI. In line with previous research, the auditory signal will be 75 dB [8,9]. For the visual signal, we will use a warning triangle symbol flashing on the screen twice for a duration of 400 ms, followed by a 400 ms break and 2400 ms visibility, similar to Erdei et al. [9]. The eHMI will be illuminated in cyan colour, indicating automation is on. The eHMI will light up green for the yielding trials, referencing that of a traffic light (see Figure 1). Early warnings will be issued before the cyclist can differentiate the yielding and non-yielding trials. As CycleSafe and the eHMI are still at the concept stage, the warnings will be triggered by GPS at pre-determined location points decided through pilot testing. The cyclist will interact with the vehicle in 20 trials and perform each combination twice, adding up to 40 trials per participant. All conditions will be randomised in blocks, starting with the baseline condition, e.g., the cyclist will receive a late and early warning to a vehicle yielding and not yielding in a randomised order for one randomised HMI modality at a time.


*Figure 2. The auditory, visual, and visual-auditory warning system features of CycleSafe*

Data will be collected with an instrumented bicycle, measuring cyclist speed, position, and swerving behaviour. The vehicle will be fitted with corresponding equipment measuring speed and position. We will use Tobii Pro Glasses 3 to measure cyclist eye-gazing behaviour. Post-trials, we will collect self-reported experiences with a short interview and questionnaire. The method of analysis of data is yet to be determined. We suggest a sample of 30 to 50 cyclists, likely recruited through social media advertisements and on-site flyers.

## Results and discussion

The envisioned study is still being planned, and there are no results to date. We hypothesise that cyclists prefer receiving warning signals over no warnings. In the user interface development study, most cyclists preferred to receive explicit communication from the AV. Cyclists will likely prefer receiving warning signals early rather than late due to early warnings' anticipatory nature in an ambiguous situation at an intersection with an AV. Lastly, we assume that auditory signals and the eHMI will perform better than the visual on-bike HMI. As the cyclists will have to place their visual attention away from traffic and to a warning displayed on the handlebars, the visual on-bike warnings will likely interfere more with the cyclists' visual attention than audio and the eHMI.

## Conclusion

This work-in-progress paper presented two studies aiming to develop and test user interfaces to improve the interaction of cyclists and AVs in future traffic. The first study indicated that cyclists need to be seen by AVs and prefer explicit communication of detection. Based on the interview data, we developed two HMI concepts, the app CycleSafe and an omnidirectional eHMI capable of communicating detection to cyclists. For the second study, we outlined an envisioned experiment to test the efficiency of the HMI's warning signals in a naturalistic study with cyclist-vehicle interaction. We hypothesise that cyclists prefer receiving warning signals over no warnings, prefer early over late warnings, and that auditory signals and the visual eHMI will perform better than the visual on-bike HMI.

**Supplementary data and acknowledgments**

Supplementary data is available at https://tinyurl.com/suppdataforIUI. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement 860410, the Institute of Transport Economics, and the Norwegian Research Council.

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## 7.4 Appendix D. Towards future pedestrian-vehicle interactions: Introducing theoretically-supported AR prototypes

Tabone, W., Lee, Y. M., Merat, N., Happee, R., & De Winter, J. C. F. (2021b). Towards future pedestrian-vehicle interactions: Introducing theoretically-supported AR prototypes. *Proceedings of the 13th International ACM Conference on Automotive User Interfaces and Interactive Vehicular Applications,* Leeds, UK, 209–218. https://doi.org/10.1145/3409118.3475149

### Abstract

The future urban environment may consist of mixed traffic in which pedestrians interact with automated vehicles (AVs). However, it is still unclear how AVs should communicate their intentions to pedestrians. Augmented reality (AR) technology could transform the future of interactions between pedestrians and AVs by offering targeted and individualized communication. This paper presents nine prototypes of AR concepts for pedestrian-AV interaction that are implemented and demonstrated in a real crossing environment. Each concept was based on expert perspectives and designed using theoretically-informed brainstorming sessions. Prototypes were implemented in Unity MARS and subsequently tested on an unmarked road using a standalone iPad Pro with LiDAR functionality. Despite the limitations of the technology, this paper offers an indication of how future AR systems may support future pedestrian-AV interactions.

### Introduction

Future automated vehicles (AVs) have to be able to drive in complex environments containing many interaction partners, including vulnerable road users (VRUs). In recent years, the ‘control loop’, in which the automated vehicle locates itself, perceives its surroundings, and decides upon the best trajectory, has changed into an ‘interaction loop’, where multiple road users cooperate through the wireless exchange of information [57]. To close the interaction loop, the AV may need to communicate its intentions to VRUs, who traditionally received such information explicitly from the driver and implicitly through vehicle kinematics [31]. Current solutions are smart infrastructure and vehicle-mounted external human-machine interfaces (eHMIs) [7, 10, 36, 51], and see [8] for a review of 70 eHMI concepts. However, these interfaces may be hard to read from a distance and potentially ambiguous, especially when encountering multiple pedestrians, as it could be unclear to whom the AV is communicating [46].

AR has already been used to support operators in many domains, including the military [32, 55], museums [52], industry [35], and entertainment [24]. As AR technology becomes more context-aware and pervasive [20], AR may benefit pedestrians. Through AR, it becomes possible to remove the display from the vehicle and place it anywhere in the world. Since each pedestrian would receive individualised communication, AR could solve the one-to-many communication problem of eHMIs [53]. Additionally, AR may prove advantageous in terms of costs, as it may be cheaper to build virtual interfaces than it would be to build their physical counterparts such as eHMIs.

AR has already been employed in traffic research, for example, to provide drivers with navigation advice in the form of augmented road signs [49] or to inform the driver about safe and unsafe slots via green and red coloured road surfaces [63]. Previous research on AR for VRUs has focused on handheld devices [28, 54] and AR glasses [40] for pedestrian route guidance and navigation. Furthermore, a ‘pedestrian in the loop’ system that uses the HoloLens to augment vehicles in the real environment for testing safety-critical situations has been developed by Hartmann et al. [22], whereas Kamalasanan et al. [25] conducted a HoloLens experiment to investigate the effect of an AR traffic light on pedestrian behaviour. Additionally, AR concepts that aim to provide crossing advice to VRUs have been presented as superimposed layers on a photo of the streetscape [23] and as part of a VR simulation [45]. However, to date, the literature presents only few AR prototypes for pedestrian-AV interactions in a real environment. Furthermore, the literature offers little guidance regarding the question: how should such prototypes function and look? This paper attempts to address this question by presenting AR prototypes for pedestrian-AV interactions that function in a real environment. The prototypes were designed using a theoretically informed approach that draws upon fundamental principles and concepts such as affordances [17], the field of safe travel [19], and risk perception [50]. In the spirit of open science, the code behind the AR concepts is provided as supplementary material (https://doi. org/10.4121/14933082) to facilitate reproducibility and encourage further development

In this paper, we present nine AR concepts that aim to support pedestrians that want to cross the road. The concepts were derived by building upon interviews with human factors experts [53] and supported by theories of perception, human factors, and spatial computing.

## Method

A four-phase process was employed to create the AR prototypes. In Phase 1, expert perspectives were analysed to extract AR design ideas. Phase 2 entailed identifying literature that served as theoretical background and inspiration for AR design. The next phase included an iterative design [43] brainstorming process that involved discussions on design considerations and sketching, followed by a heuristic evaluation Phase 4 covered the implementation of the sketched concepts.

### Phase 1: Collection of ideas

In Tabone et al. [53], experts in human factors provided their views on automated driving in future urban environments, eHMIs, and the use of AR in future traffic. For the present study, the experts' statements were extracted from [53] and its corresponding interview transcripts to identify concepts for pedestrian-AV interaction using AR. The analysis yielded seven quotes from the experts that could be turned into implementable concepts:

1. "It would be ideal to provide a unified affordance of the intentions of the vehicle, rather than just a visual colouring. For example, it would be interesting to alter the perceived surface of the AV to make it appear as more or less threatening, contingent on need." (P. A. Hancock, [53, p. 6]).
2. "Make objects stand out using subjective contours." (Peter A. Hancock, personal correspondence with Joost C. F. de Winter based on Hancock [21]).
3. "The AR system should provide information related to safety. The pedestrian could be presented with safety corridors related to which vehicles will stop for them. The advantage of this safety corridor concept is that it is integrating information from several vehicles. In doing so, it is clear to whom the vehicles are communicating, in contrast to the undirected

communication of traditional eHMIs." (Martin Baumann, [53, p. 4]). "AR glasses may allow for hands-free navigation and assist pedestrians with speed estimations by projecting the AV's trajectory." (Neville A. Stanton, [53, p. 11]).

4. "AR should not overwhelm the user. Information should include highlighting of hazards such as specific alerts that a vehicle is approaching." (Shuchisnigdha Deb, [53, p. 5]).
5. "Augmented 3D traffic light in the form of a virtual fence to stop pedestrians from crossing a vehicle lane. It would be ideal for tram lanes as well, and simple enough for a child to understand even in ambiguous situations when multiple pedestrians are present." (Riender Happee, [53, p. 7]).
6. "It would be interesting to be notified not just about the AV's intention to stop but also about where it intends to stop." (Marieke Martens, [53, p. 8]).
7. "The design should ensure that users direct their attention to the right information at the right time." (Natasha Merat, [53, p. 9]). These quotes served as the foundation for designing the concepts during the following phases.

**Phase 2: Collection of relevant literature**

Literature was collected to serve as a theoretical foundation for the subsequent design phase. For each idea reported above, two authors (Authors 1 and 5) identified supported theories and related concepts from a previously compiled literature folder containing 357 papers on eHMIs, AR, and other supports for VRUs. The selection of papers was based on seminal works in the field of Human Factors and Ergonomics.

**Phase 3: Brainstorming design sessions**

Brainstorming design sessions were conducted amongst the authors (Authors 1, 2, 4, & 5). The same scenario with a vehicle approaching from the right was envisaged for all concepts. An unmarked twoway road in Malta was chosen as the environment on which the AR concepts would be mapped. The car was stationary in front of the pedestrian crossing area to allow all AR concepts to be demoed irrespective of technical limitations.

It was agreed that two states would be created per concept, namely, 'vehicle is yielding', and 'vehicle is not yielding'. These states would be communicated using green and red, respectively, consistent with a study that showed these colours to be most intuitive for pedestrians judging the intentions of an approaching vehicle [2]. None of the concepts would communicate instructions, as instructions may lead to erroneous crossing decisions [30]. Moreover, it was decided that concepts that were not augmented on the ground would be made of translucent material not to block the user's view of the real world. It was agreed that each concept had a supporting cue, such as movement or iconography, to facilitate redundancy gain [29].

MIRO [38], an online collaborative environment, was used as a supporting tool. The MIRO board contained an affinity diagram and a table with 15 design principles for human-computer interaction [29]. Images taken from a LiDAR scan of the chosen environment were added to the board to aid the participants.

During the brainstorm, each concept idea from Phase 1 and corresponding literature from Phase 2 was brought forward. Design elements (e.g., dimensions, form, iconography, animation) were discussed at length with reference to the literature identified for the concept (see Phase 2). For each concept, virtual post-it notes representing different design elements were added to the board. The authors also used experience-based design to reach decisions. In total, the brainstorming was spread across three separate sessions for a total of 5 hours.

Through the design process, the seven design ideas extracted from Tabone et al. [53] evolved into the following nine AR concepts: (1) augmented zebra crossing, (2) planes on vehicle, (3) conspicuous and looming planes, (4) field of safe travel, (5) fixed pedestrian traffic lights, (6) virtual fence, (7) phantom car, (8) nudge HUD, (9) pedestrian traffic lights HUD.

A low-fidelity paper sketch was created for each concept based on the design elements identified for each concept. Finally, a heuristic evaluation was carried out based on nine AR heuristics proposed by Endsley et al. [12]. If shortcomings in the design were flagged through the heuristic evaluation, a design modification was conducted to accommodate. Examples include modifying Concepts 8 and 9 so that the messages were placed at the top of the field of view (FOV) rather than the middle to support the heuristic 'fit with the user's perceptual

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abilities'. Heuristics that were approved without modification to the concepts include 'alignment of physical and virtual worlds', 'accounting for hardware capabilities', and 'adaptation to user position and motion', amongst others. Once all authors were confident with the modified sketches and heuristic checklist, the concepts were moved to Phase 4.

**Phase 4: Implementation**

***Hardware and software***

The implementation was carried out using Unity 3D and its new tool for AR developers: Mixed and Augmented Reality Studio (MARS) v.1.2, together with Apple ARKit (v.2.1.9) and AR Foundation (v.2.1.8) libraries. A 15" MacBook Pro (2019) with 2.3 GHz 8-Core Intel Core i9 processor, 16 GB DDR4 memory, and Radeon Pro 560X 4 GB GPU was used for development, whereas an iPad Pro 11" (2020) was used as the target device because of its inbuilt LiDAR. A Toyota Yaris Hybrid vehicle was used for demonstrating the AR concepts.

A LiDAR 3D scan of the crossing and surrounding area of the road was captured (Figure 1) using the 3dScanner app [56] on the iPad set on a lower quality setting to reduce storage requirements. The scan with 1.1 million vertices was exported as an OBJ file and imported into Blender, where texture files extracted from the 3D scanning software were added, and the final scan was exported as an FBX file. A Unity MARS simulation environment was created using the FBX to test the augmented concepts in the Unity editor before actual testing on site.

*Figure 1. Left: The chosen unmarked crossing in Malta. Right: The captured LiDAR 3D scan on location.*

***Implementing the AR concepts in MARS***

To anchor the concepts to the real world, several Unity MARS tools were used [61]. Proxies, representing real-world objects (e.g., a flat surface, vehicle) that the final application could detect, were used to define regions where augmented elements could appear. Some proxies included semantic tags (i.e., to specify that they represent the user in the real world or the floor), whereas others included Conditions, Rules, and Forces, which affect the behaviour of the proxies.

Our implemented app, built through Unity MARS, used the camera and LiDAR of the iPad to scan the real environment, generate planes of the world, and spawn objects if proxy conditions were met (e.g., horizontal surface of a certain size). During the first visit to the testing location, the Unity MARS companion app [62] was used to capture the environment dimensions, image markers, and proxy data of the crossing region and vehicle, to be used in the implementation.

For each implementation, the objects that comprise the AR concept were added as children to their Proxy object. ShowChildrenOnTrackingAction was applied, so that child objects were spawned, oriented, and anchored with the proxy object once the proxy's conditions were met.

For concepts that were augmented on the ground (i.e., Concepts 1 and 6), the crossing region's horizontal proxy data was used together with a number of conditions. More specifically, IsPlaneCondition, FlatFloorCondition, and a 'floor' semantic tag were added to specify that the object to augment upon had to be a flat surface and a floor. An AlignmentCondition was added to align objects in a HorizontalUp orientation, whereas a PlaneSizeCondition specified that a 1.5 m x 1.5 m flat plane had to be scanned and mapped for augmentation to occur. To make the AR concept align with the user, the objects augmented on the proxy were aligned to a ProxyObjectReferencePerson (representing the user's position) through a ProxyAlignmentForce.

Image markers (i.e., doorway across the street, photo of the car) were used for instances where a crossing region (i.e., Concepts 5 and 7) or a car (i.e., Concepts 2 and 3) had to be recognised. In these cases, a MarkerCondition was added to the proxy, and the image to be recognised was selected from the Marker Library imported through the companion app. The child objects would spawn and anchor to the real-world region that was mapped through the image marker.

For Concept 4, a direct placement script by the Unity MARS team [60] was used so that an object could be spawned and mapped to any surface found by raycasting. Lastly, concepts with a HUD (Concepts 8 and 9) used the traditional Unity UI workflow in a Unity MARS session.

***Creating the final application and testing on-site***

For each concept, a plane or point cloud visualisers were added to offer visual feedback to the user that the system was detecting the environment during operation. The shifting from the yielding to the non-yielding state was performed manually via a tap on the iPad screen.

