

Learning a Simple Directional eHMI: A VR Study of AV-Pedestrian Interaction

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External Human-Machine Interfaces (eHMIs) for automated vehicles must remain quickly interpretable if they are to scale to realistic traffic. This study examines a deliberately simple directional light-based windshield eHMI as a first step toward that goal. The eHMI uses a minimal light strip whose highlighted segment shifts based on the pedestrian's relative position, aiming to convey yielding intent without text or complex visual elements. In a virtual-reality study with 30 participants, pedestrians encountered an automated vehicle with and without the eHMI; half received a brief onboarding video, while the others learnt through repeated exposure. Results suggest that the eHMI supported earlier crossing initiation and increased perceived safety and trust. Onboarding produced immediate benefits, whereas participants without onboarding showed gradual improvements over repeated encounters. These findings indicate that the signal is learnable in a controlled dyadic setting and motivate future VR studies of multi-pedestrian interaction, social influence, and traffic complexity.

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1 Introduction

As automated vehicles (AVs) become part of public traffic, pedestrians must judge whether a vehicle has detected them, intends to yield, and can be safely crossed in front of. In human-driven traffic, such judgments are informed by vehicle motion and social cues, such as eye contact, gaze, and gestures [9, 16, 17, 19]. With driverless vehicles, some of the cues may be reduced or absent, motivating research into external Human-Machine Interfaces (eHMIs) to communicate vehicle intent. However, eHMIs should not be treated as necessary or beneficial in all encounters. Vehicle kinematics remain a primary communication cue, and any external signal should complement, rather than replace, safe and legible yielding behaviour [12, 14]. The central question is therefore when an external cue can support pedestrians' interpretation of AV intent without encouraging misplaced confidence.

Prior eHMI research has explored a wide range of visual concepts, including text, symbols, projections, and light-based signals [2, 5, 8, 18]. Text-based eHMIs can communicate explicitly, but they are language-dependent, require legibility under time pressure, and may raise concerns when they appear to instruct pedestrians what to do [2, 7]. Light-based eHMIs are visually lightweight and language-independent, but their meaning may be less immediately obvious, especially to pedestrians encountering the signal for the first time [4, 5, 10, 11]. This creates a design challenge for AV-pedestrian communication: external signals should be simple enough to scale across traffic contexts, yet informative and learnable enough to support pedestrians' interpretation of vehicle intent.

This challenge becomes more pronounced in realistic traffic, where pedestrians may need to monitor multiple vehicles, other pedestrians, cyclists, occlusions, and competing motion cues. In such settings, visually rich or highly specific eHMIs may not scale well, because pedestrians may need to interpret signals from several vehicles while

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53 also observing the behaviour of surrounding road users. Simplicity is therefore not merely a design preference, but a
54 potential requirement for eHMIs intended to function in multi-agent traffic.

55 Directional light-based eHMIs offer one possible way to preserve simplicity while adding contextual information.
56 Rather than only indicating that an AV is yielding, a directional signal may help pedestrians understand how the
57 vehicle’s yielding behaviour relates to their own position. This is especially relevant for real traffic scenarios, where the
58 key ambiguity may not only be whether the vehicle will stop, but also for whom it is stopping: an individual pedestrian,
59 another nearby pedestrian, or a group. At the same time, this potential cannot be fully evaluated in a dyadic setting
60 with only one pedestrian, where the yielding target is usually obvious. A necessary preliminary step is therefore to
61 examine whether pedestrians can first interpret and learn the basic meaning of such a signal in a controlled encounter.
62

63 In this paper, we present a VR study of a deliberately simple directional light-based windshield eHMI. The eHMI
64 consists of a minimal light strip positioned at the bottom of the windshield. When the AV yields, a highlighted segment
65 shifts along the horizontal axis according to the pedestrian’s relative position. The design avoids text and complex
66 visual elements while aiming to provide more contextual information than a coarse go/no-go signal. We treat the eHMI
67 as a design probe: its purpose in the present study is to test whether a simple directional signal is interpretable and
68 learnable enough to justify further investigation in more realistic traffic scenarios.
69

