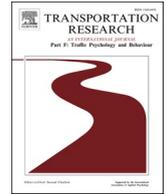




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Pedestrian interaction with multiple highly automated vehicles: Effects of LED- and augmented reality-based external HMI communication in complex urban environments[☆]

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ABSTRACT

The introduction of highly automated vehicles (HAVs) promises safer, more efficient, and inclusive mobility, but also challenges pedestrian-vehicle communication. Without human drivers providing explicit cues, pedestrians rely on other signals for safe interactions. External human-machine interfaces (eHMIs) show potential, yet, their performance in complex scenarios remains insufficiently researched. In particular, research on the combined use of multimodal eHMIs – such as vehicle-mounted LEDs and wearable Augmented Reality (AR) – is scarce, despite their potential to offer both universal visibility and personalized, context-sensitive feedback.

This study examined the impact of light-based and AR-based eHMIs – both individually and in combination – on pedestrian-HAV interaction in a Virtual Reality environment. Forty participants encountered HAVs approaching from both sides of a shared space. Vehicles employed one of four communication strategies: no eHMI, communication of HAV's intention via 360° LED light band, communication via AR, or novel multimodal setup combining LED and AR, as well as four different vehicle kinematics. Objective and subjective measures, including crossing initiation time, perceived safety, mental workload, understandability, and predictability, were collected and analyzed using repeated-measures ANOVAs with Bonferroni-corrected post-hoc tests.

Communicating the HAV's intention via 360° LED or AR significantly improved crossing initiation time, perceived safety, and understandability, and reduced mental workload compared to no eHMI. Additionally, communication of HAV's intention via AR outperformed the LED condition, while the combined LED+AR interface preserved these benefits without increasing mental workload. Although yielding patterns influenced participants' behavior, eHMI benefits remained stable regardless of the actual traffic scenario.

These findings demonstrate AR's potential in enhancing eHMI effectiveness and highlight the added value of a multimodal design. LED + AR combinations may guide the development of inclusive, intuitive, and context-sensitive eHMIs, ultimately supporting confident pedestrian interaction in future automated urban environments.

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1. Introduction

Highly automated vehicles (HAVs), defined as vehicles capable of operating at SAE level 4 or Level 5 (SAE International, 2021), promise a range of benefits for future urban mobility. These include enhanced traffic safety (Chan, 2017) and more inclusive mobility solutions (Milakis et al., 2017). As these HAVs are introduced into mixed traffic environments, they will share the road with a diverse array of other road users (ORUs): pedestrians, cyclists, other two-wheelers, manually driven vehicles, and other automated vehicles (Madigan et al., 2019; Schieben et al., 2019). In such complex contexts, effective communication between HAVs and other road users is essential for safe, efficient, and trustful interactions (Habibovic et al., 2018; Rasouli & Tsotsos, 2020; Schieben et al., 2019; Wilbrink et al., 2021a). Pedestrians as ORUs represent a vulnerable group in these interactions, as HAVs can pose a substantial safety risk if intentions are unclear or misinterpreted (Habibovic et al., 2018; Rasouli et al., 2017).

2. Background

Traditionally, communication between pedestrians and manually operated vehicles relies on a combination of implicit and explicit signals (Färber, 2016; Markkula et al., 2020). Implicit communication relies on pedestrians reading a vehicle's kinematics and movement patterns. For example, a reduction in speed is often interpreted as an implicit signal that the vehicle intends to yield. (Markkula et al., 2020; Risto et al., 2017). Although some studies suggest that pedestrians rely primarily on implicit cues (Dey & Terken, 2017; Moore et al., 2019), several studies show that pedestrians find these cues harder to interpret when interacting with HAVs whose kinematics differ from human-driven vehicles. (Crosato et al., 2021; Millard-Ball, 2016). Human-driven vehicles often exhibit subtle vehicle kinematic variations (e.g. early deceleration, small speed adjustments, or brief forward movements) that pedestrians routinely interpret as socially meaningful cues (Dey & Terken, 2017). In contrast, HAVs typically follow smoother, more efficiency-oriented and later-initiated braking profiles that are not designed with communicative intent. Research by Crosato et al. (2021) and Millard-Ball (2016) shows that these differences can make HAV kinematics harder for pedestrians to interpret, reducing pedestrians' ability to anticipate whether the vehicle intends to yield.

Explicit cues, such as eye contact or hand gestures, are often provided by human drivers and serve as additional confirmation and help resolve ambiguities when traffic situations are unclear (Dey & Terken, 2017; Lee et al., 2021). The introduction of HAVs disrupts established interaction patterns. Without a human driver to provide explicit feedback, pedestrians lose important communication channels such as eye contact or gestures (Habibovic et al., 2018; Lau et al., 2022b; Merat et al., 2018; Stanciu et al., 2017). Especially in unclear traffic situations or unregulated environments, this limitation of communication can lead to misunderstandings between pedestrians and HAVs. Shared spaces represent a typical example of such contexts, as they involve low-speed, close-range interactions and lack formal traffic regulation, which can increase uncertainty for road users (Brill et al., 2023; Hamilton-Baillie, 2008). One proposed solution to fill this communication gap is the development of external Human-Machine Interfaces (eHMIs).

A wide range of eHMI concepts has been proposed in the literature, including auditory signals, text- or icon-based displays, anthropomorphic cues, and projected ground symbols (e.g., Bazilinsky et al., 2019; Brill et al., 2023; Chang et al., 2017; Nguyen et al., 2019). While these modalities offer various benefits (e.g., higher subjective safety), most empirical HAV-VRU research focuses on visual eHMIs, particularly light-based systems such as LED bands (Schieben et al., 2019). This dominance is largely due to their technological simplicity, robustness under different environmental conditions, and accessibility for most road users. Consequently, visual light-based eHMIs represent the most established baseline in the field and thus serve as the primary comparison point in the present study.