During each iteration, the prototype was built as an iOS app onto the iPad and tested at the chosen location until its performance concerning the mapping of the visual elements to the real world was satisfactory. A single app comprising all implemented concepts and a menu was exported and executed on-site. The prototypes were recorded using the in-built iOS screen capture. These recordings, together with an additional number of demos involving a moving car, which yielded or maintained speed, were compiled into a single video, which is available as supplementary material. In addition, the material includes a photograph detailing how the iPad was used.

## Results and discussion

### Concept 1: Augmented zebra crossing

Concepts 1 and 2 were derived from the first quote in Phase 1. For Concept 1, the part on "providing a unified affordance rather than just a visual colouring" was taken into account for the road. Hence, for Concept 1, we decided to change the surface and colour of the road (Figure 2). Similar non-augmented concepts have used LEDs embedded in the road to display crossings on-demand [59]. In the same vein, Eriksson et al. [13] presented an in-vehicle augmented HMI that showed a red demarcation or green carpet on the motorway depending on whether it was unsafe or safe to change lanes.

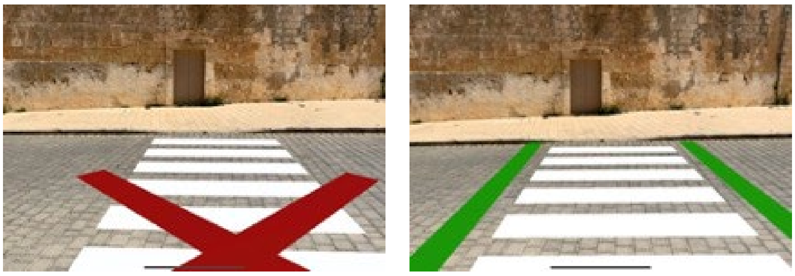

*Figure 2. Concept 1. Left: non-yielding state with an 'X' placed on top of the augmented zebra crossing. Right: yielding state with two green bars flanking the zebra crossing.*

Our prototype for Concept 1 in a non-yielding state consists of a zebra crossing with a red cross overlaid on top. For the yielding state, the red cross is replaced by two rectangular green bars that flank the zebra crossing on either vertical side. These display elements were inspired by a previously published implementation of a smart road [33]. A zebra crossing with additional elements was preferred over an entire green/red surface with overlaid arrows because the latter may offer an instructive suggestion to cross.

**Concept 2: Planes on vehicle**

This AR concept entailed a change of the vehicle surface (Figure 3). We added a plane that would appear at the top front part of the vehicle. While vehicle kinematics combined with such an AR concept may already offer a rich cue, there is still the issue that a red car may be perceived as yielding (rather than the green car) [2, 30]. Therefore, redundancy gain was employed [65] by superimposing standard icons representing yielding (walking human figure) and non-yielding (hand palm) on the windshield, considering that pedestrians are likely to focus their visual attention on that region [9, 66].

*Figure 3. Concept 2. Left: non-yielding state with the red plane and hand icon augmented on the vehicle. Right: yielding state with the green plane and crossing figure icon augmented on the vehicle. In our prototype and supplementary video, the non-yielding red plane is spawned as soon as the image marker condition for the vehicle is satisfied (that is, the vehicle used for the image marker is detected).*

**Concept 3: Conspicuous looming planes**

For the third AR concept, which is based on the second quote from Phase 1, the theories of looming and conspicuity [21] were drawn upon. In the study of perception, looming concerns the human response to the rapid approach of a solid body [50]. Through looming, it is possible to communicate threat and distinguish an approaching object from one that is stationary or receding [6, 18]. Conspicuity is defined as "something that is obvious to the eye or mind, or something that is striking and attracts attention" [37]. Using these principles, Concept 2 was modified so that the red plane (non-yielding) grows in size as it approaches the user and fills the entire FOV by the end, while conversely, the green plane (yielding) shrinks as the vehicle approaches. Hence, threat is mapped to the size of the plane as the vehicle approaches the crossing. In the supplementary video, the camera moves towards the vehicle as the planes grow or shrink, dependent on the state, to simulate the vehicle approaching.

**Concept 4: Field of safe travel**

The point of departure for this AR concept (Figure 4) was a 'safety corridor' presented to the pedestrian, as mentioned in the third quote from Phase 1. Gibson's field of safe travel [19] was the theory behind this concept. The field at any given moment represents the paths that a car may take unimpeded, and it would look like a "sort of tongue protruding forward along the road" [19, 27]. The concept relates to the theory of affordances [17] since the shape of the field is not based on arbitrary rules but reflects physical laws. In simpler terms, the projected field indicates where a vehicle may be in a given amount of time. Hence, if a person enters a red zone, they risk being hit by the vehicle. For the non-yielding state, the red field extends beyond the crossing point, whereas for the yielding state, the field switches to green, widens, and terminates prior to the point of crossing to emphasize the vehicle will not cross beyond this point.

*Figure 4. Concept 4. Left: non-yielding state with the red field of safe travel extending over the crossing area. Right: yielding state with the green field of travel shortened and truncating before the crossing area.*

In our approach, the field is represented as a flat plane emerging from the front of the vehicle. If the prototype was to be fully implemented, the plane's length would be proportional to the vehicle's speed. However, to demonstrate both states using the prototype for the supplementary video, the length of the plane was hardcoded. Hesenius et al. [23] presented a similar concept of Safe Zones for pedestrians, highlighting regions on the road. Areas marked in green denoted zones that could be safely traversed; conversely, areas marked in red denoted potentially dangerous areas to navigate.

**Concept 5: Fixed pedestrian traffic lights**

For this AR concept (Figure 5), based on the fourth quote in Phase 1, the familiar concept of binary pedestrian traffic lights was chosen. These lights would pop up on the other side of the crossing area to alert the pedestrian whether a vehicle is approaching and intending to yield. As an additional cue to the red and green traffic light beams used for the non-yielding and yielding states, icons of a static and walking human figure are superimposed, respectively. Moreover, since this pedestrian traffic light is a replica of its realworld counterpart, it is attached to the ground to comply with the user's mental model.

*Figure 5. Concept 5. Left: non-yielding state with red pedestrian icon. Right: yielding state with green pedestrian icon.*

For the implementation, the 3D model of the lights was set as a child of the crossing image marker proxy. Once the iPad was pointed towards the doorway across the road, the traffic lights model was augmented on the pavement.

**Concept 6: Virtual fence**

Concept 6 was to "augment a 3D traffic light in the form of a virtual fence", as stated in the fifth quote from Phase 1. Discussions commenced with the idea of having a fence preventing pedestrians from entering the road. However, concerns arose that the fence could invite the pedestrian to walk around it, which is undesirable. Therefore, the fence concept was operationalized in the form of a tunnel (Figure 6).

The tunnel is created using semi-translucent green walls on either side of the crossing area, high enough to enclose a person with an average height. A zebra crossing is displayed on the tunnel's floor to offer redundancy gain, while a semi-translucent red gate of the same height blocks the pedestrian's path to the other side of the road in the non-yielding state. The sides of the tunnel are green to indicate that cars could cross through that side of the tunnel. The gate's colour switches to green for the yielding state, and an animation of the gate swinging open plays out. For the implementation, the proxies and zebra crossing used in Concept 1 were built upon.

The 'tunnels in the sky' [41, 58] AR/HUD concept from the domain of aviation was a source of inspiration for the design. Furthermore, a 'safe corridor' augmented in-vehicle HMI, which

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communicates to the driver whether an area on the road should be avoided (if red) or safely steered into (green) [34], served as an additional source of inspiration. It has similarities to the on-the-road carpet HMI consulted for Concept 1 [13]. These carpet metaphors inspired the addition of a zebra crossing placed on the ground between the walls.

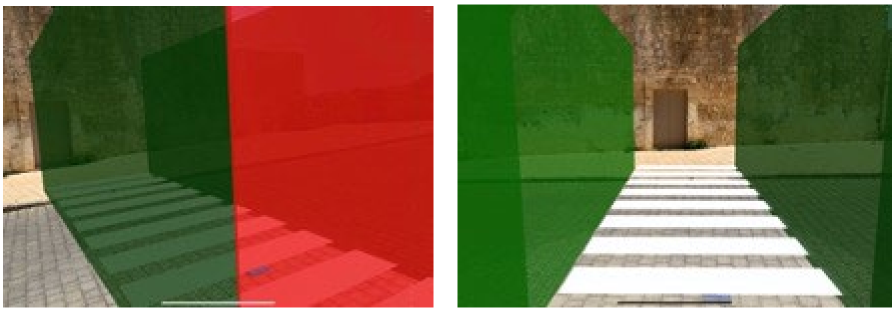

*Figure 6. Concept 6. Left: non-yielding state with the closed red gate 'blocking' the pedestrian. Right: yielding state, where the gate is green and opened.*

**Concept 7: Phantom car**

In this case, in addition to the vehicle's intention to yield, the concept communicates its intended stopping location (Figure 7). A previously published concept called 'Vehicle Intents' [23] highlighted the vehicle's path with an arrow and added stopping lines to communicate where the vehicle would stop if the pedestrian was to cross. The idea was further developed to include an augmented representation of a hatchback car, similar to what could be seen as part of a ghost replay system in a racing computer game or Tesla's shadow mode [14].

*Figure 7. Concept 7. Left: non-yielding state with the red phantom car blocking the crossing area. Right: yielding state with the real car entering the green phantom car.*

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Hence, the phantom car concept was created. A semi-translucent vehicle, which switches between green and red depending on the scenario, is augmented. The phantom car moves in front of the real vehicle to indicate where the vehicle would be after a particular time (e.g., 2 seconds into the future). In the yielding scenario, as the real vehicle slows down, the distance between itself and the green phantom car will shrink until the real vehicle has fully entered the phantom car. In the non-yielding scenario, the red phantom car will communicate its intent by moving in front of the actual vehicle at a constant distance.

In the prototype and supplementary video, the non-yielding red phantom car was augmented on the crossing to simulate that the vehicle intends to move beyond the stopping area; hence, it is unsafe to cross. In the yielding scenario, the green phantom car was augmented next to the stationary real vehicle to simulate the moment before the real vehicle had fully entered the area occupied by the phantom car.

**Concept 8: Nudge HUD**

Distracted pedestrians are the cause of many accidents [1, 42]. An interface that assists the pedestrian with looking towards the right direction may therefore be beneficial. This concept addresses a different challenge from the previous concepts, as the latter assume that the pedestrian is looking at the AR display anchored to the environment. In Concept 8, a HUD that follows the pedestrian's FOV regardless of where they are looking, was created (Figure 8).

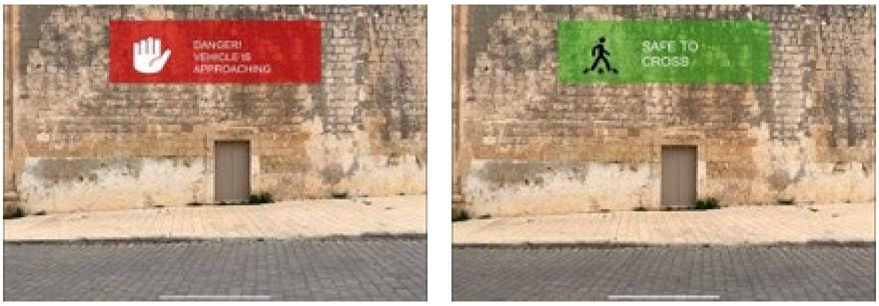


*Figure 8. Concept 8. Left: the non-yielding state with the red HUD showing the hand icon and corresponding text message. Right: the yielding state with the green HUD, walking pedestrian icon, and corresponding text message.*

The HUD was drawn in a billboard style where text in sans serif typeface Arial was placed on a background plane of a different colour to offer good performance in terms of readability [3, 16, 47]. For the non-yielding state, the text is “DANGER! VEHICLE IS APPROACHING”, which changes to “SAFE TO CROSS” in the yielding state [15]. The messages use non-instructing language since there are dangers of misinterpretation in providing explicit advice [30]. Icons were added to the left of the text and switched between an outstretched hand and a walking human figure, respectively.

The HUD was display-locked so that it stayed in the same position on the display, which would be analogous to head-locked positioning on a head-mounted display such as AR glasses. This placement decision was based on empirical research recommending head-locked text placement if the real-world task involves permanent visual monitoring in the central or near-peripheral visual field [26], which in our case would be monitoring of the vehicle. Moreover, the HUD was placed in the centre top section of the FOV since it is recommended to place text in top positions in complex environments that require constant monitoring [26]. Top positioning would also leave the bottom part of the FOV not occluded so that the pedestrian could still see where they are walking.

**Concept 9: Pedestrian traffic lights**

HUD For this concept, the pedestrian traffic light model used for Concept 5 is displayed as a HUD that follows the user’s FOV (Figure 9). The model was modified to remove the pole that attaches the traffic light to the ground to create a ‘detached’ interface element. Moreover, the same interface placement location used for Concept 8 was adopted, with the difference that instead of using UI elements, the 3D traffic light model was made a child of the main camera to follow the FOV.

*Figure 9. Concept 9. Left: non-yielding state with the red pedestrian icon. Right: yielding state with the green pedestrian icon.*

## General discussion

In this paper, nine AR concepts that aim to support pedestrians in making crossing decisions when encountering future traffic in an urban environment were presented as implemented prototypes. Expert perspectives [53] were analysed to extract AR concept ideas. Subsequently, a literature analysis was performed to identify similar approaches and theories that aided in transforming the idea into a prototype. Following this phase, brainstorming design sessions were conducted, resulting in nine designs in the form of sketches on paper. Underlying these ideas were theories of affordances [17], multimodal communication [5], looming and conspicuity [21, 50], and AR research in aerospace [41, 58]. Finally, implementation was conducted using Unity MARS, a new tool for AR developers, and the AR concepts were tested and filmed at an uncontrolled crossing.

During the brainstorming process and based on the literature consulted, it was decided that colour alone was ‘not enough’ and that redundancy gain had to be employed [65]. Therefore, icons were added. In the same vein, the mere presence of a zebra crossing does not guarantee safety in the real world. With the addition of the red cross and the green bars, the interface communicated that it was unsafe or safe to cross at that moment. Moreover, based on the literature, it was decided that messages should not be instructive [30]. Hence, the concepts were made comparable in the sense that none instructed pedestrians but rather gave the suggestion that it is safe or unsafe to cross.

Occlusion [39, 67] was a difficult factor to handle, which is why this was discussed in detail during the brainstorming session and the subsequent heuristic evaluation. The occlusion issue [44] was experienced first-hand, where the gate and walls of the virtual fence (Concept 6) had to be semi-translucent so that the vehicle could be seen. The same principle was applied to the other concepts that were not augmented on the road surface.

### Limitations and future work

Several assumptions were made, and the presented concepts should not be viewed as fully finished AR interfaces that VRUs can already use. The implemented concepts and videos take only one vehicle into account. Furthermore, although most of the prototypes were augmented using Unity MARS functionalities such as Proxies, Conditions, and Forces, for all concepts, the state change for vehicle intent (i.e., yielding, non-yielding) was manually triggered using a tap on the iPad. In real-life applications, the path planner of the AV, connected to its CAN bus, could send out a wireless signal to the VRU's AR system when the AV-VRU distance or time-to-arrival drops below a threshold value.

Concepts such as 8 and 9 were easy to implement as little context is needed for these to operate. However, because of the nascent status of the technology used, various workarounds were implemented for concepts that required knowledge of the position of the approaching vehicle (Concepts 2, 3, 4, 7) and its speed (Concepts 3, 4, and 7). These workarounds included having the real vehicle remaining static since moving real-world objects are not yet supported by the libraries used. While the road position was handled by Unity MARS through the camera and LiDAR, vehicle position was hardcoded, or image markers were relied upon. Moreover, the dimensions of the zebra crossing and tunnel for Concepts 1 and 6 were set manually, based on the 3D LiDAR scan model of the environment. For Concept 3, vehicle position readouts from LiDAR raycasts were tried to map the looming plane's size with AV-pedestrian distance. However, the desired precision was not attained, and hence an animator script was used to resize the planes. Future improvements could be accomplished through edge computer vision methods to detect the distance and speeds of approaching road users. Alternatively, IoT communication could be used, where AVs transmit their yielding intent, position, and speed wirelessly to the VRU, as pointed out above.

