

# Distance-Dependent eHMIs for the Interaction Between Automated Vehicles and Pedestrians

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# Distance-Dependent eHMIs for the Interaction Between Automated Vehicles and Pedestrians

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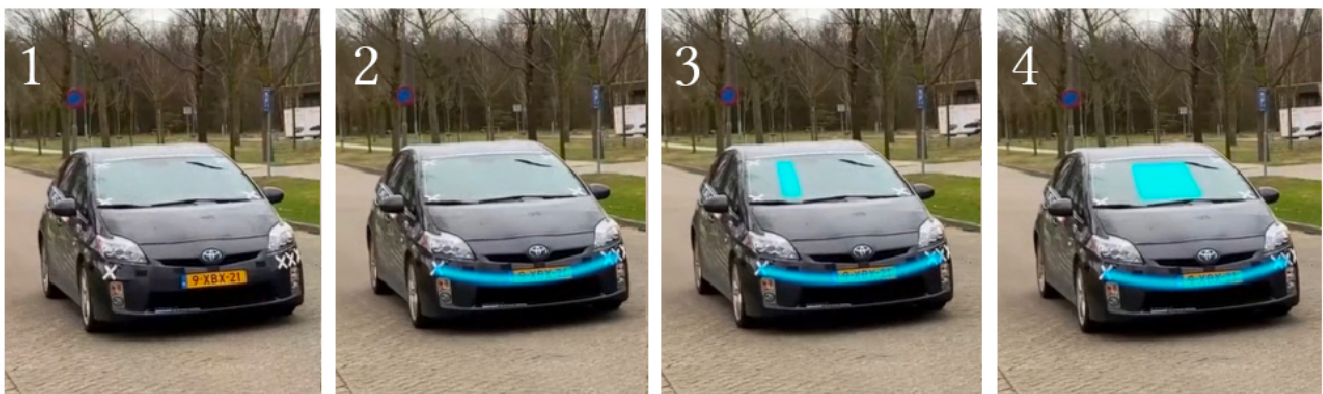
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**Figure 1:** We conducted a video-based study comparing 4 different conditions of eHMIs; left to right: (1) *no eHMI*, (2) a *bumper eHMI* announcing the vehicle's yielding intent without any additional information, (3) a bumper eHMI supplemented by a windshield display showing the vehicle's *situational awareness* of the pedestrian's location, & (4) a bumper eHMI supplemented with a windshield display showing a *progress bar* regarding when and where the vehicle will stop.

## ABSTRACT

External human-machine interfaces (eHMIs) support automated vehicles (AVs) in interacting with vulnerable road users such as

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pedestrians. While related work investigated various eHMIs concepts, these concepts communicate their message in one go at a single point in time. There are no empirical insights yet whether distance-dependent multi-step information that provides additional context as the vehicle approaches a pedestrian can increase the user experience. We conducted a video-based study ( $N = 24$ ) with an eHMI concept that offers pedestrians information about the vehicle's intent without providing any further context information, and compared it with two novel eHMI concepts that provide additional information when approaching the pedestrian. Results show that additional distance-based information on eHMIs for yielding vehicles enhances pedestrians' comprehension of the vehicle's intention

and increases their willingness to cross. This insight posits the importance of distance-dependent information in the development of eHMIs to enhance the usability, acceptance, and safety of AVs.

## CCS CONCEPTS

• **Human-centered computing** → **Interaction design**; *Interaction techniques*.

## KEYWORDS

Automated vehicles; eHMIs; VRU; pedestrians; vehicle-pedestrian interaction

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## 1 INTRODUCTION

In the absence of a human driver, external human-machine interfaces (eHMIs) are expected to facilitate automated vehicles (AVs) to communicate with vulnerable road users (VRUs). There are numerous approaches to eHMIs; examples include projections [4, 31, 37], displays [13, 21, 23, 28], light-bands [18, 20, 41], and more [3, 10, 39]. Existing eHMI concepts vary from each other on account of different modalities or in the nature and content of the message. Prior work suggests that the eHMI of an automated vehicle should not issue an instruction, advise, or call-to-action towards a pedestrian, but rather communicate its own intent [19, 22]. However, even within this specification, there are no empirical insights yet on the nature or content of the ‘intent-to-yield’ message that an eHMI should communicate.