A substantial body of research has investigated light-based eHMIs, which signal the vehicle's automation status or deliver intention-based information regarding vehicle's future driving behavior (Bengler et al., 2020; Dey et al., 2020; Weber et al., 2019; Lau et al., 2020; Wilbrink et al., 2023b). Studies have shown that such eHMIs can increase pedestrians' subjective safety, trust, and willingness to cross, and can lead to reduced crossing initiation times (Faas et al., 2020; Lau et al., 2022a, 2022b; Othersen et al., 2019; Schieben et al., 2019; Wilbrink et al., 2021b). Earlier crossings may improve traffic flow by preventing unnecessary stops (Faas et al., 2020; Wilbrink et al., 2021b). Several studies conducted in low-speed or shared-space-like environments suggest that eHMIs can support pedestrians by increasing clarity and reducing ambiguity in relatively simple interactions (Brill et al., 2023; Lau et al., 2022a; Wilbrink et al., 2021a).

However, simple light-based eHMIs may face limitations in complex traffic scenarios. We define complex traffic scenarios as low-speed, close-range situations where several automated and human road users must negotiate priority with few formal rules. Shared space layouts and similar urban settings often exhibit this complexity, making implicit and explicit cues from vehicles ambiguous. As a result, misunderstandings can occur when simple light-based eHMIs broadcast signals to the general environment rather than targeted at specific individual ORUs as relevant interaction partners. A pedestrian might interpret a vehicle's yield signal as being meant for them, even though the HAV intended to communicate with another pedestrian nearby (Dey et al., 2020; Habibovic & Davidsson, 2012; Wilbrink et al., 2021b). This confusion could lead to unsafe crossing decisions resulting in critical traffic situations. Consequently, simple light-based eHMIs may be inadequate in the complex situations that readily arise within shared-space environments, where multiple HAVs and human road users must coordinate their movements with minimal formal rules.

Augmented Reality (AR) interfaces offer a promising complementary solution. AR technology enriches the user's perception of the environment by overlaying digital information directly onto real-world scenes (Azuma, 1997). In traffic contexts, AR has the potential to provide context-relevant, spatially embedded information, enhancing situational awareness and anticipation without forcing the user to shift gaze away from the road (Currano et al., 2021; Schwarz & Fastenmeier, 2017; Tong et al., 2021; Tran et al., 2023). Early studies with AR-based eHMIs for pedestrians interacting with HAVs show promising results, increases in perceived safety, and more

confident crossing decisions compared to no eHMI or light-based eHMI conditions (Heseniuss et al., 2018; Praticcò et al., 2021; Tabone et al., 2023; Wilbrink et al., 2023).

However, findings regarding the impact of AR-based eHMIs on mental workload are mixed. Some studies report increases in cognitive effort when AR overlays present dense, multi-element, or highly dynamic information (Heseniuss et al., 2018; Praticcò et al., 2021). In contrast, other work demonstrates that simple, spatially embedded AR cues can enhance pedestrians' understanding of vehicle intentions without adding mental strain (Tabone et al., 2023). Similarly, Wilbrink et al. (2023) showed that AR-based eHMIs can be effective when designed with minimal and intuitive visual elements that align with pedestrians' perceptual expectations. Together, these findings suggest that the effect of AR eHMIs on mental workload depends strongly on the specific design characteristics of the AR overlays, such as visual complexity, spatial grounding, and congruence with the surrounding environment. Consequently, the influence of AR-based eHMIs on cognitive workload remains an open question in the literature.

Additionally, AR shouldn't be considered as sole solution. The adoption of AR smart glasses or similar devices is still limited, and reliance on such technology may create inequities, as not all pedestrians will have access (Tabone et al., 2021; Tran et al., 2022). Additionally, experts caution that AR eHMIs might induce overtrust or increase mental workload, especially in complex, information-rich environments (Moore et al., 2019; Tabone et al., 2023; Tabone et al., 2021). Therefore, a combination of AR-based cues with vehicle-mounted signals like LED light bands offering a promising solution while ensuring that all road users (equipped and unequipped with AR devices) benefit from clear, intuitive communication strategies (Lee et al., 2021; Tabone et al., 2021; Wilbrink et al., 2023). Beyond these human-machine interaction considerations, AR-based eHMIs must also be viewed within the broader context of HAV acceptance. Systematic reviews highlight perceived safety, trust, and the ease of understanding vehicle behavior as central determinants of users' willingness to adopt automated vehicles (Jing et al., 2020). Recent machine-learning analyses further show that predictability, risk perception, and clarity of communication significantly shape attitudes toward HAVs (Ziakopoulos et al., 2023). Because AR has the potential to enhance these factors by providing spatially embedded, intuitive cues, it could positively contribute to overall HAV attractiveness. At the same time, requirements such as wearable hardware or visually complex overlays may introduce barriers that negatively influence acceptance. This underscores the importance of evaluating multimodal eHMIs, such as the combined LED+AR approach, which may balance clarity, inclusiveness, and cognitive simplicity, thereby supporting both safe interaction and wider acceptance of HAV technology.

Building on the established value of LED-based eHMIs in simpler traffic situations, a key question emerges: can LED-based eHMIs also effectively support pedestrians' decision-making and situational understanding in more realistic and complex, multi-HAV interaction environments? Therefore, shared spaces with their unregulated, low-speed traffic environment represent a promising use case. A recent review by Brill et al. (2023) emphasizes that these environments pose particular challenges for eHMIs, as multiple pedestrians and vehicles interact simultaneously, increasing the risk that simple light-based signals may be misinterpreted or not perceived as intended.

It remains unclear whether AR-based eHMIs can support pedestrians in crossing situations by providing enhanced feelings of safety and improved predictability. Consequently, a combination of both, LED+AR eHMI interfaces should be investigated regarding their potential to support pedestrians without increasing their cognitive workload. To investigate these questions, this work employs a Virtual Reality (VR) simulation of pedestrian-HAV interactions in a complex traffic environment with multiple HAVs in an urban shared space traffic situation.

3. Hypotheses

Building on prior research, combining well-established LED light bands as eHMIs with spatial AR cues may offer particular advantages for vulnerable road users (VRUs) in complex, multi-HAV scenarios. This integrated approach has the potential to improve perceived safety and the predictability and understandability of HAV behavior, reduce mental workload, and shorten crossing initiation time - key determinants identified as major predictors of automated vehicle acceptance (e.g., Jing et al., 2020; Ziakopoulos et al., 2023).