Although the current implementation was done on an iPad Pro (to make use of its LiDAR), the concepts could be readily exported to the head-mounted displays currently supported by Unity and Unity MARS. In that case, sensor requirements would need to be met, and issues such as outdoor luminance levels that may hinder perception [11], ocular vergence-accommodation conflicts [48, 64] and latency issues leading to visually induced motion sickness [4] have to be considered. Sensor requirements vary between concepts according to complexity, as shown in Table 1.

**Table 1**

Sensor requirements for the concepts.

| Concept | Road position | Vehicle intent | Vehicle position | Vehicle speed |
|---|---|---|---|---|
| (1) Augmented zebra crossing | X | X | | |
| (2) Planes on vehicle | | X | X | |
| (3) Conspicuous looming planes | | X | X | X |
| (4) Field of safe travel | X | X | X | X |
| (5) Fixed pedestrian traffic lights | X | X | | |
| (6) Virtual fence | X | X | | |
| (7) Phantom car | | X | X | X |
| (8) Nudge HUD | | X | | |
| (9) Pedestrian traffic lights HUD | | X | | |

In the future, user studies are needed to identify which concepts are best accepted, how the concepts would function on AR glasses in the urban environment, and what triggers should be used to change between yielding and non-yielding states. The intuitiveness of the mappings used, such as the intuitiveness of the looming cues in Concept 3 and the red vs. green colours used for the tunnel walls in Concept 6, needs to be investigated as well. Furthermore, it would be important to include provisions for VRUs with visual impairments, for example, by adding tactile or auditory signals. Finally, it would be worthwhile to explore how to integrate the AR concepts with other communication modalities for VRUs, such as eHMIs and smart infrastructure.

## Conclusion

In conclusion, this paper presents an outlook on future AV-VRU communication through AR in the form of prototypes. This paper presents nine such concepts designed using theory, expert opinion, literature, brainstorm, and implementation in Unity. In the spirit of open science, the code is provided as supplementary material to encourage further development.

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## 7.5 Appendix E. Augmented reality interfaces for pedestrian-vehicle interactions: An online study

Tabone, W., Happee, R., García, J., Lee, Y. M., Lupetti, L., Merat, N., & De Winter J. C. F. (2023a). Augmented reality interfaces for pedestrian-vehicle interactions: An online study. *Transportation Research Part F: Traffic Psychology and Behaviour, 94*, 170–189. https://doi.org/10.1016/j.trf.2023.02.005

**Abstract**

Augmented Reality (AR) technology could be utilised to assist pedestrians in navigating safely through traffic. However, whether potential users would understand and use such AR solutions is currently unknown. Nine novel AR interfaces for pedestrian-vehicle communication, previously developed using an experience-based design method, were evaluated through an online questionnaire study completed by 992 respondents in Germany, the Netherlands, Norway, Sweden, and the United Kingdom. The AR indicated whether it was safe to cross the road in front of an approaching automated vehicle. Each interface was rated for its intuitiveness and convincingness, aesthetics, and usefulness. Moreover, comments were collected for qualitative analysis. The results indicated that interfaces that employed traditional design elements from existing traffic, and head-up displays, received the highest ratings overall. Statistical results also showed that there were no significant effects of country, age, and gender on interface acceptance. Thematic analysis of the textual comments offered detail on each interface design's stronger and weaker points, and revealed unintended effects of certain designs. In particular, some of the interfaces were commented on as being dangerous or scary, or were criticised that they could be misinterpreted in that they signal that something is wrong with the vehicle, or that they could occlude the view of the vehicle. The current findings highlight the limitations of experience-based design, and the importance of applying legacy design principles and involving target users in design and evaluation. Future research should be conducted in scenarios in which pedestrians actually interact with approaching vehicles.

## Introduction

Future traffic, in which automated vehicles (AVs) will be driving in city environments, requires transparent communication of the intentions of the vehicle with interaction partners, such as vulnerable road users (VRUs). In traditional traffic, transparent communication between vehicles and vulnerable road users is achieved through implicit and explicit cues (Lee et al., 2021; Schieben et al., 2019). Implicit cues include vehicle speed, dynamics, and gap size, while explicit cues include the horn, hand gestures, and eye contact. VRUs base their crossing decisions primarily on implicit cues (Dey & Terken, 2017; Lee et al., 2021), whereas explicit cues tend to be used when implicit cues are ambiguous (Onkhar et al., 2021; Uttley et al., 2020). With the introduction of AVs in the urban environment, the lack of a driver or attentive passenger may require a different approach to communicating intent from the AV to the VRU (Ackermans et al., 2020; Carmona et al., 2021; Faas et al., 2020; Hensch et al., 2019). Several communication methodologies have been proposed to alleviate the problems of AV-VRU interactions. These include the use of smart road infrastructure (Löcken et al., 2019; Pompigna & Mauro, 2022; Toh et al., 2020), smart vehicle kinematics through the use of vehicle pitch, deceleration, and lateral position (Bindschädel et al., 2022; Dietrich et al., 2020; Fuest et al., 2018; Sripada et al., 2021), and external human-machine interfaces (eHMIs).

Various forms of eHMIs have been developed, including LED strips, LED screens, anthropomorphic elements, actuated robotic attachments, and projections on the road, amongst others (see Bazilinskyy et al., 2019; De Winter & Dodou, 2022; Dey et al., 2020a; Rouchitsas & Alm, 2019, for reviews of such interfaces). Despite their effectiveness in encouraging VRUs to (not) cross in front of the AV's path, current eHMI designs have some drawbacks, namely if the eHMI needs to signal to a single pedestrian in a group, or, for text-based eHMIs, if the message is in a language unfamiliar to the pedestrian. Furthermore, so far, there has been no standardisation of eHMIs, and therefore pedestrians may encounter a variety of different eHMIs on vehicles, which could cause confusion (Rasouli & Tsotsos, 2020; Tabone et al., 2021a), with potentially dangerous consequences.

In an effort to address some of these problems, augmented reality (AR) has been proposed as a new type of communication in traffic. AR used by individual VRUs can alleviate several issues, especially the one-to-many communication problem, where multiple actors (vehicles and pedestrians) are present in the environment and it is not clear which actor is communicating to whom. Through AR, the communication signal could be sent individually and separately to each pedestrian, and does not have to be constrained to the AV itself but can be presented anywhere in the environment (Tabone et al., 2021b; Tran et al., 2022).

So far, studies on AR for pedestrian-vehicle interaction consider the driver as the AR user, by highlighting pedestrians and/or cyclists in front of the vehicle (e.g., Calvi et al., 2020; Colley et al., 2021; Currano et al., 2021; Kim et al., 2018; Pichen et al., 2020). Such solutions are becoming technologically feasible when considering that the most recent vehicle models already feature AR-based head-up displays (Volkswagen, 2020). The use of AR by VRUs themselves is still relatively rare and has mostly been constrained to route navigation tasks (e.g., Bhorkar, 2017; Dancu et al., 2015; Dong et al., 2021; Ginters, 2019), for example as an add-on to Google Maps (Ranieri, 2020). Only a small, but growing number of studies have examined the use of AR for supporting VRUs in making safe crossing decisions. Examples include road projections such as zebra crossings, safe paths, and arrows (Hesenius et al., 2018; Li et al., 2022; Pratticò et al., 2021; Tran et al., 2022), visualisation of obstructed vehicles (Matviienko et al., 2022; Von Sawitzky et al., 2020), visualisation of collision times and conflict points (Tong & Jia, 2019), warning signs (Tong & Jia, 2019; Von Sawitzky et al., 2020), and car overlays (Tran et al., 2022). Using virtual reality, Oudshoorn et al. (2021) developed bioinspired eHMIs for pedestrian-AV interaction, whereas Mok et al. (2022) developed eHMIs in the form of laser-type rays emitted from the AV. The authors noted that these types of eHMIs may be hard to physically implement on real AVs, and that AR used by pedestrians (such as through AR glasses or handheld devices) could be a viable alternative.

It should be noted that most AR concepts for VRUs are still in a conceptual stage (videos, virtual reality), while only a few AR interfaces for VRUs have been demonstrated on a real road (Maruhn et al., 2020; Tabone et al., 2021b), or in a laboratory environment (Matviienko et al., 2022; Pratticò et al., 2021; Tran et al., 2022). In Tabone et al. (2021b), novel AR interfaces for pedestrian-AV interaction were developed and demonstrated in a real crossing environment. The interfaces were designed to assist pedestrians in the decision to cross the road in front of an approaching automated vehicle which was either yielding (stopping) or non-yielding. The interfaces were based on expert perspectives extracted from Tabone et al. (2021a) and designed using theoretically-informed brainstorming sessions (see Figure 1 for the interfaces). In total, nine AR interfaces were designed, each with a non-yielding and yielding state, depicted in red and green respectively. These colours were selected based on their high intuitiveness rating for signalling 'please (do not) cross' (Bazilinskyy et al., 2020).

Three of the interfaces were mapped to the road, four were mapped to the vehicle, and two were head-locked to the user's field of view. The ones mapped to the road were the *augmented zebra crossing*, which is a traditional zebra crossing design (1 in Figure 1), *fixed pedestrian traffic lights* (5), which depicts a familiar pedestrian traffic light design across the road, and a *virtual fenc*e (6), which includes semi-translucent walls around a zebra-crossing and a gate that opens in the yielding state. The interfaces that were mapped to the vehicle included the *planes on the vehicle* (2), which displays a plane on the windshield area of the vehicle, the *conspicuous looming plane* (3), which grows or shrinks as the vehicle approaches the pedestrian depending on the AV's yielding state, the *field of safe travel* (4) which projects a field on the road in front of the vehicle to communicate safety, and the *phantom car* (7) which projects the vehicle's predicted future motion. The finaltwo interfaces are head-up displays: the *nudge head-up display* (HUD) (8), which displays text and icons, and the *pedestrian lights HUD* (9), which displays a head-locked version of the pedestrian traffic lights.

In Tabone et al. (2021b), the interfaces were implemented on a handheld device (iPad Pro 2020) and demonstrated in a real crossing environment (Figure 1), but no user study was performed. The concepts were designed using a 'genius'-based design approach (Saffer, 2010). In contrast to other design approaches, genius design does not involve users as part of the formal research phase. Instead, the design team relies on personal experience, existing knowledge of human behaviour, the problem space, and human cognition and psychology (Saffer, 2010). This approach offers the benefit of time efficiency, coherence of solutions with the original vision, and the flexibility to generate ideas quickly. Yet, such an approach could be contested as it addresses the problem space only from a designer's viewpoint without the involvement of the intended users (Nielsen, 2007).

Although a theoretical evaluation based on nine AR heuristics (Endsley et al., 2017) was performed in Tabone et al. (2021b), it is vital that AR concepts are evaluated empirically to assess whether the theoretically informed ideas are valid. Such an empirical evaluation would assess the viability of the 'genius' design approach in Tabone et al. (2021b) and whether the designers' intended effects would generalise to potential target users. Conducting a real-world study with the implemented AR prototypes would have been very difficult at the time of writing due to AR technology limitations, such as outdoor luminance levels that may hinder perception, latency issues that may lead to visually induced motion sickness, and ocular vergence-accommodation conflicts in open spaces (Buker et al., 2012; Rolland et al., 1995; Wann et al., 1995). Therefore, an online questionnaire study approach with a large number of participants was selected. A substantial number of previous works have conducted online user surveys to evaluate eHMIs for pedestrian-AV interaction (e.g., Bai et al., 2021; Bazilinskyy et al., 2020, 2021; Dey et al., 2020b; Lau et al., 2021). However, no large-sample survey of AR interfaces for VRU-AV interactions has been conducted so far.

Hence, we attempt to fill this gap and build upon the previous design work reported in Tabone et al. (2021b) by conducting an online video-based questionnaire study that investigates user acceptance of the AR interfaces across large numbers of participants, exploring key moderator variables (e.g., nationality, gender). Ratings of intuitiveness, convincingness, usefulness, aesthetics, and satisfaction with the interface were captured, which were thought to represent key dimensions of interface quality. These measures were based on previous studies which explored intuitiveness (Bazilinskyy et al., 2020), usefulness (Adell, 2010), quality of information (Lau et al., 2021), as well as aestheticism, attractiveness, and visibility (Métayer & Coeugnet, 2021). More specifically, it was reasoned that a high-quality AR interface should be easily understood (intuitive) and encourage people to follow up its recommendations (convincing), and be seen as useful in supporting pedestrian decision-making (usefulness). Furthermore, apart from encouraging performance, whether people like the AR interface (attractiveness, satisfaction) was seen as relevant, as when people might reject/disuse an (otherwise useful) AR interface on aesthetic grounds, it will still fail to be effective.

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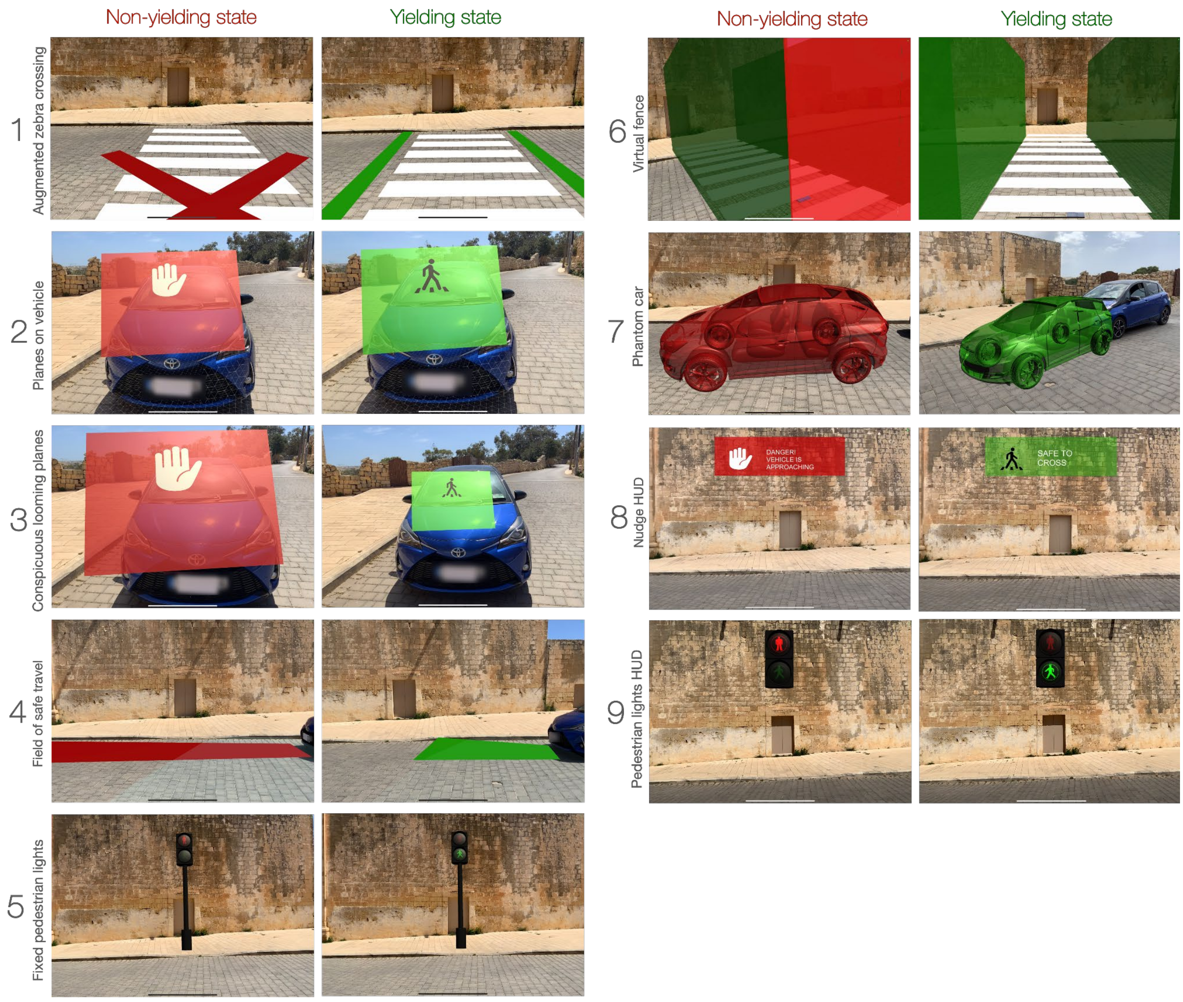


*Figure 1.* The nine AR concepts for pedestrian-vehicle interactions designed and developed by Tabone et al. (2021a). In total, nine AR interface concepts were developed, each with a yielding and non-yielding state: 1. *Augmented zebra crossing, 2. Planes on vehicle, 3. Conspicuous looming planes* (i.e., planes which grew or shrank in size)*, 4. Field of safe travel, 5. Fixed pedestrian traffic lights, 6. Virtual fence, 7. Phantom car* (i.e., a transparent car which indicates the vehicle's predicted future position)*, 8. Nudge HUD* (i.e., a floating text message and icon which informed the pedestrian whether or not it was safe to cross)*, 9. Pedestrian traffic lights HUD.* Interfaces 1, 4, 5, 6, and 7 are projected on the road surface, while Interfaces 2 and 3 are projected on the car. Interfaces 8 and 9 are head-locked, i.e., they remain in the user's field of view.