Most eHMI concepts that follow this recommendation simply announce the vehicle’s stopping or yielding intention. Literature shows that eHMIs communicating this intention perform better than vehicle without any eHMI [5, 6] in reducing pedestrians’ ambiguities about the vehicle’s yielding intention.

However, previous research into the theory of pedestrian behavior showed that pedestrians exhibit a specific distance-dependent gaze pattern when observing oncoming (manually driven) vehicles [12]. It shows that at a distance, pedestrians tend to look at the grill or bumper of the vehicle to make road-crossing decisions. As the car approaches, the gaze shifts towards the windshield. Taking this into account, we posit that the kind of information pedestrians look for and the point of reference change with the remaining distance/time-to-arrival of the vehicle. Although prior work answers ‘where’ pedestrians look to make road-crossing decisions, the question ‘why’ they do so (i.e. which kind of information pedestrians look for) remains unanswered. It is possible that today pedestrians seek to identify the drivers’ intent and verify their situational awareness to understand where/for whom the car will stop and whether the driver has seen the pedestrian. An ideal interface catering to such a user behavior will provide relevant information in the moment and context it is desired. This is, in principle, similar to

other distance-dependent, context-based interfaces explored in the past in different domains, such as the Hello.Wall concept [34] – an ambient art display that provides contextually relevant information to the user as their distance from the interface changes. Extending this to eHMIs, the goal of our research is to evaluate the merit of designing an eHMI that offers communication in phases. Such an eHMI could offer a general message about its yielding intention at a distance and furnish more specific contextual information (e.g. whom it is yielding to, or where it will stop) as it comes closer. This may address any ambiguities that arise from an eHMI that only announces its yielding intention without any further clarification as to the context of the yielding message.

To this end, we designed a two-part eHMI that adds contextual details to the nature and the content of the communication based on the distance/ time-to-arrival to the pedestrian. We evaluate its efficacy compared to a single-fire eHMI which only offers the same message irrespective of distance. In a video-based study (N = 24), we compared the effects of an approaching AV under four conditions as shown in Figure 1: (1) no eHMI, (2) a single-fire eHMI that only provides information about the vehicle’s yielding intention, (3) an eHMI that combines a static yielding intention with showing the vehicle’s situational awareness of pedestrians around it, and (4) an eHMI that combines a static yielding intention with showing an estimation of when and where the vehicle will stop.

Our results show that a two-part eHMI with additional distance-based information helps pedestrians to better comprehend the intention of the vehicle and resolve ambiguity. The participants perceive both eHMIs with distance-based contextual information as more helpful than eHMIs without contextual information, and any kind of eHMI provides a better experience than an AV without an eHMI. Additionally, quantitative data also indicate that providing the vehicle’s situational awareness works better as contextual information than presenting the vehicle’s stopping point.

We postulate that presenting more contextually relevant information on eHMIs based on distance or time-to-arrival of an AV can significantly improve the usability and user experience of pedestrians’ interacting with AVs.

*Contribution Statement.* To our knowledge, this is the first work that empirically tests the impact of eHMIs providing distance-based information to pedestrians. We found that distance- or time-to-arrival-based contextual information in eHMIs which clarify the yielding intent of an approaching AV aids the usability and improves the user experience of interactions between pedestrians and AVs over eHMIs that do not provide such additional context. This can assist the design of eHMIs to improve the communication between AVs and pedestrians.

## 2 eHMI CONCEPTS

Adhering to the best-practices of user-centered design, an ideal communication interface should offer the right information at the right place and time – communication must take place when and where it is expected by the user. To our knowledge, there are no existing concepts or empirically validated studies on distance-based eHMIs. Therefore, we base our concepts on existing eHMI recommendations and on findings regarding current pedestrian behavior:

Recent research by Eisma et al. [14] showed that the bumper, windshield, or the roof of a vehicle are the most effective locations for an eHMI. Furthermore, Dey et al. [12] showed that in order to make road-crossing decisions, pedestrians looked at the bumper of the vehicle at a distance, and shifted their fixations to the windshield when the vehicle comes closer. Thus, we decided to use the bumper to show the general intent-communication interface at a distance, and the windshield to proximally show additional information clarifying the context of the vehicle’s yielding intention. To evaluate the influence of distance-based eHMIs, we designed three concepts that we explain in detail below.