However, it remains essential to examine whether AR-based interfaces can deliver these benefits effectively, and whether their combination with LED eHMI solutions sustains or enhances these advantages. Furthermore, the robustness of such designs needs to be tested across various traffic conditions, including more complex situations where multiple HAVs and human road users need to coordinate their actions. Prior work offers mixed evidence regarding the cognitive effects of AR-based eHMIs: complex overlays can increase mental workload (Heseniuss et al., 2018; Praticcò et al., 2021), whereas simple, spatially embedded AR cues can support comprehension without additional cognitive demand (Tabone et al., 2023; Wilbrink et al., 2023). Because the AR design used in the present study is intentionally minimal and redundantly reinforces the LED signal in the combined condition (LED+AR), we did not expect a systematic increase in mental workload.

This study systematically investigates how different eHMI configurations (no eHMI vs. LED light bands vs. AR vs. their combination LED+AR) affect pedestrian-HAV interaction in a dynamic shared-space scenario. Based on prior findings and current research gaps, we addressed the following hypotheses in our experimental study:

In scenarios where both HAVs yield to the pedestrian:

H1a: Providing an intention-based eHMIs (LED, AR, or LED+AR) will lead to lower crossing initiation times, higher perceived safety, lower mental workload, and higher understandability and predictability ratings compared to scenarios without any eHMI.

H1b: An AR-based eHMI will lead to lower crossing initiation times, higher perceived safety, lower mental workload, and higher understandability and predictability ratings compared to the LED light band condition.

H1c: A combined LED+AR eHMIs (LED+AR) will lead to lower crossing initiation times, higher perceived safety, equal mental

workload, and higher understandability and predictability ratings compared to the LED light band condition.

Under varying vehicle kinematic conditions (e.g., only one HAV yielding):

H2: All intention-based eHMIs (LED, AR, LED+AR) will lead to higher perceived safety, lower mental workload, and higher understandability and predictability compared to no eHMI.

In the following sections, we detail the methodology, experimental design, and measures employed to test these hypotheses, followed by the results and a discussion of the implications for future eHMI development and pedestrian-HAV interaction strategies.

4. Method

4.1. Research design

To systematically examine how eHMI type and HAV kinematics influence pedestrian crossing initiation time and experience (perceived safety, mental workload, understandability and predictability of the HAV), a 4 (eHMI condition) x 4 (vehicle kinematics) within-subject design was used. The eHMI design factor comprised four levels: (1) no eHMI, (2) LED Light Band, (3) AR eHMI and (4) Combined (LED+AR) (see section 4.2). The vehicle kinematics of the HAV represents the second factor with also four levels: (1) Both HAVs yield, (2) Only the right-side HAV yields, (3) Only the left-side HAV yields, and (4) Neither HAV yields.

Each participant completed 16 trials (one for each unique combination of eHMI design and vehicle kinematics) presented in a randomized order to counterbalance potential learning or order effects. A within-subjects design was chosen to control for inter-individual variability and ensure direct comparisons between conditions within the same participant.

4.2. Stimulus material

Within a shared space environment presented in VR, this experimental study compared four eHMI conditions to assess their impact on pedestrians' decision-making, perceived safety, and understanding of HAV behavior.

- A baseline condition with no eHMI (no eHMI)
- A vehicle-mounted 360° LED light band (LED)
- An Augmented Reality interface integrated into the pedestrian's smart glasses (AR)
- A combined interface featuring both modalities (LED+AR)

The following section provides a more detailed description of the stimulus material used in each condition, including their visual characteristics, communication function, and intended interaction cues.

4.2.1. No eHMI

By relying solely on vehicle kinematics for implicit communication (i.e., approaching movement patterns such as deceleration), the no eHMI baseline condition allows a direct assessment of the added value provided by explicit cues from the LED, AR, and combined LED+AR interfaces (Fig. 1).

1.1.1.1 360° LED-based Light Band (LED).

The LED light band concept was developed during the EU interACT project (Weber et al., 2019) and has been extensively studied in



Fig. 1. Visualization of the baseline without eHMI (no eHMI)

previous work (e.g., Lau et al., 2021; Lee et al., 2022; Schieben et al., 2019; Wilbrink et al., 2021a; Wilbrink et al., 2021b; Wilbrink et al., 2023). The 360° cyan-colored LED light band mounted externally around the entire vehicle chassis, signals full automation mode by continuously glowing (Fig. 2). Its external placement ensures that it is not visible from inside the vehicle and therefore does not interfere with driver or passenger visibility. In addition, the LED light band is able to communicate the intention of the HAV to yield by pulsating at 0.66 Hz. The color choice complies with legal regulations and avoids privacy or liability concerns (Dey et al., 2020; Schaarschmidt et al., 2021). According to the taxonomy by Dey et al. (2020), this vehicle-mounted, visually abstract eHMI broadcasts its messages to all road users, conveying the HAV's intention but not its exact trajectory or stopping position.

4.2.2. AR-based eHMI (AR)

The AR-based eHMI was implemented by augmenting the VR environment with spatially aligned, semi-transparent graphical overlays, following the core definition of augmented reality as the integration of virtual information into a user's perception of the surrounding environment (Azuma, 1997). In VR, this allowed us to simulate AR smart-glasses by rendering the eHMI elements directly into the participant's field of view without occluding the scene. This AR-based interface, adapted from Wilbrink et al. (2023), consists of a cyan semi-transparent path projected onto the road in front of the HAV indicating the HAV's planned trajectory. As soon as the HAV initiated braking, the projected HAV path was shortened and a thick white line appeared, marking the precise stopping position of the vehicle (Fig. 3). These design elements draw on evidence that spatially embedded information and explicit stopping indicators improve pedestrian's understanding of vehicle behavior (Pratticò et al., 2021; Tabone et al., 2021).

In line with the taxonomy by Dey et al., (2020), the AR-based eHMI operates “on the VRU side”, as only users equipped with AR smart glasses would perceive the additional information. Within our VR implementation, AR cues were therefore shown solely for the HAV directly relevant to the participant, ensuring targeted rather than broadcast communication. This approach prevented overlapping graphical layers when multiple vehicles were present and maintained clear attribution of the AR cues in multi-vehicle scenarios.