## Method

In this study, participants viewed videos in a within-subject design, with 9 AR interfaces and 2 yielding behaviours. Participants rated each video according to a number of criteria. The video content, questionnaire design and procedures, and statistical analysis methods are explained below.

**Videos**

A total of 19 videos (at 30 fps) depicting an approaching AV with a representation of the AR interface in the virtual reality (VR) environment were created (Figure 2). More specifically, nine videos depicted a yielding AV featuring a green-coloured (RGB: 32, 244, 0) AR interface, and nine videos depicted a non-yielding AV featuring a red-coloured (RGB: 244, 0, 0) AR interface.

A 19th video was created to depict a non-yielding AV without any interface. The latter was used at the start of the questionnaire to demonstrate how confusing and dangerous a situation without any form of signal would be, especially if the vehicle does not yield, while the other 18 videos were shown to participants in the experiment section of the questionnaire.

The videos were created based on a simulation created in a Unity-built VR environment (Unity, 2022). The road environment was obtained from previous research (e.g., Kaleefathullah et al., 2020) performed in the Highly Immersive Kinematic Experimental Research (HIKER) simulator located at the University of Leeds (University of Leeds, 2022). The videos mimicked the first-person view of a stationary pedestrian considering to cross in front of an approaching vehicle and looking to the right, on a one-way street. A one-way street was selected in order to standardise the direction of traffic flow, considering that the target population of the study were from countries with different traffic systems. Other studies focusing on road crossing have also utilised a one-way street scenario (e.g., Cavallo et al., 2019; Kaleefathullah et al., 2020; Weber et al., 2019).

Trigger points and speeds were adopted from a study on pedestrian crossing in the HIKER simulator (Kaleefathullah et al., 2020). The AV, represented by the same car model in each video, spawned out of sight from the field of view (Figure 3, Point A) and moved at a constant speed of 30 mph (48 kph). All interfaces, irrespective of location and state, were triggered

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when the vehicle reached Point B, located 43 m from the participant (camera) location at Point E. For yielding AVs, the vehicle started decelerating at a rate of 2.99 $m/s^2$ at Point C, which is located 33 m from Point E, and it came to a full stop 3 m from Point E, at Point D. In the case of a non-yielding AV, the vehicle maintained its initial speed of 30 mph throughout.

Each video started with the camera pointing towards the other end of the crossing (Figure 4, at time 0 s). The camera then slowly panned to the right as the vehicle approached from point A, starting at an elapsed time of 0.5 s. At an elapsed time of 2 s, the camera would have rotated by an angle of 45°, and the approaching vehicle and AR interface (regardless of type) could be seen simultaneously. At 4 s, the camera started to rotate back to the front-facing position, and it stopped rotating at 20° to the right for the yielding state (elapsed time: 9 s), and fully facing the front for the non-yielding AV (elapsed time: 8 s) so that the vehicle could be observed driving over the crossing area.

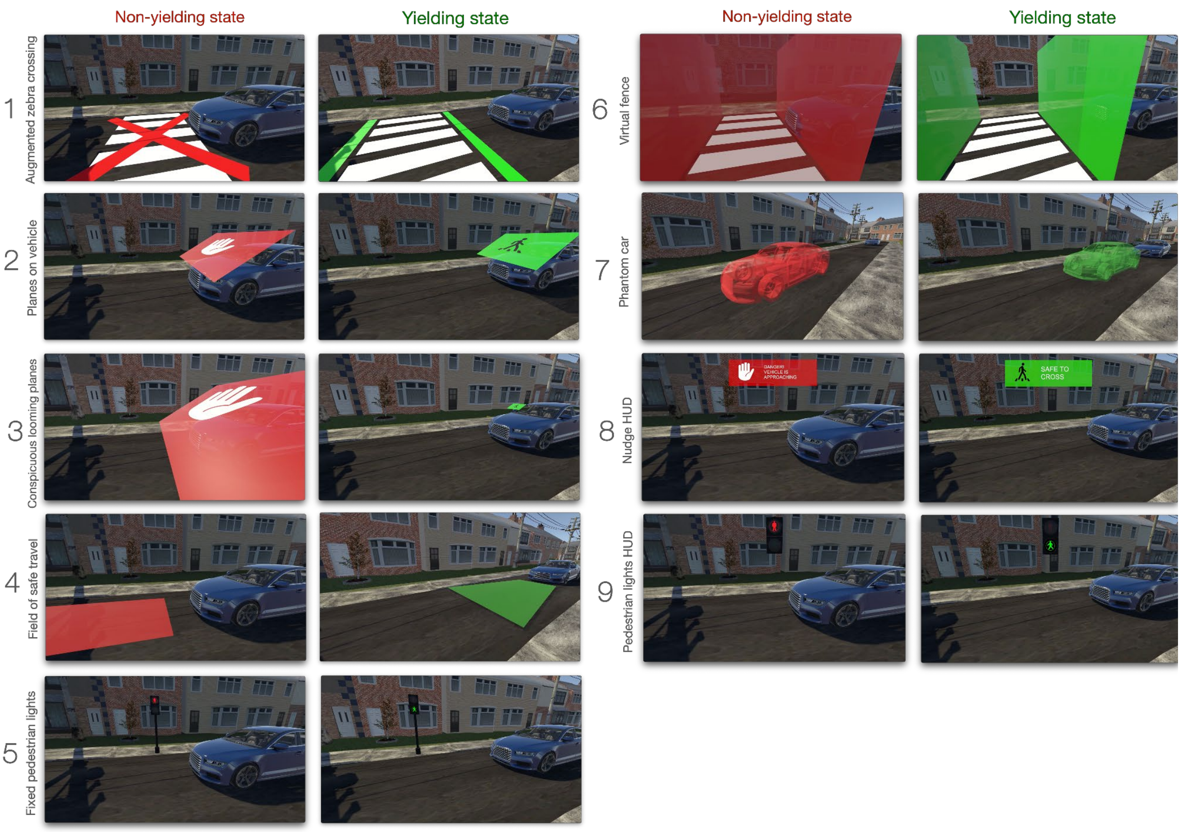

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*Figure 2.* The nine AR interfaces presented in a VR environment used for this online questionnaire study. Interfaces 1, 4, 5, 6, and 7 are projected on the road surface, while Interfaces 2 and 3 are projected on the car. Interfaces 8 and 9 are head-locked. The interfaces were adapted from Tabone et al. (2021b).

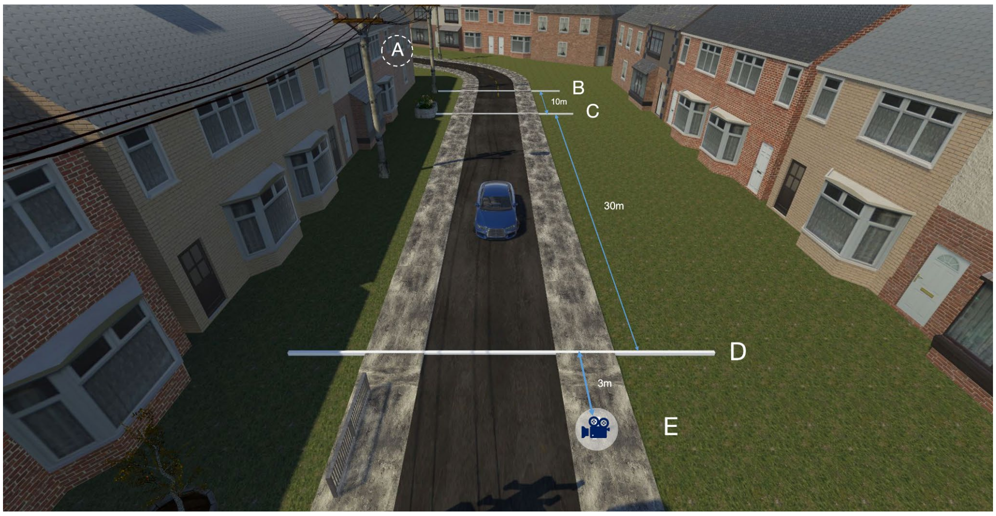


*Figure 3.* Virtual environment used in the videos. Each salient point is demarcated by a label, together with the distance (in metres) between each point. A: spawn point, B: AR interface onset, C: AV deceleration onset, D: stopping point, E: participant location. The participant position is also marked with a camera icon.

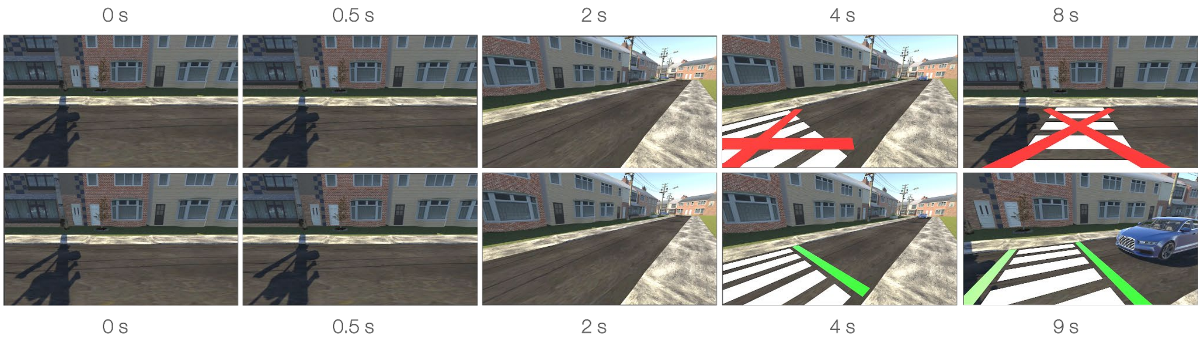


*Figure 4.* Screenshot of the camera view for *Augmented Zebra Crossing* at key timestamps. The screenshot at the top are for the non-yielding state, while the bottom screenshots correspond to the yielding state.

In addition to videos, side-by-side images were created per AR interface, for insertion in the questionnaire (see Figure 5 for an example). For the yielding AV, the frame where the vehicle came to a complete stop was selected, while for the non-yielding state, the frame at an elapsed time of 6 s was used so that each screenshot had a similar perspective on the road. The only exception was the side-by-side comparison of the *phantom car*, where the screenshots were taken with respect to the location of the phantom car interface, rather than the actual vehicle, so that both the interface and the vehicle could be seen in the screenshots. The 19 videos produced for the experiment are included in the Supplementary Material.

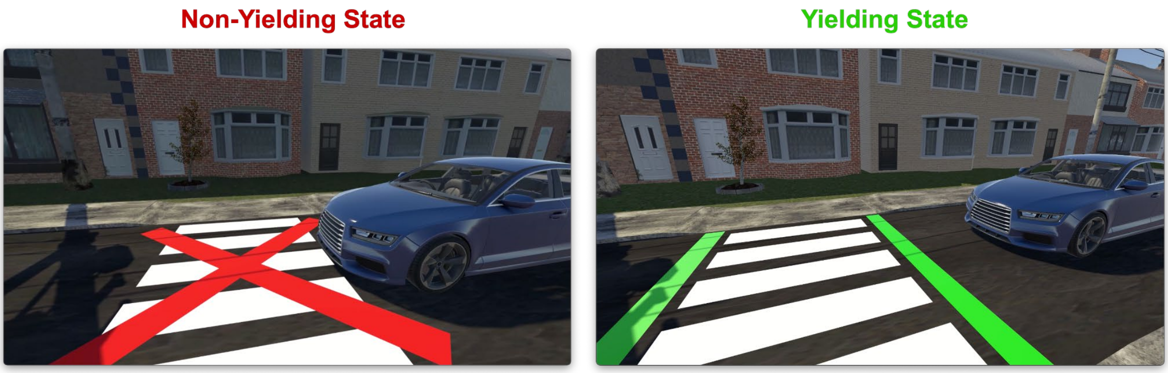


*Figure 5.* Example of side-by-side image for AR concept 1, Augmented zebra crossing. Left: non-yielding state, Right: yielding state.

**Questionnaire Procedure**

The online questionnaire was administered to 1500 respondents from Germany, the Netherlands, Norway, Sweden, and the United Kingdom. These countries were selected based on the geographical locations of the participating partners of the Horizon 2020 SHAPE-IT project, which funded this research. These five European countries also have a strong research base in automated vehicle development (Hagenzieker et al., 2020) and are likely candidates for the early deployment of eHMIs and AR interfaces. The questionnaire was developed in English using the Qualtrics XM (Qualtrics, 2022) survey platform and distributed to representative Internet panels through the German market research institute INNOFACT AG (Innofact, 2022), which has been used in previous research on the acceptance of AVs (Nordhoff et al., 2021).

A screening questionnaire, prepared in the national language of each of the target respondents' countries, was added by INNOFACT, to control for age, gender, and nationality and filter out respondents who were uncomfortable with completing the questionnaire in English. Our requested target sample was an equal distribution across countries, gender, and split between five (18–29, 30–39, 40–49, 50–59, 60–69) age groups. INNOFACT ensured that participants only participated using a desktop device, and safeguards against bots and duplicate respondents were also taken.

The survey ran from February to April 2022, and the respondents were financially compensated with approximately €3. The study was approved by the Human Research Ethics Committee of the TU Delft under application number 1984.

**Questionnaire Design**

***Introductory information***

First, a brief overview of AR and VR technologies was presented, together with examples of popular AR apps, so that the unfamiliar respondents would have a clearer picture of what would be discussed in the rest of the questionnaire. This was followed by an example of what the future could look like with the introduction of AR glasses, a brief introduction to the future urban environment, and the need for communication between AVs and pedestrians. The problem of having no clear signals from the car due to the lack of a driver was demonstrated through the baseline video (i.e., without AR interface) of a non-yielding AV. The respondents were provided with an explanation of the purpose of the study, where the potential of solving the communication issue using AR interfaces would be explored.

***Consent***

Respondents were provided with a consent section, which contained the experimenters' names, contacts, conditions to participate (being 18 years or older), the main purpose of the study, and the approximate length of the questionnaire (30 min). It was also highlighted that there were no risks associated with participation and that the questionnaire was anonymous and voluntary. Respondents were encouraged to close the page if they disagreed. Moreover, a question asking whether the instructions were read and understood was provided (Q1). If 'No' was selected, the questionnaire was terminated.