## 2.1 Bumper eHMI – Pulsating light Bar on Bumper

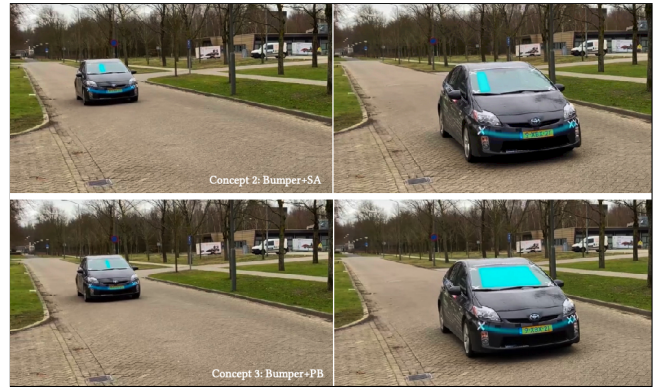
This concept represents an iteration of prior ‘light band’ concepts [10, 20, 41] and it integrates insights from prior research [8, 15] which show that a uniform pattern like a pulsing animation is a good solution for showing yielding intention. The eHMI is a one-dimensional light bar mounted on the bumper of the vehicle. When the car drives in automated mode, it glows in a solid, turquoise color. When the car intends to yield, it pulsates in a sinusoidal pattern (the entire light bar alternately dims and glows). When the car wants to start driving again, the light bar returns to a steady glowing state. While the pulsating eHMI conveys the vehicle’s yielding intention in general, it does not provide any additional information regarding whom the vehicle is yielding to or when / where it will come to a stop. In essence, the pulsating eHMI tells the pedestrian, “I am yielding”.

The subsequent two eHMIs (*Bumper+SA* and *Bumper+PB*) add in the element of distance-based contextual information on the windshield.

## 2.2 Bumper+SA eHMI – Light bar & Windshield “Situational Awareness” Display

This concept extends the light bar eHMI on the bumper as described in the *Bumper* eHMI, which again shows the overall yielding intention of the vehicle. Subsequently, an additional windshield eHMI activates when the car is at a certain closer distance from the pedestrian. This interface provides additional information about the car’s yielding intention. In this case, it informs the pedestrian about the vehicle’s situational awareness regarding whom the vehicle is yielding to. In essence, this concept tells the pedestrians “I have seen you and I am yielding”. We developed this concept by taking inspiration from other ‘*tracker*’ eHMIs as proposed in prior work [10, 32, 40].

The interface on the windshield is a light segment, which only activates at a closer distance to provide further contextual information while yielding: a part of the windshield lights up corresponding to the relative position of the pedestrian with respect to the car to show that the car has recognized the pedestrian and wants to yield to them (Figure 2 - top). During this time, the light bar on the bumper continues to pulsate. As the car comes closer to the pedestrian while slowing down, the light on the windshield moves across the windshield to reflect the change in the relative position between the car and the pedestrian. When the car intends to start driving again, the windshield interface deactivates, and the light bar on the bumper returns to a solid glow. Thus, at a closer proximity,



**Figure 2: Top row: *Bumper+SA*** – The light bar in the bumper pulsates as the vehicle is yielding. The windshield shows the AV’s situational awareness by reflecting the position or the location of the pedestrian with respect to the car, and informs whom the car intends to yield to. As the car approaches the visualization on the windshield moves accordingly to map to the pedestrian’s relative location.

**Bottom row: *Bumper+PB***– The light bar in the bumper pulsates as the vehicle is yielding. Additionally, the windshield displays a progress bar that fills up in the windshield as an indication of when the vehicle will come to a complete stop. The linear growth of the windshield visualization – from empty to full – reflects the slowing of the car, and offers observers an estimate of when the car will come to a complete stop.

the windshield interface gives the pedestrian(s) more detailed information on the situational awareness, i.e., the fact that the vehicle is aware of the pedestrian, and the yielding intention of the car.

## 2.3 Bumper+PB eHMI – Light Bar & Windshield “Progress Bar” Display

This concept, too, extends the light bar eHMI on the bumper as described in the *Bumper* eHMI. The light bar still activates to show the yielding intention of the vehicle. Similar to *Bumper+SA*, additional information is provided by a second windshield eHMI that activates when the car is at a certain closer distance from the pedestrian. We use the form of a linear progress bar to give the observers an estimate of when the car will come to a complete stop. In essence, this concept tells the pedestrians “I am yielding and here is an estimate of when I will come to a full stop”. We developed this concept by iterating on prior ‘*countdown timer*’ eHMI concepts which, however, did not take the context into account. [1, 10, 20].