4.2.3. Combined LED light band and AR eHMI (LED+AR)

Previous research pointed out that AR technology alone may not be ideal as a sole communication channel (Lee et al., 2021; Tabone et al., 2021). AR smart glasses are not yet widely adopted and relying solely on them could exclude many road users from accessing potentially safety-critical information. Moreover, combining AR with the LED light band may leverage complementary strengths: while AR can provide informative overlays about distant objects, such as the vehicle's intended path, the LED light band is more effective at closer ranges due to its high visibility and its ability to effectively capture pedestrian attention (Dey et al., 2019). This combined design ensures that both AR-equipped and non-equipped road users receive relevant information. The AR and LED light band complement each other: when the HAV is in automation mode, AR-equipped ORU see the HAV's projected driving path alongside the continuous LED light band at its chassis. As the HAV begins to brake, the AR path displays a white stopping line, while the LED light band switches to a pulsing pattern (Fig. 4). Users without AR glasses still benefit from the visible light signals, while those with AR receive both layers of information, enhancing situational awareness across user groups.

By examining these four experimental conditions in a VR-based shared-space environment, this study aims to determine whether, building on the cues already provided by vehicle kinematics, AR-based or combined LED+AR eHMIs improve pedestrian safety, understanding, and decision-making beyond what is achieved with the well-established LED light band alone. In particular, we investigate whether integrating AR can provide more precise information without causing cognitive overload, and whether a combination of LED and AR signals can support pedestrians without undermining the benefits of each approach.

4.3. Sample

The study targeted adults aged 20 to 45 who were free of red-green color blindness, had normal or corrected-to-normal vision, and possessed at least C1-level German language proficiency to fully understand the instructions. Participants were recruited through an online study database, printed flyers distributed on the university campus, and announcements on the university's bulletin board.

A total of 45 datasets were initially collected. Five were excluded for the following reasons: three were incomplete due to technical



Fig. 2. Visualization of the 360° LED light band (LED) condition. Left: low light intensity while pulsation. Right: high intensity while pulsation.



Fig. 3. Visualization of the AR-based eHMI. Top left: AR cue showing the intended path of a yielding HAV. Top right: AR cue indicating the stopping position via a white stopping line. Bottom left: AR trajectory cues for two vehicles approaching from different directions. Bottom right: AR stopping line for a yielding HAV while the second vehicle continues through the intersection.



Fig. 4. Visualization of the combination of LED light band and AR eHMI (LED+AR).

issues, and another two were excluded because these participants began crossing so early that the HAVs had not yet initiated their yielding maneuver.

This resulted in a final sample of 40 participants (12 female) between the ages of 20 and 43 ($M = 26.35$, $SD = 4.90$). All but two participants reported that they were in possession of a driver's license with an average of 7327 km driven per year ($SD = 9042$). All participants had heard of HAVs before and their interest in HAVs was quite high ($M = 4.05$, $SD = 0.81$, on a 5-point Likert scale from 1 = "no interest at all" to 5 = "very strong interest"), similar to their affinity to technology on the ATI Scale (Franke et al., 2019; $M = 4.58$, $SD = 0.87$, on a 6-point Likert scale from 1 = "completely disagree" to 6 = "completely agree"). Participants rated their experience with VR technology as rather low ($M = 2.53$, $SD = 1.18$, on a 5-point Likert scale from 1 = "very little" to 5 = "a lot").

4.4. Dependent variables

In this experimental study, we examined how different eHMI designs and vehicle kinematics, i.e., braking behaviors, of HAVs influence pedestrians' crossing initiation time (CIT), perceived safety, mental workload as well as understandability and predictability of the HAVs behavior. We defined CIT as the interval from the start of each experimental trial until the participant pressed a handheld controller button indicating readiness to cross. Oehl et al. (2022) emphasize the value of such objective metrics in evaluating pedestrian-HAV interaction. Subjective safety ratings were collected immediately after each trial using a single-item, 7-point Likert scale (from 1 = "very unsafe" to 7 = "very safe"). In addition to CIT and perceived safety, we also measured mental workload using the NASA-TLX (Hart, 2006; Hart & Staveland, 1988) rated on a 21-point scale (from 0 = "very low" to 20 = "very high"), as well as two items from the TiA (Trust in Automation) questionnaire (Körber, 2019) regarding understandability ("I was able to understand why

things happened”) and predictability (“It is difficult to identify what the automated vehicle will do next”). The TiA questionnaire employs a 5-point Likert scale (from 1 = “strongly disagree” to 5 = “strongly agree”) to evaluate reliability, understandability, and predictability of automated systems. Together, these subjective measures offer a more holistic perspective on how different eHMI solutions shape pedestrians’ experiences and decision-making in complex, mixed-traffic scenarios.

4.5. Virtual environment and task

To investigate pedestrian decision-making in a complex traffic context, the experiment was conducted in a Virtual Reality (VR) environment that simulated a realistic shared space scenario. Shared spaces are traffic-calmed urban areas in which all road users—including vehicles and pedestrians - interact with equal rights and without dedicated crossing infrastructure. The simulation included key characteristics of such environments, including a speed limit of 20 km/h and application of the “right before left” rule. Participants were instructed to behave according to the principle of mutual consideration.

The environment was developed in Unreal Engine (version 4.27, Epic Games Inc.) and presented via HTC Vive Pro Eye headsets and handheld controllers (HTC Corporation).

At the start of each trial, participants found themselves at the edge of the shared space as two groups of vehicles approached from opposite directions (left and right; Fig. 5). Each group consisted of three vehicles: a leading highly automated vehicle (HAV), followed closely by two conventionally driven vehicles modeled after familiar passenger cars (Tesla Model S, VW Golf V, or BMW i3). The HAVs, represented by a Mercedes EQS model to ensure a realistic and recognizable vehicle appearance. The HAV were equipped with one of the four eHMI variants and either yielded or did not yield for the pedestrian (depending on the factor vehicle kinematics).

All vehicles traveled at an initial speed of 20 km/h. In the yielding conditions, HAVs approached the participant at 20 km/h and initiated a constant deceleration of -1.0 m/s^2 at a distance of 20 m. They came to a full stop 4.72 m in front of the participant, resulting in a braking duration of approximately 5.5 s, which ensured that participants had sufficient time to perceive both the implicit and explicit signals and decide whether they felt safe to initiate crossing. The selected deceleration value reflects a realistic and comfortable “defensive braking” profile commonly recommended for low-speed automated vehicle behavior in urban environments. Recent empirical work by Hub et al. (2023) shows that such defensive braking profiles are perceived by road users as more understandable, predictable, and less critical than moderate or hard braking. To ensure synchronized arrival at the crossing point across all conditions, vehicle starting distances were adjusted. In trials where both HAVs yielded, each vehicle started 60 m. In trials where only one HAV yielded, the yielding HAV started at 60 m, whereas the non-yielding HAV started at 75 m.