***Demographics***

Next, respondents were asked about their identifying gender (Q2), age (Q3), country of residence (Q4), and their highest level of formal education completed (Q5). Respondents were presented with the Affinity for Technology Interaction (ATI) scale (Franke et al., 2019) to gauge their affinity with technological systems (Q6). Respondents were then asked if they had ever used VR headsets (Q7) and AR apps (Q8), and how willing they would be to use AR wearables in general (Q9), specifically on the road as a pedestrian (Q10), and for the specific task of assisting pedestrians in crossing a road in front of an AV (Q11).

The respondents were then asked whether they had ever encountered AVs before (Q12), their daily walking time as pedestrians (Q13) (as used in Deb et al., 2017), and their primary mode of transportation (Q14). The last part in the demographic section treated any constraints in personal mobility (Q15) and included a colour blindness test (Q16) (Ishihara, 1917; as used in Bazilinskyy et al., 2020).

***Video presentation of AR interfaces and rating questions***

Following a brief introduction to the experiment, participants proceeded to the main part of the study, where the yielding and non-yielding state of the nine interfaces were presented, together with various rating questions.

The videos from each interface were presented on a separate page, having the title of the respective interface (see Figure 2). The order in which the nine interfaces were presented was randomised for each respondent. Each interface page first presented the non-yielding-state video, followed by the yielding-state video. The videos auto-played and looped. All 18 videos were presented to each participant.

Below each video depicting a non-yielding AV, the respondents used a 7-point Likert scale (Strongly disagree, Disagree, Somewhat disagree, Neither agree nor disagree, Somewhat agree, agree, Strongly agree) to rate whether:

- "The interface in the video above is intuitive for signalling 'Please do NOT cross the road'" (Intuitiveness: Q17)
- "The interface in the video above convinced me NOT to cross the road" (Convincingness: Q18).

and below each video depicting a yielding AV, the following two questions were asked:
- "The interface in the video above is intuitive for signalling 'Please cross the road'" (Intuitiveness: Q19)
- "The interface in the video above convinced me to cross the road" (Convincingness: Q20).

Intuitiveness and convincingness were regarded as two key elements of interface quality, where the former refers to whether the message is readily understandable, and the latter refers to whether the interface would empower people to cross or not cross the road.

The video subsection containing the yielding and non-yielding videos along with the respective intuitiveness and convincingness items was followed by a side-by-side screenshot of the interface's states. A matrix table was presented with a 5-point descriptor scale (Q21) for interpretability, where the respondents had to rate the following:
- "Do you think that the interface was triggered too early or too late?" (too early – too late) (Q21.1)
- "Do you think that the interface is too small or too large? (too small – too large) (Q21.2)
- "How clear (understandable) was the interface to you?" (very unclear – very clear) (Q21.3)
- "How visually attractive is this interface to you?" (very unattractive – very attractive) (Q21.4)

Q17–Q21 were inspired from previous work which looked at perceived quality/clarity of information (Adell, 2010; Bazilinskyy et al., 2020; Lau et al., 2021; Rahman et al., 2017), and attractiveness, aestheticism, ease of understanding, and the adequacy of information, amongst others (Métayer & Coeugnet, 2021).

Each interface page ended with a 9-item acceptance scale (Van Der Laan et al., 1997) to collect further ratings on facets of usefulness and satisfaction (Q22.1–Q22.9). A free text area (Q23) was added to let respondents elaborate on their ratings, “Please add a few words to justify your choices above (eg. comment on the shape, colour, functionality, and the clarity of the interface).”

***Final questions***

The final section of the questionnaire opened with a question on whether such AR interfaces would be useful for crossing the road in future traffic (Q24). This query was followed by three side-by-side screenshots contrasting various interface elements, and the following three statements:

- “I prefer interfaces mapped to the street rather than on the vehicle” (Q25)
- “I prefer interfaces with text rather than interfaces with just graphical elements” (Q26)
- “I prefer interfaces that move around with my head rather than interfaces that stay fixed” (Q27), to which the respondent was answered with a 5-point Likert agreement scale from Strongly disagree to Strongly agree.

The penultimate question related to whether the respondent would like to have the ability to customise the interfaces (Q28). The final question once again asked whether the respondent would be willing to use such interfaces as an aid for crossing after having seen all examples, assuming that they own AR glasses (Q29).

***Analysis***

Mean item scores for the AR interfaces in their yielding and non-yielding states were computed and visualized in scatter plots, together with 95% confidence intervals. The confidence intervals were computed by applying a correction for within-subjects effects of the nine AR interfaces, according to a method presented by Morey (2008).

Differences between ratings of AR interfaces were examined using a repeated-measures ANOVA with an alpha level of 0.05. This was followed by paired-samples *t*-tests. Here, an alpha value of 0.005 was used to reduce the occurrence of false positives, compared to the more commonly used alpha value of 0.05 (Benjamin et al., 2018). It should be noted that because our sample size was large, even small within-subject differences between the AR interfaces were strongly significant.

For the assessment of the effects of the moderator variables (gender, age group, educational level), a repeated-measures ANOVA was used with the AR interface as a within-subject variable and the moderator variable subgroup (e.g., male, female) as a between-subjects variable (alpha = 0.05). Additionally, statistical comparisons between ratings for AR interfaces between participant groups (e.g., males vs. females) were performed using independent-samples *t*-tests (alpha = 0.005).

Apart from testing differences between AR interfaces and the effects of moderator variables, Pearson product-moment correlation coefficients among item scores were computed to evaluate redundancy among items. Highly correlated items were aggregated to form a composite score.

The textual responses were evaluated through thematic analysis (Kiger & Varpio, 2020). All text responses were read, with responses copied into a separate document if a common theme emerged. For example, if multiple participants commented that a particular interface was ‘slow’, then all comments with such a statement were extracted and placed in a text document under the section pertaining to the AR interface. Following the collation of all comments, four comments per interface (two per positive and two per negative valence were selected), depending on which theme was featured the most in that interface’s comment section.

## Results

In total, 1500 participants answered the questionnaire. An initial quality filtering process was carried out to remove respondents who did not complete the entire questionnaire (*n* = 357) or answered 'no' to the consent item (Q1) (*n* = 39). Next, the recorded duration in seconds was used to omit the top 10% of fastest respondents (i.e., those who completed the questionnaire in 593 s or less, *n* = 110), since the fastest respondents are likely to yield relatively low-quality data (De Winter & Hancock, 2015). The resulting sample size was 992 (492 males, 491 females, 8 non-binary, 1 not specified). Within the resulting sample, the median time to complete the questionnaire was 23.3 min (25th percentile = 16.4 min, 75th percentile = 33.6 min).

General characteristics of the 992 retained respondents were as follows:

- Country: 202 were from Germany, 197 were from the Netherlands, 184 were from Norway, 197 were from Sweden, and 212 were from the United Kingdom (Q4).
- Age: The age (Q3) ranged from 18 to 69 (*M* = 45.10, *SD* = 14.17).
- Education: 54% (*n* = 536) indicated that they went to university, 25% (*n* = 246) attended trade or vocational school, whereas 21% (*n* = 210) indicated 'none of these' (Q5).
- Constraints: 17% (*n* = 170) reported some form of mobility constraint (Q15).
- Constraints: 3% (*n* = 32) were considered colour blind as they submitted three or more incorrect answers (Bazilinskyy et al., 2020) for the six-item Ishihara colour blindness test (Q16).

The results regarding AR and VR use indicated the following:

- 42% of respondents had used a VR headset before (Q7).
- 45% had used AR apps before (Q8).
- On a scale of 1 (Strongly unwilling) to 5 (Strongly willing), the mean response to "How willing would you be to use AR glasses?" (Q9) was 3.59 (*SD* = 1.04).
- For "How willing would you be to use AR glasses on the road as a pedestrian" (Q10), the mean was 3.10 (*SD* = 1.13).

- For "How willing would you be to use AR glasses on the road if these warn you about how safe it is to cross in front of a self-driving car?" (Q11), the mean was 3.30 (*SD* = 1.12).

Since the goal of this research was to perform a population-level evaluation of the AR interfaces, colour blind participants or participants with a mobility constraint were not excluded from the analysis.

**Ratings of Videos Depicting AR Interfaces**

Table S1 in the Supplementary material shows the means across the 992 respondents for the 17 items for each of the nine AR interfaces. From this table, it can be seen that there are clear redundancies among the items, with some AR interfaces producing considerably higher ratings than others on almost all of the 17 items.

In an attempt to better understand item redundancy, several correlational analyses were performed. In particular, Figure 6 shows the mean intuitiveness ratings (Q17, Q19) and convincingness ratings (Q18, Q20) for the nine AR interfaces. The ratings were very highly correlated ($r = 0.998$), indicating that the intuitiveness and convincingness questions yielded nearly the same information. Figure 6 also shows that the *Nudge HUD* scored highest, followed by the *Augmented zebra crossing, Fixed pedestrian lights, Pedestrian lights HUD,* and *Virtual fence.* The *Phantom car* yielded the lowest ratings.

In the same vein, Figure 7 shows the averaged intuitiveness and convincingness rating for the nine AR interfaces for yielding AVs versus non-yielding AVs. Again, a strong association ($r = 0.93$) is seen, indicating that the AR interfaces were rated similarly regardless of whether the vehicle was stopping or not. We performed a two-way repeated-measures ANOVA of the averaged intuitiveness and convincingness rating with AR interface and yielding state as within-subject factors. Results showed a significant effect of the AR interface, $F(8,7928) = 197.4$, $p < 0.001$, partial $\eta^2 = 0.17$, but not of yielding state $F(1, 991) = 0.12$, $p = 0.728$, partial $\eta^2 = 0.00$. There was, however, a significant AR interface × yielding state interaction, $F(8, 7928) = 41.5$, $p < 0.001$, partial $\eta^2 = 0.04$. Follow-up paired-samples *t*-tests showed that several AR interfaces (i.e., *Augmented zebra crossing, Field of safe travel, Fixed pedestrian lights, Nudge HUD, Pedestrian lights HUD*) yielded somewhat higher ratings for the non-yielding state than for the yielding state ($p < 0.005$ according to paired-samples *t*-tests). The *Virtual fence* and the *Planes on vehicle*, on the other hand, were rated statistically significantly higher for yielding AVs than for non-yielding AV.

A correlation matrix (Figure 8) of the mean ratings for each interface revealed strong associations between all 17 measured items, except for the small/large item (Q21, Item 1) and early/late item (Q21, Item 2). The correlation coefficients between the means of the 15 other items ranged from $r$ = 0.862 (for irritating/likeable [Q22, Item 6] vs. sleep-inducing/raising alertness [Q22, Item 9]) to $r$ = 0.999 (unpleasant/pleasant [Q22, Item 2] vs. irritating/likeable [Q22, Item 6]).

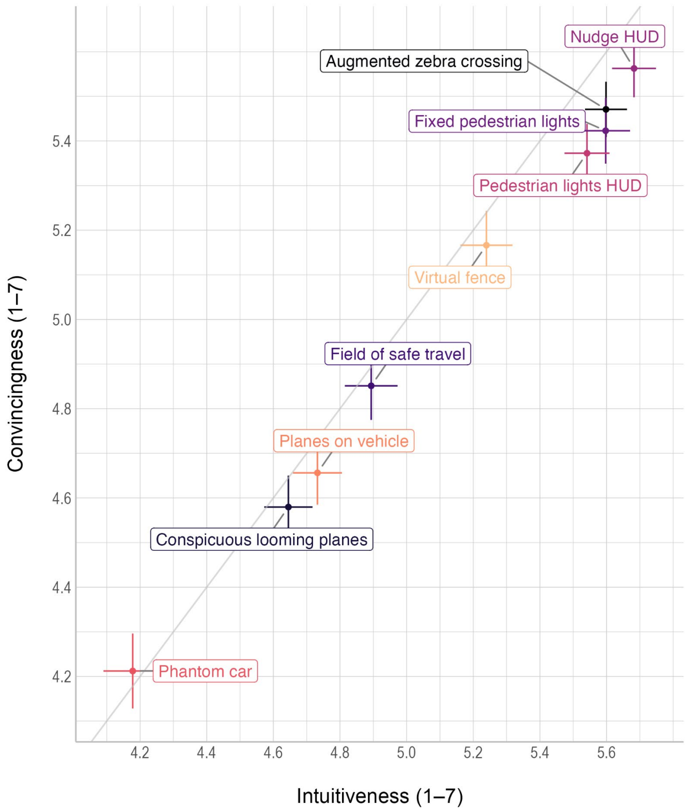

*Figure 6.* Scatter plot of intuitiveness ratings (mean of Q17 and Q19) and convincingness ratings (mean of Q18 and Q20) per AR interface. In this figure, ratings for the yielding and non-yielding states were averaged. The error bars represent 95% confidence intervals.

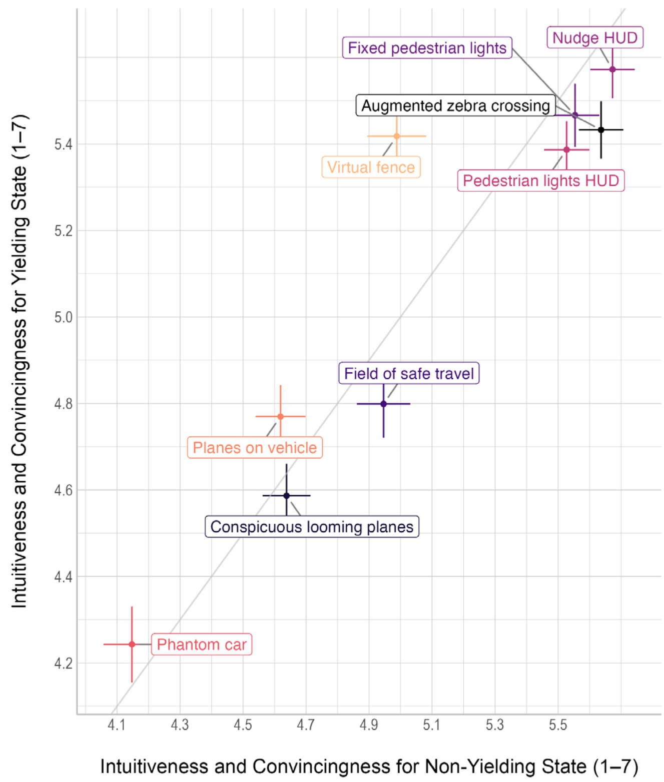


*Figure 7.* Scatter plot of averaged intuitiveness and convincingness ratings of the yielding state (mean of Q19 & Q20) versus the non-yielding state (mean of Q17 & Q18) of each AR interface. The error bars represent 95% confidence intervals.

## Descriptor Scale (Q21), Acceptance scale (Q22), and Composite Score

Because correlation coefficients between items were very high, it was decided to compute a composite score of the 15 strongly-correlated items (unit-weight method, see DiStefano et al., 2009)*. More specifically, for each AR interface, a 992 participant x 15 matrix was available.