The windshield interface shows a vertical band of light that originates from the center of the windshield and expands horizontally as the vehicle approaches the stopping point. When the entire windshield is lit up, the car is at rest. The idea behind this concept is that the windshield interface can act as a kind of ‘timer’: an observer can estimate when the car will come to a complete stop by mapping the windshield progress bar to the actual position of the car on the road as illustrated in Figure 2. The windshield interface stays lit (glowing steadily) as long as the car is yielding and the light bar on



the bumper continues to pulsate. When the car intends to start driving again, the windshield interface diminishes in size and turns off. Subsequently, the light bar on the bumper returns to a solid glow. Thus, as the car intends to start driving, the windshield interface once again acts as a timer for the pedestrian giving information regarding how long will it take until the car starts driving again.

## 2.4 Research Question & Hypothesis

We use the presented eHMI concepts to evaluate the efficacy of providing distance- or time-to-arrival-based contextual information to pedestrians about the intention of the AV to answer the following research question:

*Does a step by step, two-part eHMI communication – where general information about the AV’s intent is offered distally, and more specific information clarifying the context of the message is provided at a closer proximity – help the efficiency of the interaction between an AV and a pedestrian compared to a generic communication of the AV’s intent decoupled from contextual information?*

Based on prior research [12] which showed that pedestrians tend to look towards the driver of an oncoming vehicle as the vehicle is approaching, we speculate that pedestrians seek additional confirmatory information about the vehicle’s action. Consequently, we hypothesize that providing additional information when the vehicle approaches will address this communication gap and increase pedestrians’ confidence in the vehicle’s intent and action.

*H1: The Bumper+SA and Bumper+PB eHMIs will yield a better user experience in terms of reducing ambiguity regarding the vehicle’s intentions than the base Bumper eHMI.*

*Rationale.* The (*Bumper* eHMI) offers its message as a single-fire, generic information about the car’s intent. In comparison, the *Bumper+SA* and *Bumper+PB* eHMIs provide information about the car’s intent in multiple steps: a generic message at a distance and an additional, more specific information at a closer distance. Based on previous research showing pedestrians’ behaviors in seeking additional information as the vehicle comes closer [12], we hypothesize that the eHMI concepts that are able to provide additional information that clarifies the context of the message will perform better.

## 3 METHOD

The proposed eHMI concepts were evaluated in a video-based within-subject experiment, as this allowed for practicable lab conditions where danger for the participants can be avoided. The experiment was submitted to and approved by the ethical review board of the researchers’ institution(s).

### 3.1 Task

In this video-based experiment, the participants had to watch several videos of an AV approaching them while they assumed the role of a pedestrian intending to cross the road. While watching the videos, the participant indicated their willingness to cross the road in real time as the vehicle in the video approached them.



(a) The setup of the experiment: the participant stood sideways in front of a 55" screen where the video stimuli were presented.

Trial #	eHMI Concept	Behavior	Exposure
1	No eHMI (Block 1)	Yielding (50km/h - 0km/h)	1
2			2
3		Not Yielding (50km/h constant)	1
4			2
5			1
6			2
7	<i>Bumper</i> (Block 2)	Yielding (50km/h - 0km/h)	1
8			2
9		Not Yielding (50km/h constant)	1
10			2
11			1
12			2
13	<i>Bumper+SA</i> (Block 3)	Yielding (50km/h - 0km/h)	1
14			2
15		Not Yielding (50km/h constant)	1
16			2
17			1
18			2
19	<i>Bumper+PB</i> (Block 4)	Yielding (50km/h - 0km/h)	1
20			2
21		Not Yielding (50km/h constant)	1
22			2
23			1
24			2

(b) Study design: All participants first experienced the ‘No-eHMI’ block. The remaining eHMI blocks followed in a randomized order. We also randomized the order of stimuli within a block.

Figure 3: The setup and design of the study

### 3.2 Apparatus and Study Setup

As video stimuli used in this experiment, we captured video clips of an approaching car (Toyota Prius) from a pedestrian’s perspective. The location of the pedestrian was at the curbside of a straight road that was free from any traffic or other road users. The interaction

took place at a location where there was no intersection or pedestrian crossing. This was done to ensure that the decision whether or not to cross the road is a direct result of the consideration of the car's behavior, and not from an expectation of right of way.