Participants were instructed to imagine they needed to reach a subway entrance on the opposite side of the street, with a sign indicating their train would depart in two minutes -introducing a mild sense of urgency. In each trial, they were asked to cross when they felt safe and comfortable. To initiate crossing, participants pressed a button on the handheld controller and stepped forward, simulating a real-world street entry. After each scenario, participants completed a short questionnaire consisting of four subjective ratings assessing perceived safety, mental workload, understandability, and predictability of the vehicle behavior. This task structure was identical across all trials. The study was approved by the German Aerospace Center's ethics board (Approval No. 15/23).

4.6. Procedure

Data collection took place at the German Aerospace Center (DLR) in Braunschweig, Germany. Each session lasted approximately 90 min, and participants received a compensation of €15 for their time. Upon arrival, participants were welcomed by the experimenter and received general information about the study, including their right to withdraw at any time without consequence.

Participants were introduced to the concept of highly automated vehicles (HAVs), described as interconnected systems capable of perceiving their environment, identifying road users, and making autonomous driving decisions. The functionality of the VR equipment was then explained, and any remaining questions were addressed. Informed consent and a data privacy agreement were signed before continuing.

Before entering the virtual environment, participants completed a demographic questionnaire and the Affinity for Technology Interaction (ATI) Scale on a laptop. Once the VR headset was placed, they were introduced to the shared space environment - initially without any traffic. To familiarize participants with the different eHMI types used in the study (LED, AR, combined LED+AR, and no eHMI), short video demonstrations were shown within the VR environment, each accompanied by a brief verbal explanation.

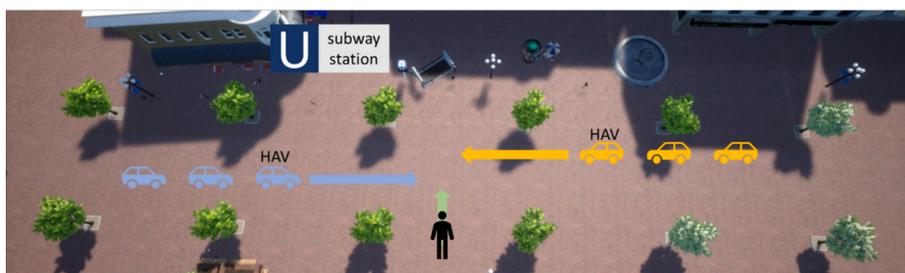


Fig. 5. Visualization of the scenario (birds-eye view), including the participant's position, the approaching vehicles, and subway station.

Before the main experiment began, participants completed four training trials featuring a single yielding HAV approaching from the left. These trials allowed participants to get accustomed to the VR setup, task mechanics, and eHMI cues. The experimental trials followed immediately after, presented in randomized order to control for sequence effects. Across the experiment, participants were asked after each trial whether they felt well or required a break. Participants were given a short break of approximately five minutes after completing the first half of the trials.

During each trial, crossing initiation time (CIT) was recorded as the interval between trial onset and the participant's button press combined with a physical step forward, indicating their readiness to cross. After each crossing, participants completed a brief set of subjective ratings (assessing perceived safety, mental workload, understandability, and predictability of the vehicle behavior) - while remaining within the VR environment. This approach avoided repeated removal and re-equipping of the VR headset, which can disrupt immersion and increase the likelihood of discomfort or simulator sickness.

In addition, participants completed several end-of-study questions to assess their overall well-being, perceptual clarity and potential discomfort in the VR environment. These items asked whether participants could clearly perceive the vehicles, changes in their behavior, the LED-based eHMI, and the AR-based eHMI, and whether any of these elements were perceived as disturbing. Participants also indicated whether they felt restricted in their field of view. No participant reported critical issues. These checks ensured that VR comfort and perceptual limitations did not confound the results.

5. Results

5.1. Data analysis approach

To investigate the effects of the eHMI communication and the HAVs kinematics, i.e., braking behavior, on crossing initiation time (CIT), perceived safety, mental workload, and understandability and predictability we conducted several repeated-measures ANOVAs (rmANOVAs). First, we used single-factor rmANOVAs to assess the isolated impact of the eHMI variants on the outcome variables, restricting these analyses to the condition where both vehicles yielded. Next, we explored potential interaction effects of eHMI design and HAV kinematics with two-factor rmANOVAs. Since a non-yielding HAV heavily influenced the CIT, the CIT was only evaluated for conditions in which both HAVs yielded. All rmANOVAs were evaluated for sphericity via Mauchly's test, and Greenhouse-Geisser corrections were applied if necessary. We interpreted effect sizes using partial eta squared (η_p^2) with the following thresholds (Cohen, 1988): small ($\eta_p^2 \leq 0.01$), medium ($\eta_p^2 \leq 0.06$), and large ($\eta_p^2 \leq 0.14$). Significant main or interaction effects were followed up with pairwise Bonferroni-adjusted *t*-tests. Where the sphericity assumption was met, no correction was required.

In scenarios where one or both HAVs did not yield, participants were required to wait for the vehicles to pass, such that no meaningful crossing initiation time could be obtained. As a result, these conditions were excluded from the rmANOVA models, and the corresponding comparisons were analyzed using Bonferroni-corrected two-tailed *t*-tests. These tests used Cohen's *d* (Cohen, 1988), with values of 0.2 for small, 0.5 for medium, and 0.8 for large effect sizes. Statistical analyses were performed in R (version 4.4.2) via RStudio (version 2024.09.0.375). The assumptions for rmANOVAs were met. Moreover, rmANOVAs are considered robust to minor