70 We evaluated the eHMI in a one-on-one VR yielding scenario. The participants encountered an AV with and without
71 the eHMI; half received a brief onboarding video explaining the signal, while the other half encountered the signal
72 without explanation and could only learn through repeated exposure. We measured crossing initiation time as an
73 action-proximal indicator of when pedestrians committed to crossing, and perceived safety and trust as subjective
74 indicators of interaction quality. In this controlled setting, the eHMI supported earlier crossing initiation and increased
75 perceived safety and trust. Onboarding produced immediate benefits, whereas participants without onboarding showed
76 gradual improvements across repeated encounters, consistent with prior work showing that familiarity and repeated
77 exposure shape how pedestrians interpret eHMIs [3, 13–15]. These findings suggest that the simple directional signal
78 was interpretable and learnable in a controlled dyadic encounter. However, we do not interpret earlier crossing or
79 higher trust as evidence of improved safety in general, given the complexity of real traffic.
80

81 This study makes three contributions. First, we present a deliberately simple directional light-based eHMI designed
82 with future multi-agent scalability in mind. Second, we report evidence that pedestrians can learn the signal through
83 either brief onboarding or repeated exposure in a controlled dyadic VR encounter. Third, we outline the next stage of
84 this research. By positioning the current study as a first step rather than a final validation, this work contributes to the
85 AutomotiveUI discussion on how eHMIs should be designed and evaluated as AV–pedestrian interaction moves from
86 isolated encounters toward complex traffic ecologies.
87

88 2 The VR Study

89 2.1 Study Design and Apparatus

90 The study used a mixed design. Onboarding was manipulated between participants: half of the participants received a
91 short explanation of the eHMI before the VR task, whereas the other half did not. eHMI presence was manipulated
92 within participants, such that each participant encountered the AV both with and without the eHMI. The full experiment
93 also included yielding and non-yielding trials; the present WIP focuses on yielding encounters, where crossing initiation
94 time, perceived safety, and trust are most directly interpretable as responses to the AV’s yielding intent. The trials were
95 presented in randomised order across two experimental blocks, separated by a short break. Each participant completed
96

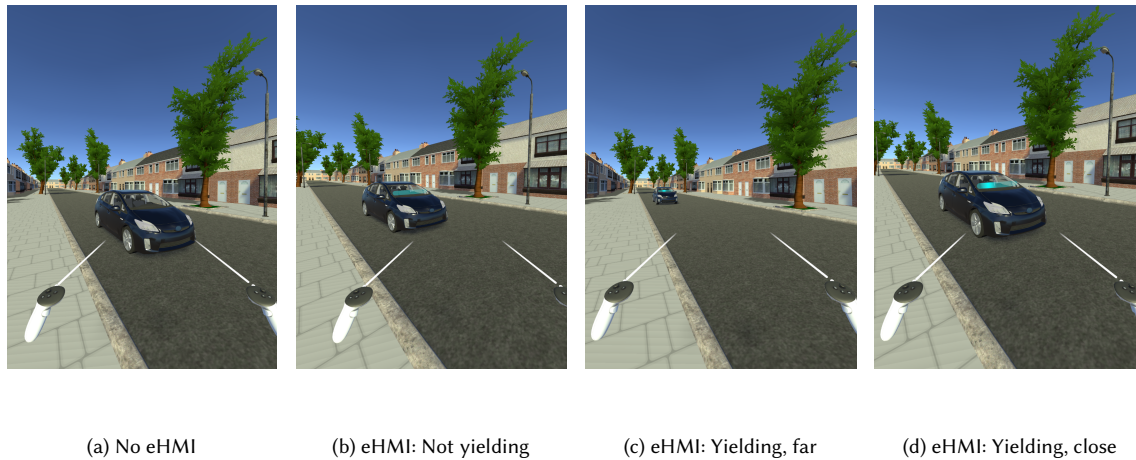


Fig. 1. Interface Conditions

32 experimental trials after two familiarisation trials. The VR environment was adapted from a previous study [1], implemented in Unity 2022.3.5f1, and presented using a Meta Quest 3 headset.

2.2 Directional eHMI and Onboarding

The eHMI was implemented as a cyan light strip positioned at the bottom of the AV's windshield (see Figure 1). When the vehicle was not yielding, the strip remained faintly illuminated across its full width, indicating that the interface was active but not communicating yielding intent. When the vehicle yielded, a segment of the strip brightened and shifted horizontally according to the pedestrian's relative position. From the pedestrian's perspective, this created a simple directional cue linking the AV's yielding behaviour to the pedestrian's location.