We used a Ghost Driver Wizard-of-Oz setup to hide the driver under a 'seat suit' and to create an illusion of an automated vehicle [38]. We captured the videos (4K resolution, 60 frames per second) during daytime on an overcast day, which led to a uniformly lit environment devoid of starkly contrasting areas of direct sunlight and shadows. We augmented these videos with the proposed eHMI concepts/visualizations post-hoc using Adobe After Effects.

The focus of this study was to investigate how pedestrians interact with automated vehicles that exhibit a yielding behavior, and the corresponding effect of eHMIs. While a car can yield to a pedestrian in different ways by employing different braking patterns and speed profiles, we investigated only one yielding behavior to simplify the scope of this study: the car approached from a distance of 200 m at 50 km/h (standard city driving speed in Europe) and slowed down to a full stop at 5 m before the pedestrian. At 45 m away from the pedestrian, the car started braking gently but purposefully to indicate a deliberate yielding behavior, resulting in a total braking distance of 40 m and a literature-supported normal braking deceleration rate of  $2.4 \text{ m/s}^2$  [7]. In the conditions displaying yielding behavior, the three eHMI concepts were applied as explained in Section 2. For each of these concepts, the light bar of the Bumper eHMI starts indicating the yielding intention (pulsate) at a distance of 60 m. For the extended concepts that also use the windshield display, the Windshield eHMI was activated at a distance of 25 m. We used this distance based on findings from earlier research [12] which showed that at a distance of 25 m pedestrians' gaze patterns shift significantly towards the windshield, which indicates information-seeking behavior.

To avoid learning effects (that the car yields every time), we added two non-yielding cases in the study. In these non-yielding conditions, the eHMI – when present – is a solidly glowing light band on the bumper as explained in section 2. In one non-yielding behavior, the vehicle keeps driving at a constant speed of 50 km/h and passes the pedestrian. In the other non-yielding case, the vehicle slows down from 50 km/h to 20 km/h and then keeps driving without stopping. We added this second non-yielding behavior to further distinguish between pedestrian reactions to the vehicle's behavior as opposed to the eHMI message. In this non-yielding behavior, the vehicle slows down, which could confuse pedestrians into thinking that the vehicle is stopping for them. However, the eHMI continues to show a solidly glowing light strip, which means that the vehicle does not intend to yield. This allowed us to further study whether the pedestrians' responses arose out of a reaction to the vehicle's behavior or the message of the eHMI.

Each stimulus is a video of the car from when it is approximately 200 m away until either 3 seconds after having stopped for the pedestrian, or until having passed the pedestrian without stopping. We recorded the pedestrians' *willingness-to-cross* to the yielding car from when the car was 12 seconds away from the pedestrian. For a yielding vehicle, we measured the pedestrians' *willingness-to-cross* relative to the 'Time-to-stop' of the vehicle, which we defined as the moment when the vehicle comes to a complete stop in front of the

pedestrian. For a non-yielding vehicle, we measured relative to the 'Time-to-arrival' of the vehicle, which we defined as the moment when the front bumper of the vehicle reached the pedestrian's location.

We programmed the stimuli into a Processing<sup>1</sup> shell so that each video stimulus could be presented one after another, and the participant responses could be stored in a synchronized manner with the video. The video stimuli were presented to the participants on a 55-inch display in landscape orientation.

To record the pedestrians' willingness to cross as a function of the vehicle's time-to-stop or time-to-arrival, we used a slider device as input device as proposed by Walker et al. [42]. The participant could move the slider to indicate their willingness to cross the road. The two ends of the slider were mapped to 0 and 100 (corresponding to no willingness to cross, and total willingness to cross), and the device recorded inputs at a rate of 10 Hz. We also instructed the participants that the continuum of the slider in between the ends can be used to express ambiguity regarding their decision. Once the participant took their position in front of the screen (see Figure 3a), the experimenter handed them the slider input device and asked them to hold it comfortably in their hand, consider the approaching experiment vehicle, and indicate their willingness to cross in real time. After the participant completed their response to a video stimulus, they were asked to press the space bar on a keyboard placed on a table in front of them to proceed to the next video stimulus.