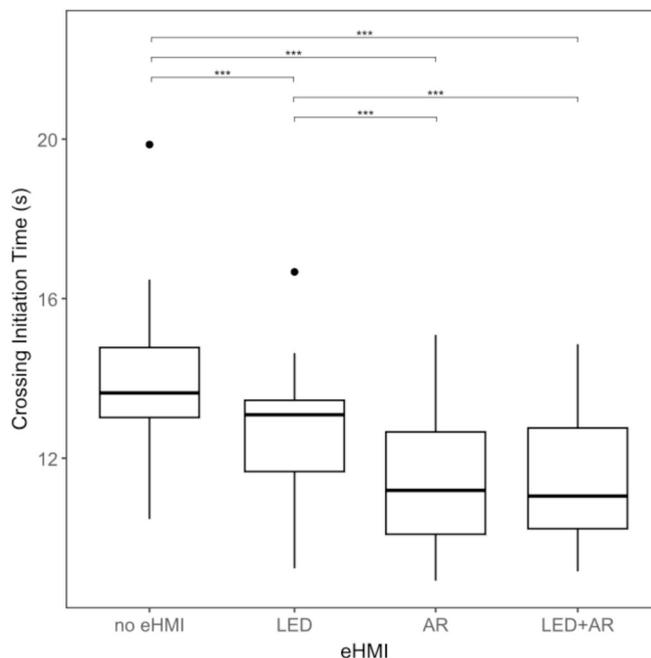


Fig. 6. Box-plot of crossing-initiation time (CIT) in the both-yield condition across the four eHMI designs (***) $p < .001$.

violations of normality, provided that other assumptions are satisfied (Berkovits et al., 2000; Pagano, 2013).

5.2. Crossing initiation time

Crossing initiation time (CIT) was analyzed only in the both-yield condition, as CIT is not meaningful when one or both HAVs do not yield and participants have to wait for the vehicles to pass. The CIT was defined as the time interval from the start of each trial until the participant pressed the button to indicate their intention to begin crossing in front of the HAV. A repeated-measures ANOVA with Greenhouse-Geisser correction revealed a significant main effect of eHMI type on CIT, $F(3, 117) = 59.40, p < .001, \eta_p^2 = 0.60$, indicating a large effect. In line with H1a, post-hoc comparison using Bonferroni correction showed that the CIT was significantly lower in all eHMI conditions compared to the no eHMI baseline (all $p < .001$, see Fig. 6). The combined LED + AR interface resulted in the shortest CIT ($M = 11.48, SD = 1.56$), followed by the AR ($M = 11.46, SD = 1.75$), LED ($M = 12.69, SD = 1.46$), and no-eHMI condition ($M = 13.92, SD = 1.55$). As hypothesized in H1c, pairwise comparisons showed that the LED+AR condition led to significantly faster crossing initiation than both LED and no-eHMI conditions ($p < .01$) but showed no significant difference between the AR and combined LED+AR condition ($t(39) = -0.18, p = 1$). These results support H1a, H1b and H1c by describing that participants initiated crossing fastest when presented with either the AR or the combined LED+AR eHMI communication design, followed by the LED condition. The longest crossing initiation times (CIT) were observed in the baseline scenario without any eHMI (no eHMI).

5.3. Perceived safety

Perceived safety plays a central role in pedestrian decision-making and trust in automated vehicle behavior - especially in traffic environments with limited rule-based structure such as shared spaces. We conducted two rmANOVAs to examine the effects of eHMI communication design and kinematics of the HAVs on perceived safety. The first one-factorial rmANOVA focused solely on the condition where both interacting HAVs yielded, assessing the influence of eHMI communication design alone. The second one was a two-factorial rmANOVA that included both eHMI communication design and HAV kinematics as factors across all experimental trials, allowing us to test for potential interaction effects. Across all conditions, perceived safety ratings were relatively high, ranging from $M = 4.40 (SD = 1.30)$ to $M = 6.48 (SD = 0.72)$ on a 7-point Likert scale (from 1 = "very unsafe" to 7 = "very safe").

First, the one-factorial rmANOVA with Greenhouse-Geisser correction revealed that the eHMI design did in fact have an influence on perceived safety, $F(2.52, 98.38) = 37.58, p < .001, \eta_p^2 = 0.49$. As predicted by H1a, post-hoc comparisons showed that, when HAVs displayed the LED ($M = 5.25, SD = 1.08$), AR ($M = 6.05, SD = 1.18$), or the combined LED+AR interface ($M = 6.48, SD = 0.72$), participants reported feeling significantly safer than with no eHMI at all ($M = 4.40, SD = 1.30; p < .001$ for all comparisons, see Table 1). Supporting H1b and H1c, perceived safety was significantly higher for the AR ($p = .008$) and combined LED+AR ($p < .001$) conditions than for only LED as eHMI. Finally, perceived safety was higher in the LED+AR than the AR condition ($p = .018$). Except for this last comparison, the pattern for perceived safety mirrored the results for CIT. Participants felt safest with combined LED+AR eHMIs, closely followed by AR, followed by the LED condition, and least safe when no eHMI was present.

Second, a subsequent two-factorial rmANOVA with Greenhouse-Geisser correction, examining both factors eHMI design and HAV kinematics, confirmed significant main effects for eHMI communication design, $F(2.78, 78.09) = 60.71, p < .001, \eta_p^2 = 0.61$, and HAVs' kinematics as vehicle kinematics for implicit communication, $F(2.17, 84.81) = 4.11, p = .017, \eta_p^2 = 0.10$, but no significant interaction effect of both, $F(1, 351) = 1.51, p = .166, \eta_p^2 = 0.04$. The results show that the influence of eHMI communication design on perceived safety did not depend on whether or not the HAVs yielded which is consistent with H2.

5.4. Mental workload

Mental workload was assessed to determine whether the combination of multiple eHMI signals (particularly the combined LED+AR interface) introduced any unintended cognitive burden during pedestrians' decision-making. Overall, subjective workload ratings were relatively low across all tested experimental conditions. On a 21-point Likert scale ranging from 0 ("very low") to 20 ("very high"), mean workload scores were 4.38 ($SD = 3.73$) for LED+AR, 4.63 ($SD = 3.06$) for AR, 7.23 ($SD = 3.83$) for LED, and 9.53 ($SD = 4.61$) for the no-eHMI condition.

Table 1
Descriptive Statistics for Perceived Safety by eHMI Variant and HAV kinematics.

HAV kinematics	No eHMI		LED		AR		LED+AR	
	M	SD	M	SD	M	SD	M	SD
None	4.45	1.18	4.80	1.38	5.48	1.34	5.75	1.35
Left	4.58	1.38	5.10	1.24	5.85	1.21	6.13	0.97
Right	4.55	1.28	4.95	1.36	6.00	0.89	6.00	0.88
Both	4.4	1.3	5.25	1.08	6.05	1.18	6.48	0.72
Overall	4.49	1.27	5.03	1.27	5.84	1.18	6.09	1.03

Note. $N = 40$. Means (M) and standard deviations (SD) for the pedestrians' crossings perceived safety ratings, separate for all combinations of the two factors eHMI communication design and HAV kinematics).