Participants in the onboarding condition watched an approximately three-minute video before the VR task. The video explained the meaning of the non-yielding and yielding states of the eHMI and illustrated how the highlighted segment moved relative to the pedestrian. Participants in the no-onboarding condition did not receive this explanation, allowing us to examine whether the signal could also be learnt through repeated exposure.

2.3 Participants and Procedure

Thirty participants took part in the study. The sample included 19 males and 11 females, aged 20–60 years ($M = 27.6$, $SD = 10.0$, median = 25). Participants were recruited through the researchers' networks and a local participant database and received monetary compensation. The study was approved by the Ethics Review Board of the University. A sensitivity analysis indicated that the sample size was sufficient to detect approximately medium within-participant effects, but only relatively large between-participant effects; onboarding-related contrasts should therefore be interpreted with appropriate caution.

After giving their informed consent, the participants received a standardized explanation of the study and completed the baseline trust questionnaire. Participants in the onboarding condition then watched the pre-recorded explanation video, whereas those in the no-onboarding condition proceeded directly to the VR task. Before the main experiment, all participants completed two familiarisation trials without the eHMI: one non-yielding trial and one yielding trial. The participants then completed two experimental blocks separated by a five-minute break. After the first block, they

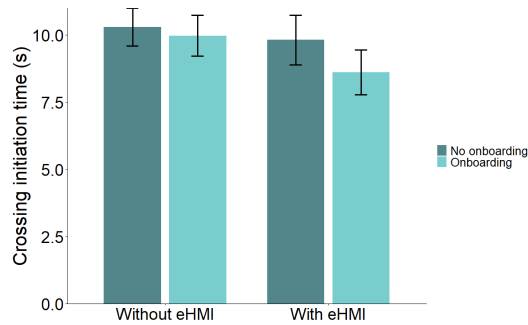


Fig. 2. Mean crossing initiation time by eHMI condition and onboarding group. Lower values indicate earlier pedestrian decisions. Error bars represent 95% confidence intervals.

completed the vehicle-specific trust questionnaires, which were administered again after the second block. The full session lasted approximately 45–60 minutes.

2.4 Measures and Analysis

We focused on one behavioural measure and two subjective measures. The behavioural measure was crossing initiation time, defined as the timestamp of the first full controller-button press indicating that the participant felt safe to cross. This measure captures when pedestrians committed to crossing in response to the AV’s yielding behaviour. The subjective measures were perceived safety and trust, each rated after every trial on 7-point Likert scales presented in VR. Participants also completed a 7-item trust questionnaire at baseline, during the break, and after the second block; it served as a broader measure of trust in the AV.

Data were pre-processed in Python and analysed using linear mixed-effects models to account for repeated observations nested within participants. For the initiation time, six observations were excluded because the participants either accidentally pressed the button or reported responding only after the vehicle had nearly left; all other observations were retained. In the main models, the eHMI presence, onboarding condition, and trial number were included as fixed effects, together with relevant interaction terms, and participant was included as a random intercept. Separate models were fitted for crossing initiation time, perceived safety, and trust. For the questionnaire-based trust measure, negatively worded items were reverse-coded and averaged to form a composite score after confirming acceptable internal consistency. Statistical significance was evaluated at $\alpha = .05$ and 80% power; the design is powered to detect an approximately medium within-participants effect and a large between-participants effect.

3 Results

3.1 Crossing Initiation Time

Figure 2 shows that the crossing initiation times were lower when the eHMI was present than when no eHMI was shown, indicating earlier pedestrian decisions in the eHMI condition. This reduction was more pronounced for participants who received onboarding. In the no-onboarding group, the difference between eHMI and no-eHMI was modest, whereas in the onboarding group, the eHMI was associated with a clearer reduction in crossing initiation time.