### 3.3 Procedure

The experiment was conducted in a closed room at the researchers' institution. After each participant gave their informed consent at the start of the study, we asked them to stand in front of the display in order to watch the video stimuli. The participants stood sideways in front of the screen at a distance of approximately 1.5 m from the screen as shown in Figure 3a. We asked them to imagine that they are standing at the curbside of a road which they would like to cross, and the road extended to their left in the screen (see Figure 3a).

Before the measured trials began, the participant had the opportunity to experience three practice trials to familiarize themselves with the setup and the slider input device. The three stimuli used for the practice trial were the same as the videos with 'No-eHMI' condition, and the participants experienced each behavior once in a randomized order. After the practice trials, the participants were asked if they understood the task and were comfortable with continuing with the study. Each participant gave a positive response, and was allowed to continue with the measured trials.

Each participant experienced 24 trials in total. The experiment conditions included the four different eHMI concepts (*No eHMI*, *Bumper*, *Bumper+SA*, and *Bumper+PB*), and the three different behaviors of the car (yielding, not yielding with a constant speed, not yielding while slowing). We presented each set of stimuli pertaining to a certain eHMI concept block-wise to the participant (see Table 3b). Since the blocks were separated by the different eHMI types, we included the two non-yielding conditions within each block to act as a corresponding control even though the eHMI behavior for all non-yielding conditions were identical. The first

<sup>1</sup><https://processing.org/>, last access 2020-04-20

block was always the ‘No-eHMI’ (baseline) condition. Subsequently, we presented all the other three blocks in a randomized order to counterbalance any learning effects. Per condition of eHMI concept and yielding / non-yielding behavior, the participant experienced 2 exposures, which led to 6 video stimuli per block. Within each block, we counterbalanced the order of presentation of the stimuli to avoid learning effects.

Before a particular block of eHMI started, the experimenter showed the participant a video of the eHMI concept and explained it to them. We did this to ascertain that the participants understood the eHMI concepts and that the results of their responses were an accurate measure of the efficacy of the eHMI and not their intuitiveness. Once the participant confirmed that they understood the eHMI concept, they proceeded with the block. At the end of each block (corresponding to an eHMI condition), the experimenter asked them to fill out a User Experience Questionnaire (UEQ)<sup>2</sup> [26] for the respective eHMI concept.

At the end of the experiment, the participants had to subjectively rank the four eHMI conditions they encountered (*No-eHMI*, *Bumper*, *Bumper+SA*, and *Bumper+PB*) in the order of their preferred interaction experience. Subsequently, the experiment concluded with a short semi-structured interview/discussion with the participant regarding how they perceived the crossing scenarios. The entire experiment took approximately 30 minutes, and each participant was compensated for their time with €5.

### 3.4 Measures

This study incorporated three different measures to evaluate the different eHMI concepts. Firstly, we used the *Willingness to Cross* data from the slider input device as an objective surrogate measure for the pedestrians’ feeling of safety around the automated vehicle as described in prior work [42]. Secondly, we used the data of the 26-item *User Experience Questionnaire* that participants filled out for each eHMI. These data are transformed into the six User Experience factors of attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty. Finally, we used the participants’ *Subjective ranking* data to determine any significant order of preference between the different kinds of eHMI concepts under investigation.

### 3.5 Participants

We conducted the study with university students and staff who were recruited via a variety of channels including the university experiment participation database, social media, and word of mouth ( $N = 26$ , 14 male, 12 female; mean age = 24.7 years ;  $SD = 5.2$  years). Only individuals who had normal, or corrected-to-normal vision were recruited. We implemented a within-subjects setup across the 4 evaluation conditions (*No-eHMI*, *Bumper*, *Bumper+SA*, and *Bumper+PB*). We lost all the data from one participant, and the willingness-to-cross data from another participant due to technical issues. Thus, we used a sample of  $N = 24$  (13 male, 11 female; mean age = 24.63 years,  $SD = 5.35$  years) for analyzing the willingness-to-cross, and a sample of  $N = 25$  (14 male, 11 female; mean age = 24.6 years,  $SD = 5.29$  years) for the analysis of the UEQ and Subjective Ranking data.

<sup>2</sup><https://www.ueq-online.org/>, last access 2020-04-20

## 4 RESULTS

We analyzed each measure (willingness to cross, UEQ response, and subjective ranking) separately, and we report the results in the following sections.