In traffic scenarios where both HAVs yielded, a rmANOVA with Greenhouse-Geisser correction indicated that the type of eHMI communication design significantly influenced the reported subjective mental workload, $F(2.42, 94.53) = 31.03, p < .001, \eta_p^2 = 0.44$. Pairwise post-hoc comparisons showed that all eHMI conditions significantly reduced reported mental workload compared to the no-eHMI baseline, confirming H1a. This effect was strongest for the AR ($p < .001$) and LED+AR ($p < .001$) conditions, and also present – though smaller – for the LED condition ($p = .014$). Consistent with H1b and H1c, both the AR and LED+AR eHMI communication designs significantly reduced reported mental workload compared to the LED condition (all $p < .001$). There was no significant difference in reported mental workload ratings between AR and LED+AR ($p = 1.00$), suggesting that the combination of both eHMI communication designs did not introduce different cognitive demand.

To examine whether the effects on mental workload were consistent across different HAV kinematics, i.e., vehicle kinematics as implicit communication, a second rmANOVA was conducted with both factors, i.e., eHMI communication design and the HAVs' kinematics as within-subject factors. This analysis revealed a significant main effect of the HAVs' kinematics, $F(3, 117) = 5.20, p < .01, \eta_p^2 = 0.12$, and a strong effect of eHMI communication design, $F(2.11, 82.35) = 41.18, p < .001, \eta_p^2 = 0.51$. Moreover, there was a significant interaction between eHMI communication design and HAV kinematics, $F(9, 351) = 2.57, p < .01, \eta_p^2 = 0.06$, indicating that the effectiveness of each eHMI depended on the HAV kinematics. Post-hoc tests for each yielding scenario provide mixed support for H2 since the LED condition offered a mental workload benefit over no eHMI exclusively when both HAVs yielded ($p = .014$). Crucially, when only one, or neither of the HAVs yielded, the LED interface no longer reduced pedestrians' mental workload, whereas the AR and combined LED + AR designs continued to deliver this benefit in these more demanding situations. All other pairwise comparisons remained consistent across all HAV yielding conditions, reflecting similar significance patterns as observed in the scenario where both HAVs yielded.

5.5. Understandability and predictability

Clear communication of each HAV's kinematics to ORUs is essential for safe and confident pedestrian-HAV interaction in shared traffic environments. In the absence of traditional manual driver cues, pedestrians must rely on alternative signals communicated by the HAV to infer each vehicle's intent. Therefore, this study assessed the perceived understandability and predictability of HAV behavior under different eHMI communication conditions. These measures reflect how effectively each eHMI conveyed the vehicle's intentions and whether its future driving behavior could be anticipated across varying traffic scenarios.

In experimental trials where both HAVs yielded, participants rated the combined LED+AR as the most understandable and predictable eHMI ($M = 6.49, SD = 0.84$), followed by the AR condition ($M = 6.15, SD = 0.91$). The LED eHMI received lower ratings ($M = 5.34, SD = 1.09$), while the no-eHMI condition was rated worst ($M = 3.40, SD = 1.18$). A rmANOVA (with Greenhouse-Geisser correction) revealed a significant main effect of eHMI communication design on participants' TiA ratings of understandability and predictability, $F(1.96, 76.45) = 101.37, p < .001, \eta_p^2 = 0.72$. Post-hoc comparisons showed significant differences between every pair of eHMI communication designs ($p < .001$ for all but one comparison), including the comparison between AR and combined LED+AR ($p = .004$). This result is consistent with the Hypothesis H1a, H1b and H1c.

To assess whether these effects were consistent across different HAV yielding scenarios, a second rmANOVA was conducted with eHMI communication design and HAV kinematics as within-subject factors. This analysis revealed significant main effects for the HAVs' kinematics, $F(2.34, 91.41) = 15.21, p < .001, \eta_p^2 = 0.04$, and eHMI communication design, $F(2.11, 82.41) = 151.34, p < .001, \eta_p^2 = 0.47$. In line with H2, there was no significant interaction between both factors, $F(9, 351) = 1.50, p = .148, \eta_p^2 = 0.04$.

Participants rated understandability and predictability significantly higher when both HAVs yielded ($M = 5.34, SD = 1.57$) compared to all other yielding scenarios involving only one or no yielding HAV ($p < .001$ for all comparisons). Among these non-fully-yielding conditions, no further significant differences emerged.

Across all HAV yielding scenarios, the AR ($M = 5.85, SD = 1.15$) and LED+AR ($M = 5.95, SD = 1.23$) conditions were rated significantly higher than the LED interface ($M = 4.85, SD = 1.30; p < .001$) and the no-eHMI baseline ($M = 3.14, SD = 1.21; p < .001$). No significant difference was found between the AR and LED+AR conditions ($p = .73$), suggesting that the combined interface did not further enhance clarity beyond the AR cues alone. However, the LED interface still outperformed the no-eHMI condition ($p < .001$).

6. Discussion

The present study investigated how different eHMI communication conditions used by multiple HAVs (no eHMI, LED, AR, and combined LED+AR) and varying HAV kinematics, i.e., vehicle kinematics, influenced pedestrian decision-making, perceived safety, and related human factors measures in a complex shared-space environment interacting with multiple relevant HAVs. These shared-space environments, heighten the need for clear, intuitive communication between pedestrians and HAVs. Our findings align with and extend the growing body of literature suggesting that eHMIs can facilitate clearer and more confident interactions between pedestrians as VRUs and HAVs, even under challenging conditions (Faas et al., 2020; Hesenius et al., 2018; Lau et al., 2022a, 2022b; Othersen et al., 2019; Praticò et al., 2021; Schieben et al., 2019; Tabone et al., 2023; Wilbrink et al., 2023; Wilbrink et al., 2021b).

In scenarios where both HAVs yielded (H1a), all eHMI conditions with explicit communication together with the implicit communication via vehicle kinematics led to faster crossing initiations, higher perceived safety, and increased understandability and predictability compared to no eHMI (together with only implicit communication via vehicle kinematics). In line with hypothesis H1a, this result was supported by the significant differences observed in our analyses, which aligns with previous findings that explicit cues enhance user confidence and reduce hesitation, especially in traffic scenarios and interactions with ambiguity.