A linear mixed-effects model supported this descriptive pattern. The proposed eHMI significantly reduced crossing initiation time ($b = -0.48$, $SE = 0.11$, 95% CI $[-0.70, -0.26]$, $z = -4.28$, $p < .001$). Trial number also had a significant

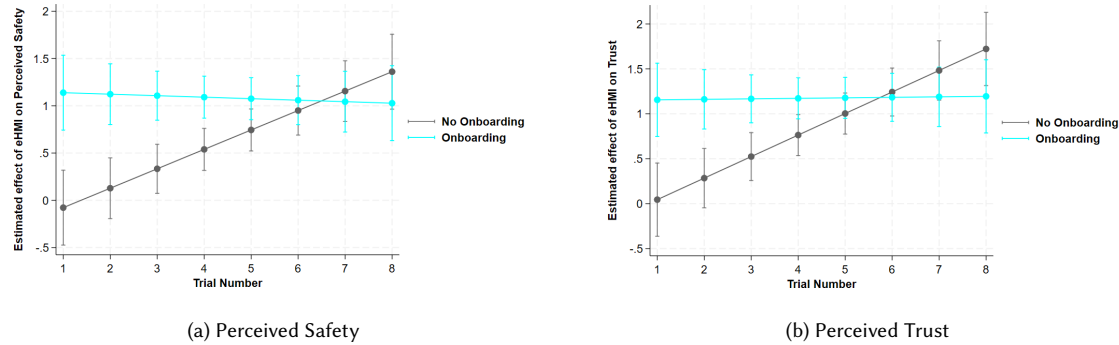


Fig. 3. Estimated marginal effect of eHMI on perceived safety and trust across repeated trials, separately for the no-onboarding and onboarding groups. Values above zero indicate that eHMI increased perceived safety or trust relative to the no-eHMI condition. Error bars represent 95% confidence intervals.

effect ($b = -0.11$, $SE = 0.02$, 95% CI $[-0.14, -0.07]$, $z = -6.22$, $p < .001$), indicating that participants initiated crossing earlier over repeated encounters. The main effect of onboarding was not significant ($b = -0.33$, $SE = 0.49$, 95% CI $[-1.30, 0.64]$, $z = -0.67$, $p = .506$). Importantly, there was a significant interaction between the eHMI and onboarding ($b = -0.87$, $SE = 0.16$, 95% CI $[-1.18, -0.56]$, $z = -5.51$, $p < .001$), indicating that the effect of the eHMI was stronger for participants who received prior explanation of the interface. Pairwise comparisons further clarified this interaction. In the no-onboarding group, eHMI reduced crossing initiation time by 0.48 s ($SE = 0.11$, 95% CI $[-0.70, -0.26]$, $z = -4.28$, $p < .001$). In the onboarding group, the corresponding reduction was 1.35 s ($SE = 0.11$, 95% CI $[-1.57, -1.13]$, $z = -12.12$, $p < .001$). Onboarding significantly reduced crossing initiation time only when eHMI was present ($b = -1.20$, $SE = 0.49$, 95% CI $[-2.17, -0.23]$, $z = -2.43$, $p = .015$), but not when it was absent ($b = -0.33$, $SE = 0.49$, 95% CI $[-1.30, 0.64]$, $z = -0.67$, $p = .506$). These results indicate that our eHMI supported earlier pedestrian crossing decisions overall, while onboarding substantially strengthened this behavioural benefit.

3.2 Perceived Safety and Trust

Figure 3a shows that the effect of the proposed eHMI on perceived safety differed markedly between the onboarding and no-onboarding groups. In the onboarding group, the eHMI produced a clear and stable positive effect on perceived safety from the first trial onward. In contrast, in the no-onboarding group, the effect of the eHMI was initially close to zero, but increased steadily over repeated encounters. By later trials, the estimated safety benefit of eHMI in the no-onboarding group approached and slightly exceeded that observed in the onboarding group. This pattern suggests that onboarding enabled participants to benefit from eHMI immediately, while participants without onboarding gradually learnt to interpret the signal through repeated exposure. A linear mixed-effects model supported this descriptive pattern. The main effect of the eHMI was not significant ($b = -0.28$, $SE = 0.24$, 95% CI $[-0.76, 0.20]$, $z = -1.16$, $p = .246$), whereas onboarding showed a significant main effect ($b = -0.86$, $SE = 0.41$, 95% CI $[-1.66, -0.06]$, $z = -2.10$, $p = .036$). Importantly, there was a significant interaction between the eHMI and onboarding ($b = 1.44$, $SE = 0.35$, 95% CI $[0.76, 2.11]$, $z = 4.17$, $p < .001$). Trial number also had a significant effect ($b = -0.13$, $SE = 0.03$, 95% CI $[-0.20, -0.07]$, $z = -3.92$, $p < .001$). In addition, both the eHMI \times trial number interaction ($b = 0.21$, $SE = 0.05$, 95% CI $[0.11, 0.30]$, $z = 4.25$, $p < .001$) and the onboarding \times trial number interaction ($b = 0.12$, $SE = 0.05$, 95% CI $[0.02, 0.21]$, $z = 2.45$,