* An inspection of the eigenvalues of the correlation matrix of the (9 AR interfaces × 15 items) matrix showed strong uni-dimensionality. More specifically, the first component explained 96.5% of the variance in the participant means, and the corresponding Cronbach's alpha value was 0.990. Additionally, the correlation matrix at the participant level (992

The matrices were concatenated, yielding an 8928 x 15 matrix, and subsequently standardised, so that the item mean was 0 and the standard deviation was 1. The scores of the 15 items were summed, thus producing an 8928-long vector, which was then standardised. Finally, the 8928-long vector was partitioned back to the nine interfaces, so that a composite score was available for each participant and AR interface. Figure 8 shows that the mean composite score correlated very strongly with each of its defining items, which confirms that the composite score captures a large amount of the variance (96.5%) in the mean ratings of the nine AR interfaces. The strongest correlations between the composite score and the individual items ($r$ = 0.997, 0.998) occurred for the items useful/useless (Q22.1), bad/good (Q22.3), and worthless/assisting (Q22.7) (see Figure 1). This suggests that the meaning of the composite score is well described by the colloquial phrase ‘whether the AR interface is good or not’.

participants x 15 items) showed strong uni-dimensionality as well, with the first component explaining 67.6% of the variance in the means of the 9 AR interfaces, and Cronbach’s alpha being 0.962.

| | Intuitiveness_NYS (Q17) | Convincingness_NYS (Q18) | Unattractive-Attractive (Q21,4) | Bad-Good (Q22,3) | Undesirable-Desirable (Q22,8) | Annoying_Nice (Q22,4) | Unpleasant_Pleasant (Q22,2) | Irritating-Likeable (Q22,6) | SleepInducing_RaisingAlertness (Q22,9) | Intuitiveness_YS (Q19) | Convincingness_YS (Q20) | Unclear-Clear (Q21,3) | Superfluous_Effective (Q22, 5) | Composite Score | Useless_Useful (Q22,1) | Worthless_Assisting (Q22,7) | Early-Late (Q21,1) | Small-Large (Q21,2) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Intuitiveness_NYS (Q17) | 1.000 | 0.996 | 0.964 | 0.985 | 0.990 | 0.968 | 0.980 | 0.979 | 0.879 | 0.938 | 0.926 | 0.975 | 0.963 | 0.986 | 0.980 | 0.979 | -0.244 | -0.460 |
| Convincingness_NYS (Q18) | | 1.000 | 0.977 | 0.990 | 0.994 | 0.979 | 0.984 | 0.983 | 0.900 | 0.934 | 0.922 | 0.975 | 0.971 | 0.989 | 0.981 | 0.982 | -0.270 | -0.423 |
| Unattractive-Attractive (Q21,4) | | | 1.000 | 0.983 | 0.988 | 0.988 | 0.985 | 0.984 | 0.919 | 0.920 | 0.913 | 0.956 | 0.968 | 0.982 | 0.972 | 0.974 | -0.251 | -0.347 |
| Bad-Good (Q22,3) | | | | 1.000 | 0.998 | 0.987 | 0.988 | 0.987 | 0.919 | 0.956 | 0.943 | 0.983 | 0.987 | 0.997 | 0.991 | 0.992 | -0.231 | -0.397 |
| Undesirable-Desirable (Q22,8) | | | | | 1.000 | 0.990 | 0.992 | 0.992 | 0.910 | 0.948 | 0.936 | 0.980 | 0.981 | 0.996 | 0.989 | 0.989 | -0.218 | -0.415 |
| Annoying_Nice (Q22,4) | | | | | | 1.000 | 0.995 | 0.996 | 0.876 | 0.906 | 0.888 | 0.949 | 0.957 | 0.977 | 0.961 | 0.963 | -0.175 | -0.447 |
| Unpleasant_Pleasant (Q22,2) | | | | | | | 1.000 | 0.999 | 0.866 | 0.909 | 0.893 | 0.954 | 0.954 | 0.980 | 0.966 | 0.967 | -0.206 | -0.474 |
| Irritating-Likeable (Q22,6) | | | | | | | | 1.000 | 0.862 | 0.911 | 0.894 | 0.956 | 0.952 | 0.980 | 0.966 | 0.965 | -0.194 | -0.489 |
| SleepInducing_RaisingAlertness (Q22,9) | | | | | | | | | 1.000 | 0.939 | 0.950 | 0.930 | 0.964 | 0.934 | 0.940 | 0.950 | -0.407 | -0.023 |
| Intuitiveness_YS (Q19) | | | | | | | | | | 1.000 | 0.997 | 0.989 | 0.978 | 0.970 | 0.983 | 0.979 | -0.238 | -0.296 |
| Convincingness_YS (Q20) | | | | | | | | | | | 1.000 | 0.980 | 0.974 | 0.962 | 0.977 | 0.974 | -0.265 | -0.237 |
| Unclear-Clear (Q21,3) | | | | | | | | | | | | 1.000 | 0.986 | 0.992 | 0.996 | 0.992 | -0.258 | -0.377 |
| Superfluous_Effective (Q22, 5) | | | | | | | | | | | | | 1.000 | 0.992 | 0.993 | 0.996 | -0.266 | -0.273 |
| Composite Score | | | | | | | | | | | | | | 1.000 | 0.998 | 0.998 | -0.252 | -0.370 |
| Useless_Useful (Q22,1) | | | | | | | | | | | | | | | 1.000 | 0.998 | -0.255 | -0.352 |
| Worthless_Assisting (Q22,7) | | | | | | | | | | | | | | | | 1.000 | -0.276 | -0.319 |
| Early-Late (Q21,1) | | | | | | | | | | | | | | | | | 1.000 | -0.318 |
| Small-Large (Q21,2) | | | | | | | | | | | | | | | | | | 1.000 |

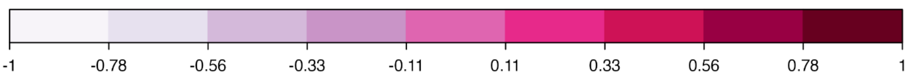


*Figure 8.* Correlation matrix for the means of the scores of the AR interfaces (*n* = 9). Responses to Q22 Items 1, 2, 4, 5, 7, 9 were reversed with respect to the questionnaire. The variables are sorted based on hierarchical clustering, i.e., similarity with the other variables.

The mean and standard deviation of the composite score per AR interface are shown in Table 1. The findings align with the above results (Figures 6 and 7) that the *Nudge HUD* was most favoured while the *Phantom car* was least favoured. A one-way repeated-measures ANOVA of the composite score showed a significant effect of the AR interface, $F(8,7928) = 195.0$, $p < 0.001$, partial $\eta^2 = 0.16$. A total of 32 of 36 pairs of AR interfaces were statistically significantly different from each other ($p < 0.005$), see Table 1.

Table 1. *Means with standard deviations in parentheses for the composite scores (z-scores) (n = 992). Also shown are results for pairwise comparisons.*

| **No** | **AR interface** | **Composite score** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Augmented zebra crossing | 0.32 (0.89) | | | | | | | | | |
| 2 | Planes on vehicle | -0.26 (1.01) | x | | | | | | | | |
| 3 | Conspicuous looming planes | -0.35 (1.00) | x | x | | | | | | | |
| 4 | Field of safe travel | -0.12 (1.00) | x | x | | | | | | | |
| 5 | Fixed pedestrian lights | 0.28 (0.88) | | x | x | x | | | | | |
| 6 | Virtual fence | 0.04 (1.00) | x | x | x | x | x | | | | |
| 7 | Phantom car | -0.52 (1.05) | x | x | x | x | x | x | | | |
| 8 | Nudge HUD | 0.37 (0.85) | | x | x | x | x | x | x | | |
| 9 | Pedestrian lights HUD | 0.25 (0.86) | | x | x | x | | x | x | x | |

*Note.* 'x' marks pairs of conditions that are statistically significantly different from each other, computed using paired-samples *t*-tests (*df* = 991).

### Assessment of Moderator Variables

Gender: Figure S2 in the supplementary material shows a strong correlation ($r = 0.980$) between the mean composite scores for male and female respondents. A repeated-measures ANOVA of the composite score, with the AR interface as a within-subject factor and gender (male or female) as a between-subjects factor showed a significant effect of AR interface, $F(8, 7848) = 192.6$, $p < 0.001$, partial $\eta^2 = 0.16$, and no significant effect of gender, $F(1, 981) = 0.36$, $p = 0.547$, partial $\eta^2 = 0.00$, but a significant AR interface × gender interaction, $F(8, 7848) = 2.00$, $p = 0.043$, partial $\eta^2 = 0.00$. The interaction effect was extremely small, however, and scores for the nine AR interfaces did not differ significantly between males and females. More specifically, independent-samples t-tests for the nine AR interfaces yielded p-values between 0.087 and 0.952 (Conspicuous looming planes: Mean (SD) males / females: -0.40 (1.03) / -

0.29 (0.97), $t(981) = -1.71$, $p = 0.087$; Nudge HUD: Mean (SD) males / females: 0.37 (0.84) / 0.37 (0.85), $t(981) = -0.06$, $p = 0.952$).

Country: The composite score of each interface was examined across the respondents' countries of residence (Figure 9). The mean composite scores of the nine AR interfaces correlated again strongly. More specifically, for the 10 pairs of countries, correlations ranged between $r = 0.972$ (between Germany and Sweden) and $r = 0.992$ (between Norway and Sweden). A repeated-measures ANOVA of the composite score, with the AR interface as within-subject factor and country as between-subjects factor showed a significant effect of AR interface, $F(8, 7896) = 194.1$, $p < 0.001$, partial $\eta^2 = 0.16$, and no significant effect of country, $F(4, 987) = 0.82$, $p = 0.515$, partial $\eta^2 = 0.00$, and no significant AR interface × country interaction, $F(32, 7896) = 0.69$, $p = 0.902$, partial $\eta^2 = 0.00$.

Age: A repeated-measures ANOVA of the composite score, with the AR interface as a within-subject factor and age (45 or younger vs. 46 or older) as a between-subjects factor showed a significant effect of AR interface, $F(8, 7920) = 195.2$, $p < 0.001$, partial $\eta^2 = 0.16$, and no significant effect of age group, $F(1, 990) = 0.44$, $p = 0.506$, partial $\eta^2 = 0.00$, and no significant AR interface × age group interaction, $F(8, 7920) = 1.52$, $p = 0.143$, partial $\eta^2 = 0.00$. The corresponding scatter plot is found in the supplementary material (Figure S3).

Education: A repeated-measures ANOVA of the composite score, with the AR interface as a within-subject factor and educational attainment (university degree, trade/technical/vocational training, none of these) as a between-subjects factor showed a significant effect of AR interface, $F(8, 7912) = 167.8$, $p < 0.001$, partial $\eta^2 = 0.15$, and no significant effect of education, $F(2, 989) = 0.72$, $p = 0.489$, partial $\eta^2 = 0.00$, and no significant AR interface × education interaction, $F(16, 7912) = 0.98$, $p = 0.476$, partial $\eta^2 = 0.00$. The corresponding scatter plots are found in the supplementary material (Figures S4 and S5).

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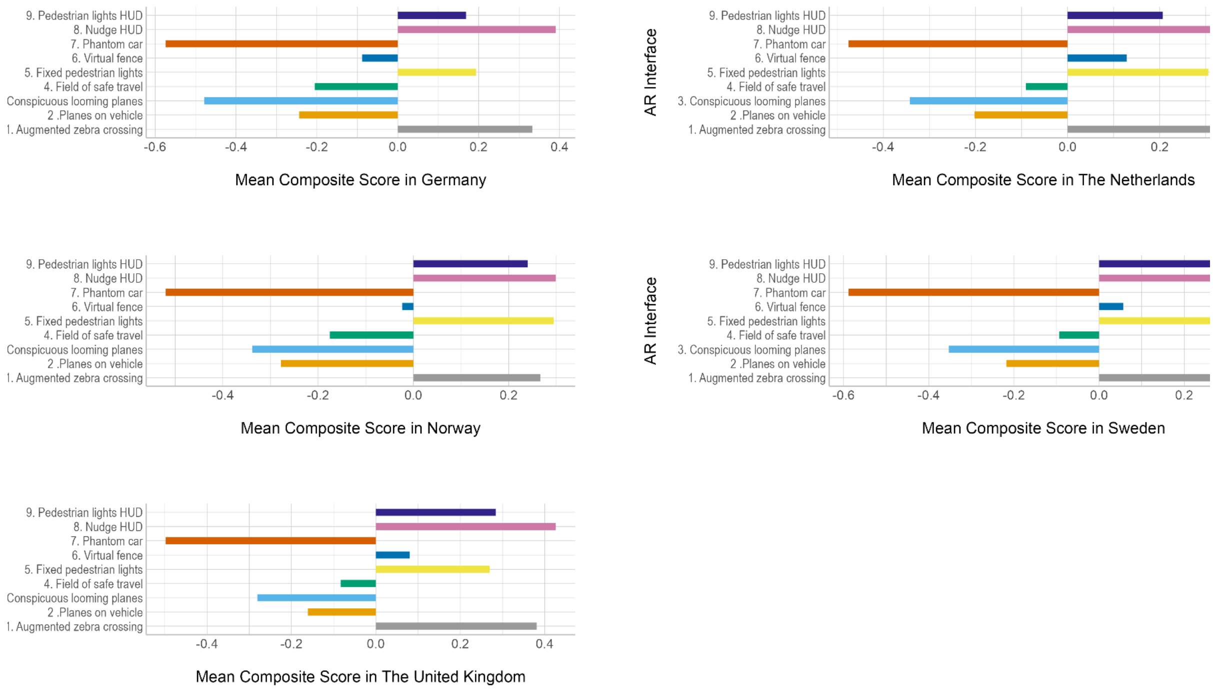


*Figure 9.* Bar plots of the composite score of each interface per respondents' country. The standard deviation across respondents for the 45 depicted AR interface × country combinations ranges between 0.78 and 1.12.

It is noteworthy that although the overall composite score (i.e., averaged across the nine AR interfaces) did not correlate significantly with gender ($r$ = 0.01 [1 = male, 2 = female]), age ($r$ = 0.02), the highest level of education completed ($r$ = 0.04, [1 = university degree, 2 = trade/technical/vocational training, 3 = none of these]), having ever used a VR headset (Q7; $r$ = -0.01 [1 = no, 2 = yes]), or having ever used AR apps or games (Q8; $r$ = 0.02 [1 = no, 2 = yes]), it did correlate moderately with willingness to use AR glasses ($r$ = 0.33, 0.32, and 0.35 for Q9, Q10, and Q11, respectively) and with the ATI scale of technology affinity (Q6; $r$ = 0.22). It is also noteworthy that older participants were less likely to have ever used VR (Q7; $r$ = -0.30) or AR (Q8; $r$ = -0.44, respectively).

**Textual Responses (Q23)**

An average of 46 comments were extracted per interface. The subset of comments was further filtered down to retain four informative comments per concept, split equally between positive and negative valence (Table 2). These final selected comments were deemed representative of some of the major themes that arose per concept.