H1b assumed that the AR-based eHMI will outperform the LED condition – not only in terms of perceived safety and crossing

initiation time (CIT), but also in mental workload, understandability, and predictability. This hypothesis was supported by significant improvements in all relevant metrics, indicating that AR can deliver context-sensitive information more effectively and addresses pedestrians' information needs more successfully than a single-modality LED system mounted on each HAV.

In line with hypothesis H1c, the significant advantage of the combined condition (LED+AR) confirms that integrating AR with a vehicle mounted LED eHMI can bring together both mediums' strengths enhancing user experience without overburdening them cognitively.

Furthermore, under varying kinematic conditions (e.g., only one HAV yielding, none HAV yielding), the presence of an eHMI (LED, AR, or LED+AR) improved perceived safety and contributed to higher understandability and predictability compared to the no-eHMI baseline. However, eHMI using only LED reduced mental workload only when both HAVs yielded. Once yielding became asymmetric, this benefit disappeared, whereas AR and LED + AR still kept workload low. Although not every result fully confirmed H2, the overall pattern shows that intention-based eHMIs deliver consistent benefits for pedestrians across a wide range of traffic dynamics.

The present findings contribute not only to the ongoing refinement of eHMI communication design for HAVs, but also to a broader understanding of Human-HAV interaction in more complex traffic scenarios. AR and combined LED+AR eHMIs significantly improved pedestrians' ratings with regard to perceived safety, understandability, and decision-making. These results highlight the importance of prospective multimodal communication strategies in future mobility systems, once the technology is ready to assist. Furthermore, they underscore the value of inclusive interface designs that accommodate both equipped and non-equipped users. As mobility ecosystems become more diverse and technologically layered, ensuring seamless and intuitive interaction will be essential for building trust and promoting equitable, safer shared spaces.

The superior performance of AR and the combined LED+AR eHMI underscores the potential of AR to enhance pedestrian understanding. By embedding spatial information directly into the user's field of view, AR fosters intuitive comprehension of HAV intentions and trajectories. However, AR remains less accessible and potentially more costly than vehicle-mounted LED solutions. Relying solely on AR to convey safety-critical information raises ethical concerns, as it may exclude non-equipped users and reinforce socioeconomic disparities. To address this, our findings suggest that a combined eHMI communication design offers a promising and inclusive solution. The LED light band provides a universally visible baseline for all ORUs, ensuring that essential information is accessible to everyone. AR can then act as an enhancement, delivering added spatial context to those equipped with smart glasses. This layered approach supports equitable access to safety cues while still leveraging the advanced capabilities of emerging technologies.

Despite concerns that multimodal interfaces could lead to information overload, our results show no increase in subjectively perceived mental workload in either the AR or combined (LED+AR) conditions. On the contrary, these interfaces facilitated quicker, more confident crossing initiations and enhanced subjective understandability and predictability. The absence of cognitive strain, along with improved decision-making, indicates that well-designed AR elements may effectively support users without overwhelming them or fostering undue reliance.

7. Limitations

Although VR-based experiments can sometimes negatively affect participants' well-being or reduce the ecological validity of the findings, this concern did not materialize in our study. Participants reported high well-being scores at the end of the session, suggesting that the virtual setting did not adversely impact their performance or subjective experience. While the present study focused on a concise set of subjective and behavioral measures, future work could benefit from more fine-grained VR presence or immersion assessments to further characterize user experience in complex shared-space scenarios. VR remains a valuable tool for safely testing complex interaction scenarios under controlled conditions. That said, transitioning from VR to real-world field studies remains a crucial next step. Future research should explore the practical deployment of especially AR-based eHMIs using augmented reality headsets in naturalistic settings. Second, the sample was recruited from a university environment, resulting in a predominantly young, educated, and technologically experienced participant group which limits the generalizability of the findings to the broader population. Such samples typically show higher familiarity with digital systems and may adapt more easily to VR and AR interfaces, which could lead to lower perceived workload and more confident interaction behavior compared to other population groups. Therefore, future research should extend eHMI evaluations to more diverse samples to ensure that AR- and LED-based communication strategies remain usable, interpretable, and beneficial across a wide range of demographic groups. Additionally, further work is needed to understand long-term user adaptation, including changes in trust, attention, and potential overreliance on eHMIs, especially when interacting in mixed traffic environments with multiple HAVs. Additionally, it will be important to investigate how these technologies scale across diverse user groups and contexts, considering differences in age, cognitive ability, cultural background, and levels of technology access. As HAVs become more prevalent, future research should also aim to define best practices for standardizing AR and LED integration in a way that ensures consistency, safety, and accessibility for all road users. While the present study relied on ANOVA-based analyses to examine within-subject differences across conditions, more advanced modelling techniques could further enrich this line of research. Classification models, such as logistic regression or random forests, may help predict pedestrians' crossing initiations based on a richer set of behavioral and subjective variables.

8. Conclusions

This study shows that AR-based eHMIs, particularly when combined with vehicle-mounted LED light bands, can significantly enhance pedestrian-HAV communication in low-speed, close-range situations where multiple HAVs and human road users must coordinate with few formal rules. The combined eHMI communication design fuses the strengths of both modalities, i.e., LED and AR: it

preserves universal accessibility (LED), avoids ethical risks of relying solely on AR, and does maintain low mental workload. Participants in the role of interacting pedestrians with multiple HAVs benefited from faster and more confident decision-making, as well as improved perceived safety and system understanding.

These findings highlight the potential of multi-modal, context-sensitive eHMI communication solutions for improving traffic safety and trust in automated traffic environments where pedestrians as VRU are interacting with multiple HAVs. As automated vehicles become more and more common on public roads, ensuring inclusive and intuitive communication with all road users (ORUs) will be crucial. Future research should focus on real-world validation, long-term user adaptation, and standardization across diverse mobility settings to ensure these technologies scale safely and equitably.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used ChatGPT4 in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRedit authorship contribution statement

Marc Wilbrink: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Conceptualization.
Michael Oehl: Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Ethics statement

Ethical approval was obtained from the German Aerospace Center's (DLR) ethical board (15/23), and informed consent was collected from all participants before the study commenced.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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