p = .014) were significant. These effects were further qualified by a significant three-way interaction between the eHMI, onboarding, and trial number ($b = -0.22$, $SE = 0.07$, 95% CI [-0.36, -0.09], $z = -3.24$, $p = .001$).

For the 7-item trust questionnaire (3 data collection points: baseline, during break, after the second block), a linear mixed-effects model that included eHMI, onboarding, and survey timing showed a strong positive effect of eHMI on trust ($b = 1.58$, $SE = 0.13$, $z = 12.54$, $p < .001$). In contrast, neither onboarding ($b = 0.09$, $SE = 0.24$, $z = 0.38$, $p = .706$) nor survey timing (break vs. end of the experiments) ($b = 0.01$, $SE = 0.13$, $z = 0.08$, $p = .940$) had a significant effect. These results indicate that the eHMI substantially increased the overall trust, whereas repeated exposure and prior explanation did not significantly alter these impressions of more global trust.

A different pattern emerged for trial-level trust ratings. Figure 3b shows that, in the onboarding group, eHMI produced a clear and stable positive effect on trust from the first trial onward. In contrast, in the no-onboarding group, the effect of eHMI was initially small and non-significant, but increased steadily over repeated encounters. A linear mixed-effects model supported this descriptive pattern. The main effect of eHMI was not significant ($b = -0.20$, $SE = 0.25$, $z = -0.78$, $p = .437$), while the registration showed a significant negative main effect ($b = -1.10$, $SE = 0.44$, $z = -2.49$, $p = .013$). Importantly, there was a significant interaction between the eHMI and onboarding ($b = 1.35$, $SE = 0.35$, $z = 3.79$, $p < .001$). Trial number also had a significant effect ($b = -0.14$, $SE = 0.04$, $z = -4.11$, $p < .001$). In addition, both the eHMI \times trial number interaction ($b = 0.24$, $SE = 0.05$, $z = 4.82$, $p < .001$) and the onboarding \times trial number interaction ($b = 0.15$, $SE = 0.05$, $z = 2.95$, $p = .003$) were significant, and these effects were qualified by a significant three-way interaction between eHMI, onboarding, and trial number ($b = -0.23$, $SE = 0.07$, $z = -3.33$, $p = .001$).

4 Discussion

The clearest behavioural effect was observed for crossing initiation time. Participants initiated crossing earlier when the eHMI was present, particularly after receiving onboarding. This indicates that the signal helped pedestrians decide more quickly that the vehicle was yielding. However, earlier crossing should not be treated as inherently safer. In the present study, the AV yielded consistently, the vehicle kinematics were held constant, and no surrounding vehicles or pedestrians were present. Under these conditions, earlier crossing can reasonably be interpreted as faster decision-making in response to a predictable yielding event. In real traffic, the same behaviour would need to be evaluated in relation to actual traffic safety, surrounding road users, and possible conflicts.

The subjective measures further highlight the role of learnability. Participants who received onboarding showed immediate improvements in perceived safety and trust when the eHMI was present. Participants without onboarding showed little or no early benefit, but their perceived safety and trust increased across repeated encounters. This pattern suggests that the signal was not fully self-explanatory at first exposure, but could be learnt through experience. Onboarding, therefore, appeared to accelerate interpretation rather than create an effect that would not otherwise have emerged. This is important for simple non-textual eHMIs: they may not need extensive training, but their first-use benefits may depend on explanation, repeated exposure, or future standardisation.