Table 2. *Sample of four comments per interface, split based on positive or negative sentiment. Spelling and grammar mistakes were not corrected.*

| AR Interface | Positive Comments | Negative Comments |
|---|---|---|
| Augmented zebra crossing | "A good idea. The zebra crossing is familiar to everyone. The big red cross over the crossing should make it clear not to cross." | "It's clear what the images mean but it doesn't fill me with confidence regarding when it would be safe to cross the road. I think if you are not looking at the approaching vehicle you will always be in danger because you are not aware as to what it is doing, moving or stopping." |
| | "Very clear and presumably understandable by most people including children once the different colours are explained to them." | "The video signalling do not cross the road, I think is very clear. However, the video signalling that it is safe to cross is not so clear. The green lines either side of the pedestrian crossing did not immediately make me think it was safe, a green tick symbol maybe would've been better." |
| Planes on vehicle | "[C]orrect colours for alert and safeness." | "[T]he walking man on the green background made sense but the hand on the red background was unclear. i didn't like it moving with the car, would prefer it to be in your face [...]" |
| | "[B]etter variant because the size stays the same and symbols are clearer." | "The problem with this signal, is that it just signals something about the car, not about the pedestrians". |

| | | |
|---|---|---|
| Conspicuous looming planes | "Very effective, the colour and hand signal stands out well." | "[T]he colours are still very clear to understand: red for warning and green for no danger BUT as the vehicle approaches from the right side (around the corner) it was difficult so identify the signs written on the coloured boxes, it was kind of a weird perspective and therefore irritating. [A]s the stop/go signs where moving with the car and where not "fixed" at the top of my AR glasses, I had to think twice if these instructions were meant for me as a pedestrian or if there was another issues not concerning me." |
| | "[T]he warning one was much better than the yielding one as the logo became larger as potential danger increased. [T]he change in size of the yielding one was hardly noticeable." | "I wondered when something would actually `ar in the screen. It took forever before I realised the notification was actually on the car itself. I find this visualisation absolutely useless." |
| Field of safe travel | "I think it is somewhat useful as it shows the path of the vehicle." | "[T]he green corridor has me confused, you see the car coming, with a corridor ahead, that makes me think it will drive on instead of stop." |
| | "There was good warning time to let me know whether I was to cross or not. I also liked how the red and green showed up a good distance off too. Very clear." | "The beam in the 'stop video' looks more like a red carpet, which I guess is something everyone would like to walk on." |
| Fixed pedestrian lights | "This interface has been familiar and useful to me for as long as I | "I think the sign for triggered too late for the non-yielding state, which would be more of a problem as I might already |

| | | |
|---|---|---|
| | remember, using it is highly intuitive and I see no need to alter it." | have started my journey across the street which can be a risk if the vehicle expects pedestrians to stand still. Otherwise the sign with a pole is very much familiar to me in my cultural context and therefore easily understood." |
| | "[T]he interface is very clear/understandable as traffic lights are common in everyday lifeit includes people who are not able to readit seems like a 'no energy' interaction for me as I already know everything I need to know and do not have to think about it." | "The signals are good, but optically too small and might well be overseen depending on the device holder (age, sight) or the background (lots of distraction on the street)." |
| Virtual fence | "It creates a safe feeling by creating a virtual wall." | "I like the crossing part of this as previously stated, but pairing it with walls is really confusing. When you just see the red one, you immediately think they are walls to stop the car from going through and it looks like you are being given access through the crossing. The green one is better, but together confusing." |
| | "Very clear in terms of the obvious colour difference but also in the size of the warnings. Very functional!" | "I realised in all examples so far, I enjoy the green signs more. I found this red one being wayyyyy too big and it literally made me jump when it appeared. It was also not clear to me that it signalled do not cross, except the red colour. When I could compare it with the green sign |

| | | |
|---|---|---|
| | | which was more intuitive it was clear that red meant stop. Before that I saw the red more as a frame/hallway around the zebra crossing.” |
| Phantom car | “[T]he phantom was very fast and clear and really did signal the options I had its sustainable as well.” | “[D]on't like the look. reminds me of a video game. so I guess it can be dangerous cause you feel like in a game.” |
| | “Really good looking and easily understandable.” | “[T]he trouble is it's just a bit too attractive and your brain does what it always does when you see something really attractive (particularly cars) and it goes 'WOW!' When it does that it sort of sucks up all of your attention and you actually pay less attention to the other car. You almost forget about it.” |
| Nudge HUD | “I liked this one. People are pretty used to something similar to a notification like this and the colour + text makes it even easier to understand it.” | “[...] I feel the non-yielding state should specify 'do not cross' as opposed to just stating a vehicle is approaching. The yielding state clearly states safe to cross so the message is much clearer with no room for misinterpretation.” |
| | “This again empowers the user to make a choice based on their actions, not based on what the car is doing. It is much bigger then some, but in some ways less distracting. More functional.” | “This example is clear enough, but a busy road is not like this. Except of cars, it can be running pets, pedestrians, bicycles coming from behind... It is dangerous to rely on this system, I think.” |

| | | |
|---|---|---|
| Pedestrian lights HUD | "The best so far because you get the information in the same direction so you are looking for incoming traffic. Very nice." | "This is a lot clearer since it already relies on traffic rules that are now established in our society. I still have the feeling though that even if it is green that you would hold back a little bit with crossing the road since the car drives pretty fast towards you and I would only cross the street if the car is completely still." |
| | "Because the interface uses an image that I am already acquainted with (as are most members of the general public, including children and senior citizens) I found it to be very effective in indicating to me whether I could or could not cross the road safely." | "The image is clearly recognisable as one which indicates whether or not to cross. My only concern is that it is too small. It actually took me a few seconds to work out where it was. It could, of course,be that in time users would automatically focus on that part of their vision, and see the signal, but for this test, I found it worrying." |

**Preferred AR Interfaces and Use of Augmented Reality in Traffic**

The results of the final questionnaire section (Table 3) showed that 66% of respondents felt that communication using AR interfaces in future traffic would be useful (Q24). Furthermore, 72% preferred interfaces mapped to the street over those on the vehicle (Q25), 52% preferred interfaces that included text rather than just graphical elements (Q26), and 51% preferred head-locked over world-locked interfaces (Q27). Moreover, 62% would like to have the ability to customise the AR interfaces (Q28), and 47% indicated they would likely use AR interfaces as an aid for crossing in front of vehicles if they owned AR glasses (Q29).

Table 3. *Descriptive statistics (i.e., means (M), standard deviations (SD), and relative frequencies) for the final questions.*

| Question | *M* | *SD* | Relative Frequencies | | | | |
|---|---|---|---|---|---|---|---|
| | | | Strongly disagree (1) | Disagree (2) | Neither agree nor disagree (3) | Agree (4) | Strongly Agree (5) |
| In future traffic, the communication from AR interfaces would be useful for crossing the road (Q24) | 3.70 | 1.02 | 4.7% | 6.7% | 23.1% | 45.4% | 20.2% |
| I prefer interfaces mapped to the street rather than on the vehicle (Q25) | 3.98 | 0.98 | 1.9% | 6.1% | 19.5% | 37.3% | 35.2% |
| I prefer interfaces with text rather than interfaces with just graphical elements (Q26) | 3.44 | 1.09 | 5.3% | 14.0% | 28.5% | 35.4% | 16.7% |
| I prefer interfaces that move around with my head rather than interfaces that stay fixed (Q27) | 3.38 | 1.13 | 7.3% | 14.3% | 27.5% | 35.0% | 15.9% |
| I would like to have the ability to customise these AR interfaces (Q28) | 3.71 | 0.95 | 3.0% | 5.4% | 29.5% | 41.4% | 20.6% |
| Now that I have seen these interfaces, if I own AR glasses, I am likely to use such interfaces as an aid for crossing in front of vehicles (Q29) | 3.30 | 1.10 | 8.9% | 11.6% | 32.9% | 34.4% | 12.3% |

## Discussion

An online questionnaire study, aiming to evaluate nine AR interfaces for pedestrian-vehicle interaction, resulted in 992 valid respondents. Respondents were asked to rate the interfaces, presented in videos, on several qualities such as intuitiveness, convincingness, aesthetics, usefulness, and satisfaction.

### Interface Preference by Respondents

When considering the intuitiveness and convincingness ratings (Figures 6 and 7), and the composite score in Table 1, it can be asserted that AR interfaces that incorporated traditional traffic elements (*Augmented zebra crossing*, *Fixed pedestrian lights*, and *Pedestrian lights HUD*) and those that were head-locked performed better than the others. In addition, respondents indicated their preference for head-locked interfaces in the final responses of the questionnaire (Table 3).

The ‘genius’ design approach yielded a number of AR interfaces that were theoretically interesting but flawed from a user’s point of view. The findings can retrospectively be explained by legacy design principles, which some AR interfaces adhered to and others did not (see Wickens et al., 2004, for thirteen established principles of display design). For example, although the *Phantom car* was designed to adhere to the principle of predictive aiding (since it showed the future position of the car), and the *Field of safe travel* adhered to the principle of ecological interface design (Kadar & Shaw, 2000; Tabone et al., 2021b; Waldenström, 2011), these two interfaces may have failed to comply with other design principles, such as redundancy gain (these interfaces displayed a coloured element, but no redundant icon or text), the proximity compatibility principle (it may be hard to perceptually separate the *Phantom car* from the real car), and the principle of top-down processing (participants are likely unfamiliar with these concepts). The most successful AR concepts, such as the *Augmented zebra crossing* and *Pedestrian light*s did adhere to the latter three principles, as described by Tabone et al. (2021b). The current observations also highlight the importance of involving the target user earlier on in the process through the use of a user-centred design methodology (Gulliksen et al., 2003) and to not rely on genius design only. The involvement of the target user early in the process could be achieved through focus groups, interviews, and card sorting, among other methods (Norman, 2013).

On the technical side, it is to be noted that the different AR interfaces involve different sensor and computational requirements (for an overview, see Tabone et al., 2021b). For instance, AR interfaces presented on the AV itself would have to rely on computer-vision techniques on the pedestrian's side, or vehicle-to-pedestrian communication of the AV's position and speed. The nudge interfaces, however, are considerably simpler and would only require the wireless communication of the AV's stopping intent to the pedestrian. These different sensor requirements were not presented to the respondents, nor were they considered in the evaluation of the AR interfaces.

Additionally, our study found that the means of questionnaire items were very strongly correlated and that the 15 acceptance-related items, in the aggregate, were well-represented by a single composite score. A recommendation that follows is that future research into the population-level mean acceptance of HMI concepts could just as well use a single acceptance item (such as a five-point scale ranging from bad to good) instead of multiple acceptance-related items. This finding aligns with previous research on the acceptance of automated driving systems, which indicated that different acceptance dimensions are hardly distinguishable and that a single factor of acceptance provides a better representation of the data (De Winter & Nordhoff, 2022; Nees & Zhang, 2020).

There were, however, two items that did not correlate strongly with the composite score, namely items related to the physical parameters of interface size and timing. As shown in Table S1 in the Supplementary Material, all nine AR interfaces yielded equivalent ratings (between 2.91 and 3.12) on the scale from 1 (too early) to 5 (too late) (Q21, Item 1), which can be explained by the fact that all interfaces were triggered at the same moment in the video. The small differences may have been caused by proximity (e.g., *Field of safe travel* extends in front of the car, "a sort of tongue protruding forward along the road"; Gibson & Crooks, 1938, p. 454), which might give participants the illusion that the interface was triggered early. The size ratings (Q21, Item 2) were also close to the midpoint for the nine interfaces, i.e., between

2.56 for the *Pedestrian lights* HUD and 3.37 for the *Virtual fence*. The differences in perceived size can also be explained by the actual size of the interfaces (see Figure 2).

In the aggregate, different groups of participants reached similar conclusions on what they deemed to be a 'good' interface, i.e., results were similar regardless of gender, age, or country. Anecdotally, it is often believed that there are major cultural differences among pedestrians in that an eHMI that is found to work well in one country may not be received well in another country (see quotes of Bärgman, Hagenzieker, Krems and Ackerman, and Stanton in Tabone et al., 2021a). The results of the present study suggest that these cultural differences are less strong as may be believed, at least for the five European countries under investigation. Our findings mirror those of others (Bazilinskyy et al., 2019; Singer et al., 2022) who found cross-cultural robustness of eHMIs in a larger number of countries on different continents.

While the online questionnaire was generally well distributed across the set quotas, it should be noted that the represented countries of residence were exclusively Western and Northern European. Therefore, cultural differences may have been relatively small. Several studies reported differences between the perceived clarity of eHMIs among participants from China versus Western Europe (Joisten et al., 2021; Lanzer et al., 2020; Weber et al., 2019). Whether or not cultural differences become apparent may depend on the clarity of the task instructions in the experiment and participants' prior expectations rather than the eHMI content itself, as noted by Singer et al. (2022).

**Free-Text Comments**

The textual inputs and opinions of the respondents were varied. Some respondents reported that theinterfaces on the road surface could distract pedestrians from approaching vehicles, while others considered interfaces on the vehicle a hazard, since these blocked the visibility of the oncoming vehicle. In a number of instances, respondents indicated that they preferred the non-yielding state over the yielding state, with the former being regarded as more clear and intuitive. In fact, the intuitiveness and convincingness, as shown inFigure 7, tended to favor the non-yielding state, except for a number of interfaces (*Planes on vehicle, Virtual fence*). Respondents described the yielding state for *Virtual fence* as clearer, but some labelled the non-yielding state as dangerous because the presence of a zebra crossing might tempt pedestrians to cross irrespective of the red gate. Similarly, the non-yielding state for the *Field of safe travel* was labelled as potentially dangerous by some because it looked like a red carpet that invited them to walk on it.

Another prevalent theme was that some respondents felt that at times it was not clear to whom the communication referred, i.e., the pedestrian or the vehicle itself. For example, the hand symbol on the *Planes on vehicle* was sometimes misinterpreted as indicating a problem with the vehicle. The *Planes on vehicle* and *Conspicuous looming planes* interfaces, which project planes on the vehicle, drew concerns about a blocked view of the vehicle, yet at the same time, the looming planes concept was commended for its clarity in communicating danger. These observations reveal the issue of unintended effects resulting from 'genius designs', where the intention is not fully grasped by the user. Our findings resonate with broader issues in human factors, namely that "*the actual, rather than presumed, impact of new technology is usually quite surprising, unintended, and even counterproductive*" (Woods & Dekker, 2000, p. 276).

Similar to the observations derived from the statistical analysis, the interfaces based on more traditional traffic elements were labelled as more understandable and intuitive due to familiar symbology (e.g., zebra crossing, traffic light). The 'worst' performing interface (*Phantom car*), while commended for its aesthetic qualities, received various critical descriptions, such as 'confusing', 'frightening', 'scary', 'startling', 'spooky', and 'unclear'. In fact, some described the interface as a video game, which in a sense confirms the original design direction of the *Phantom car* concept from Tabone et al. (2021b), where the idea of ghost cars from racing video games was drawn upon.

The HUD interfaces were praised for being 'logical', 'visible', 'clear', and 'perfect' to capture the attention of distracted pedestrians. However, it was also stated that HUDs could be a distraction from other hazards, especially when text is used (for further discussion on text-based eHMIs, see Bazilinskyy et al., 2019). Moreover, a number of respondents complained that the text was in English, and that this would be a danger for pedestrians unfamiliar with the language. The latter feedback resonates with an advantage of AR communication, where personalization of the interface could solve the language issue. In fact, 62% of the respondents were in favour of such a possibility. Finally, a number of times, respondents suggested that they would still rely on the vehicle coming to a full stop before making any decision, confirming that implicit communication plays an important role in shaping pedestrian decisions (Lee et al., 2021).

**Limitations and Future Work**

Although the online questionnaire was distributed to a wide respondent pool, the analysis revealed that more than half of the respondents (54%) reported having attained a university degree. Research suggests that university graduates are more inclined towards the adoption and usage of technology (Burton-Jones & Hubona, 2005; Nielsen & Haustein, 2018). At the same time, we found strong convergence in ratings for participants with and without a university degree, suggesting that educational level was not an important moderator of the current findings (see Figures S4 and S5). A possible reason is that participants were not asked to understand or use complex technology; instead, the present task was largely one of perceptual nature.

A further limitation is that the high correlation of acceptance-related items may have arisen from the uniform questionnaire format, giving rise to acquiescence bias. However, this limitation may not be significant as the acceptance scale (Q22) contained reversed items (from high to low, and from low to high), yet these items still correlated very strongly with the responses to the intuitiveness and convincingness items.

A number of free-text comments mentioned drivers being blinded by the interfaces that appeared on the car, indicating that those respondents did not fully grasp what AR technology is. Additionally, there were instances where the terms ‘AR’ and ‘VR’ were used interchangeably in the comments, with a number of respondents expressing total opposition towards wearing ‘VR headsets’ when they walk around outside. This confusion may have been caused by the fact that participants only saw VR videos of AR concepts, rather than experiencing AR themselves. That said, such confusion would only have affected the overall understanding of AR, and probably not the relative differences in the participants' assessments of the nine AR concepts.

Many respondent comments were unusable in the thematic analysis. While gibberish text entries were uncommon, many of the textual comments were too brief to provide useful information (e.g., “This one was clear”). This highlights a limitation of online studies, where there is the risk that some respondents do not thoroughly read the information provided at the beginning or aim to complete the questionnaire items quickly. A further limitation of online studies with videos is that, while offering high repeatability, they do not offer high ecological validity and present only low perceived risk to participants (for a similar discussion, see Fuest et al., 2020; Petzoldt et al., 2018; Tabone et al., 2021a).