These findings support the value of simplicity as a design principle, especially when considering future traffic complexity. In a one-on-one interaction, a more detailed or explicit signal may be easier to interpret. However, in real traffic, pedestrians may need to monitor several vehicles, other pedestrians, cyclists, occlusions, and vehicle motion cues simultaneously. A visually complex eHMI may therefore become difficult to scale. The present design intentionally uses a minimal light strip and avoids text or complex visual elements. The results suggest that such a simple signal can be learnt in a controlled setting, providing a basis for testing whether the same design logic remains interpretable when traffic becomes more complex.

313 The directional nature of the signal is also more relevant to future multi-pedestrian scenarios than to the current
314 dyadic setting. In the present study, there was only one pedestrian, so the target of the AV's yielding behaviour was
315 relatively clear. In realistic traffic, the key ambiguity may be different: pedestrians may need to judge whether the
316 AV is yielding to them, to another pedestrian, or to a group. This is where a directional eHMI could offer additional
317 value. The next stage of this work will therefore extend the VR environment to include multiple pedestrians and more
318 surrounding traffic. This will allow us to examine whether the directional signal helps pedestrians identify the intended
319 recipient of the AV's yielding behaviour.
320

321 A further direction concerns pedestrian group behaviour and social influence. Pedestrians rarely make crossing
322 decisions in isolation; they may follow, hesitate because of, or be reassured by the behaviour of others. In a group setting,
323 an eHMI may influence not only the individual pedestrian who sees the signal, but also nearby pedestrians who observe
324 that person's response. This raises several questions for future work: Does the eHMI change who initiates crossing first?
325 Does one pedestrian's crossing decision encourage others to follow? Does the signal reduce uncertainty in groups, or
326 could it amplify over-trust through social imitation? Addressing these questions would move eHMI evaluation beyond
327 individual interpretation and toward the social dynamics of pedestrian crossing.
328

329 Finally, future work should examine calibration between eHMI signals, vehicle motion, and surrounding traffic. The
330 present study used consistent yielding behaviour, which was appropriate for testing basic learnability but insufficient
331 for evaluating safety-critical use. More realistic VR scenarios should include varied braking profiles, multiple vehicles,
332 delayed or inconsistent eHMI signals, and situations where another vehicle may create risk even when the AV itself
333 yields. Such scenarios would help determine whether the eHMI supports appropriate trust or encourages premature
334 crossing. In this sense, the current study provides a foundation rather than a conclusion: it shows that the simple
335 directional signal can be learnt, and it motivates the more important next question of whether that learnt interpretation
336 remains useful and appropriately calibrated in complex traffic.
337

338 5 Limitations and Conclusion

339 This study has several limitations. The VR scenario involved a single AV and a single pedestrian, without surrounding
340 vehicles, pedestrian groups, occlusions, or competing traffic cues. Vehicle kinematics were also held constant across
341 yielding trials, which helped isolate the effect of the eHMI but may have made the vehicle's behaviour easier to
342 anticipate over repeated encounters. In addition, the onboarding manipulation was tested with a relatively small
343 between-participants sample, so onboarding-related findings should be interpreted with caution. Finally, the study
344 compared the directional eHMI only with a no-eHMI baseline, and therefore cannot determine whether this design
345 performs better than other light-based, symbolic, textual, or motion-based communication approaches.
346

347 Despite these limitations, the present study provides a useful first step for the proposed research direction. The
348 findings suggest that a simple directional light-based eHMI can be interpreted and learnt in a controlled one-on-one
349 VR yielding encounter, with onboarding accelerating early interpretation and repeated exposure supporting learning
350 without explicit explanation. These results do not establish real-world safety or deployment readiness, but they motivate
351 the next stage of work: evaluating whether the same simple directional logic remains interpretable and appropriately
352 calibrated in more realistic VR traffic involving multiple vehicles, multiple pedestrians, and pedestrian group behavior.
353

354 6 Supplementary Material

355 Following open science practices and transparency recommendations in automotive user research [6], the authors
356 openly share study artefacts to support reproducibility and collaboration. The simulator and analysis code, as well
357

as the materials used in the experiment, are available at https://www.dropbox.com/scl/fo/wp4hsxv4jknzmpnos7q9c/AD2qe_I69lrc0Qje09nyg3A?rlkey=zrne0tckku91g6q9xy3o86azv.

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