A further limitation was that the environment consisted of a one-way road, with only one vehicle. The addition of more traffic, with varying trajectories, would add more natural cues to the testing environment. It can be hypothesized that the *Nudge HUD* will be particularly effective when multiple vehicles approach from different directions since the *Nudge HUD* does not require the pedestrian to distribute attention across those vehicles. In contrast, the *Planes on vehicle* require the pedestrian to first locate the planes in the environment before crossing, which may be time-consuming and inefficient. A potential advantage of *Planes on vehicle*, on the other hand, is that it may prevent overreliance in situations of e.g., vehicle-to-pedestrian communication failure. Another limitation was the lack of environmental sound, and the fact that participants were not asked to interact with the scene (e.g., to indicate when it is safe to cross). To better understand the behaviour of users of such interfaces, ecological validity must be increased. Therefore, in the future, the stimuli could be presented to the participants in a virtual simulation environment and ultimately, in the real world.

## Conclusion

Nine augmented reality interfaces for pedestrian-vehicle interaction were presented in a video-based online study that yielded 992 respondents from Germany, the Netherlands, Norway, Sweden, and the United Kingdom. Each interface was shown in its non-yielding and yielding states at a pedestrian crossing area represented in a VR environment. Respondents were asked to rate each interface based on its intuitiveness and convincingness in communicating whether or not a vehicle would yield. Other ratings related to functional and aesthetic qualities, usefulness, and satisfaction.

Statistical and qualitative thematic analysis indicated that respondents preferred head-locked interfaces over their world-locked counterparts, with interfaces employing traditional traffic interface elements receiving higher ratings than others. These results indicated that legacy design principles performed better than designs generated through an expert-based approach ('genius' design), further highlighting the importance of involving the user early in the process. A further qualitative analysis provided more context to the ratings, such as the preference of the non-yielding state over the yielding state for a number of interfaces, preference towards traditional traffic symbols, and reliance on implicit cues.

Responses related to the general use of interfaces indicated a preference for interfaces that are mapped to the street instead of the vehicle. Moreover, respondents preferred interfaces that make use of text compared to interfaces that use just graphical elements, and interfaces that are head-locked rather than world-locked. Most respondents also indicated that they would like to personalise the AR interfaces, and that communication using AR interfaces in future traffic would be useful.

Although the current online study offered an indication of what kinds of AR interfaces, placement in the world, and design elements are more suitable for pedestrian-vehicle interactions, there are limitations related to the ecological validity dimension of the study. In order to better understand the behaviour of potential users of the system, in the future, the ecological validity of such a user evaluation should be increased.

The practical implications of the present study depend on the progression in vehicle automation and communication, and in AR. It seems plausible that computers will become increasingly compact, and that the use of AR, either via handheld or head-mounted devices will become increasingly feasible in the real world. At the same time, questions about inclusivity, affordability, and user acceptance remain to be addressed, as discussed by

Tabone et al. (2021a). A likely way forward is that the use of AR for pedestrians will see its introduction first in professional transportation contexts (e.g., warehouses, airport personnel) before becoming available to the general public.

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# SUPPLEMENTARY MATERIAL

Table S1. *Means for the 17 questions asked for each AR interface.*

| | | 1. Augmented zebra crossing | 2. Planes on vehicle | 3. Conspicuous looming planes | 4. Field of safe travel | 5. Fixed pedestrian lights | 6. Virtual fence | 7. Phantom car | 8. Nudge HUD | 9. Pedestrian lights HUD |
|---|---|---|---|---|---|---|---|---|---|---|
| Q17 | Intuitiveness, Non-yielding | 5.67 | 4.61 | 4.64 | 4.95 | 5.62 | 5.00 | 4.07 | 5.68 | 5.59 |
| Q18 | Convincingness, Non-yielding | 5.60 | 4.63 | 4.64 | 4.94 | 5.48 | 4.97 | 4.23 | 5.67 | 5.47 |
| Q19 | Intuitiveness, Yielding | 5.53 | 4.85 | 4.65 | 4.84 | 5.57 | 5.48 | 4.29 | 5.69 | 5.50 |
| Q20 | Convincingness, Yielding | 5.34 | 4.69 | 4.52 | 4.76 | 5.36 | 5.36 | 4.20 | 5.46 | 5.28 |
| Q21, 1 | Too early - Too late | 3.03 | 3.02 | 3.06 | 2.91 | 3.12 | 2.99 | 3.10 | 2.94 | 2.99 |
| Q21, 2 | Too small - Too large | 3.05 | 2.95 | 2.88 | 3.17 | 2.60 | 3.37 | 3.13 | 2.92 | 2.56 |
| Q21, 3 | Very unclear - Very clear | 3.77 | 3.26 | 3.17 | 3.33 | 3.79 | 3.60 | 2.92 | 3.91 | 3.77 |
| Q21, 4 | Very unattractive - Very attractive | 3.52 | 2.91 | 2.86 | 3.16 | 3.47 | 3.20 | 2.85 | 3.55 | 3.43 |
| Q22, 1 | Useless - Useful | 3.84 | 3.25 | 3.17 | 3.38 | 3.81 | 3.61 | 2.96 | 3.89 | 3.79 |
| Q22, 2 | Unpleasant - Pleasant | 3.70 | 3.15 | 3.04 | 3.32 | 3.69 | 3.28 | 2.97 | 3.69 | 3.66 |
| Q22, 3 | Bad - Good | 3.79 | 3.23 | 3.10 | 3.32 | 3.71 | 3.44 | 2.97 | 3.79 | 3.69 |
| Q22, 4 | Annoying - Nice | 3.62 | 3.11 | 3.01 | 3.23 | 3.59 | 3.24 | 2.99 | 3.63 | 3.53 |
| Q22, 5 | Superfluous - Effective | 3.79 | 3.28 | 3.17 | 3.35 | 3.67 | 3.57 | 3.04 | 3.79 | 3.66 |
| Q22, 6 | Irritating - Likeable | 3.62 | 3.11 | 3.01 | 3.26 | 3.64 | 3.24 | 2.94 | 3.64 | 3.59 |
| Q22, 7 | Worthless - Assisting | 3.78 | 3.27 | 3.17 | 3.39 | 3.72 | 3.56 | 3.01 | 3.80 | 3.68 |
| Q22, 8 | Undesirable - Desirable | 3.58 | 3.10 | 3.04 | 3.22 | 3.55 | 3.29 | 2.92 | 3.59 | 3.50 |
| Q22, 9 | Sleep-inducing - Raising Alertness | 3.72 | 3.38 | 3.31 | 3.49 | 3.59 | 3.66 | 3.27 | 3.76 | 3.58 |

*Note.* Q17–Q20 were measured on a scale of 1 = Strongly disagree to 7 = Strongly agree. Q21 and Q22 were measured on five-point scales. Colour coding is applied for Q17–Q20 and Q21 & Q22 separately, where the lowest value is red, the median is white, and the highest value is blue.

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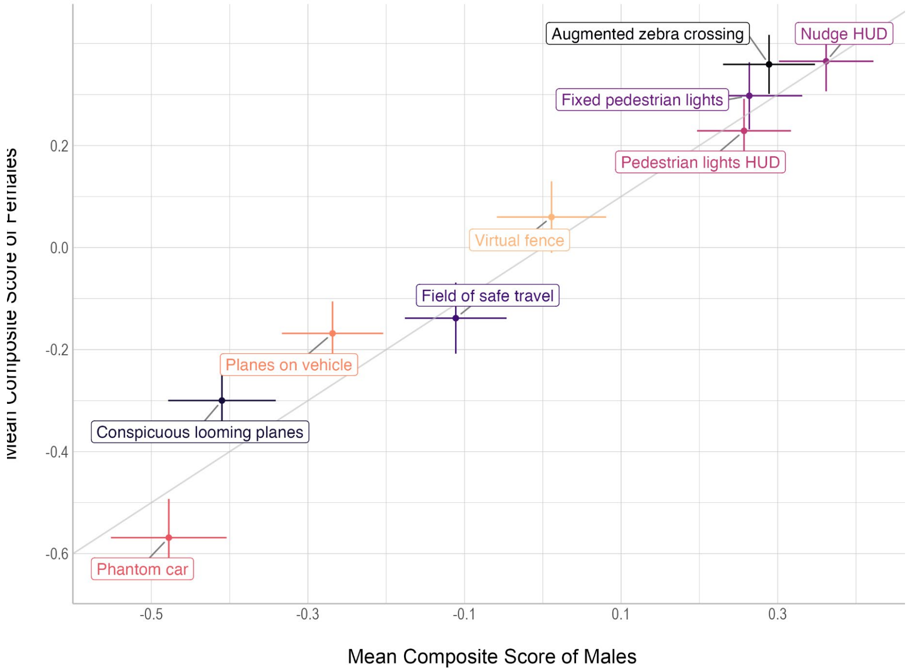


*Figure S2.* Scatter plot of the composite score for the nine AR interfaces, for females ($n$ = 491) versus males ($n$ = 492). The error bars represent 95% confidence intervals.

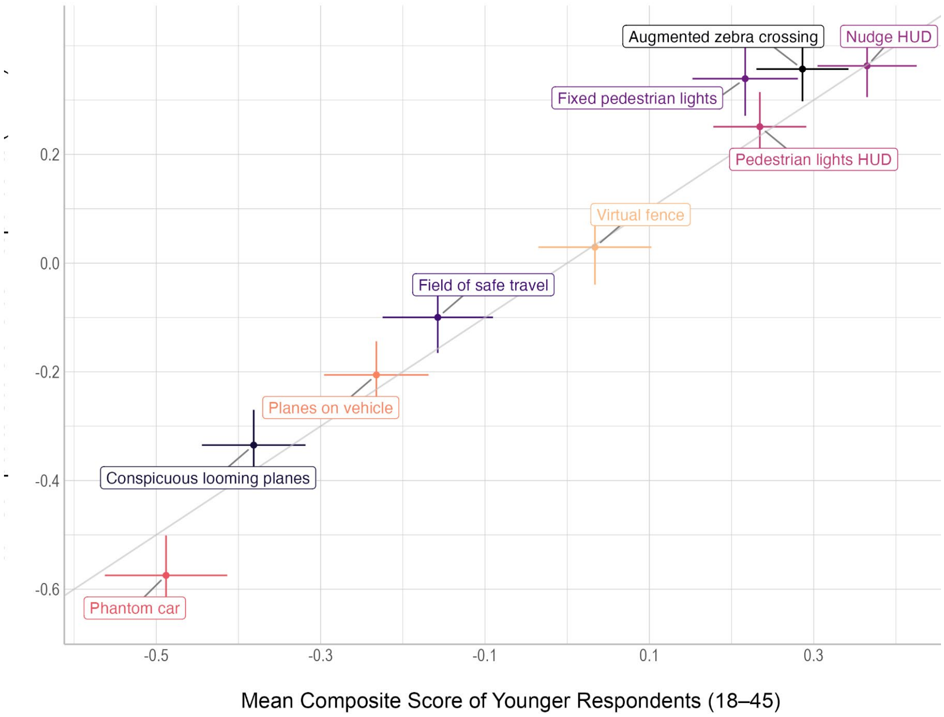

*Figure S3.* Scatter plot of the composite score for the nine AR interfaces, for older respondents (*n* = 493) versus younger respondents (*n*= 499) (*r* = 0.988). The error bars represent 95% confidence intervals.

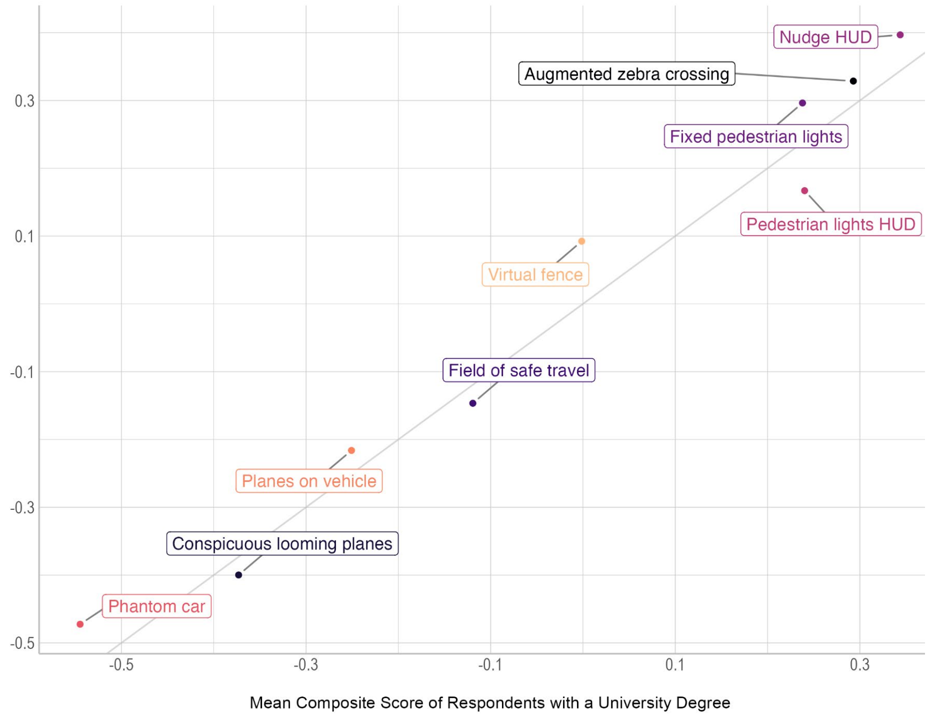


*Figure S4.* Scatter plot of the composite score for the nine AR interfaces, for respondents with trade/technical/vocational training (*n* = 246) versus respondents with a university degree (*n* = 536) (*r* = 0.986). The error bars represent 95% confidence intervals.

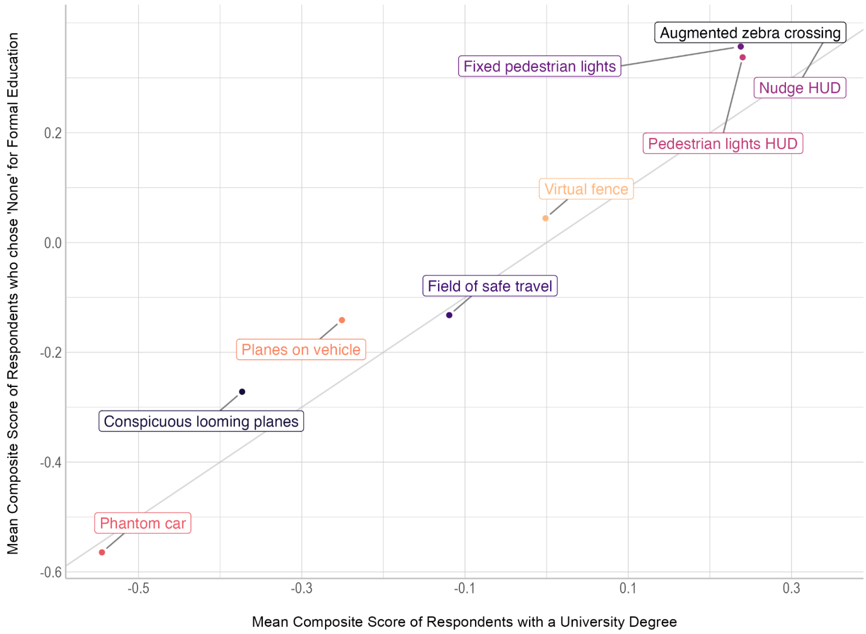


*Figure S5.* Scatter plot of the composite score for the nine AR interfaces, for respondents who indicated 'none of these' for the choice of trade/technical/vocational training or university degree ($n$ = 210) versus respondents with a university degree ($n$ = 536) ($r$ = 0.990). The error bars represent 95% confidence intervals.

The 19 videos, raw data, and a PDF version of the questionnaire are available on a repository (https://doi.org/10.4121/21603678) to facilitate reproducibility and encourage further development.