### 4.1 Willingness to Cross

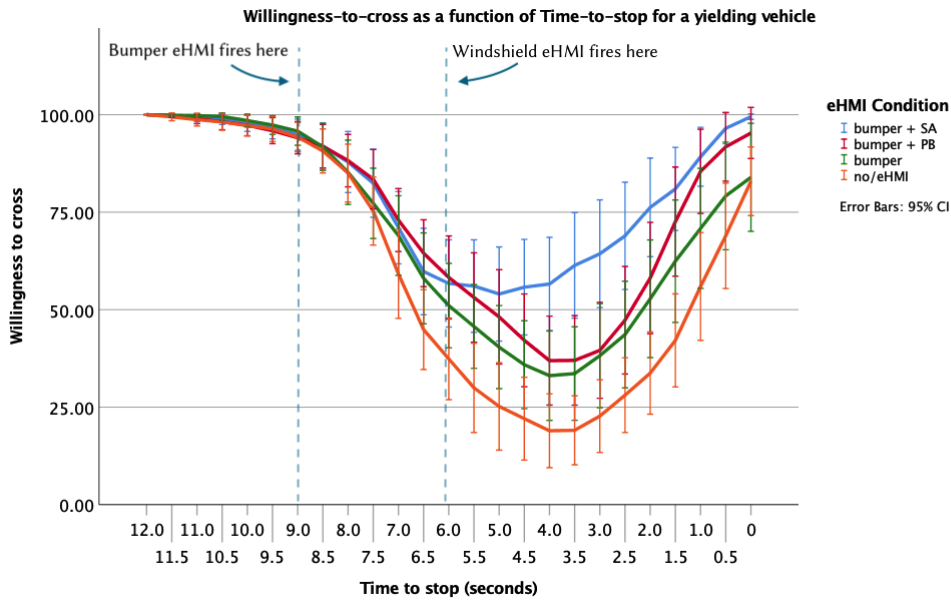
For each eHMI concept/ Behavior condition combination, there were two exposures. For the analysis, we extracted the *willingness-to-cross* values in 0.5 s intervals and took the average of the values from both exposures.

**4.1.1 Yielding.** Figure 4a shows the pedestrians’ willingness to cross as a function of time (until the car comes to a complete stop) for each of the four eHMI conditions.

We conducted a repeated-measures ANOVA across the four eHMI conditions and the Time to Stop (TTS) for the vehicle ranging from 9 seconds (approximately when the bumper eHMI activated) until 0 seconds (the car comes to a complete stop) (Figure 4b). Results show that the effect of *eHMI* was statistically significant and had a medium effect size. As expected, *Time* had a highly significant effect on pedestrians’ willingness to cross in all behaviors – it varied as the vehicle came closer (TTS decreased). We executed post-hoc tests (pairwise comparison of the different eHMI conditions with Bonferroni confidence interval adjustment) and found that the *No-eHMI* condition was significantly different from all eHMI conditions. Among the eHMI conditions, there was a statistically significant difference between *bumper* and *bumper+SA*. However, no significant differences were observed between *bumper* and *bumper+PB* or *bumper+SA* and *bumper+PB*.

To investigate whether the different eHMI concepts had a significant effect at any specific TTS points in addition to its holistic effect across the entire experience, we conducted a repeated-measures ANOVA for each moment of Time-to-Stop (TTS) Figure 4c shows the main effects of the eHMI in each measured TTS. The condition of sphericity was met for some TTS measurements, and violated for others, so we report multivariate tests for all TTS measurements as they are more conservative and do not assume sphericity [16, 17].

The results show a statistically significant effect of the eHMI as the AV comes closer, particularly from a TTS measurement of 6.5 s and less. Post-hoc tests (pairwise comparison of the different eHMI conditions with Bonferroni confidence interval adjustment) show that the estimated marginal means for all eHMIs are statistically significantly different from the no eHMI condition - when eHMIs indicated that the vehicle was yielding, pedestrians’ willingness-to-cross decreased less. Furthermore, we found that augmenting an eHMI with the vehicle’s situational awareness (*Bumper+SA* condition) was the most effective concept in resolving ambiguity and helping pedestrians comprehend the vehicle’s yielding intention: the vehicle’s yielding intention was comprehended sooner. With this concept, the willingness-to-cross decreased the least and increased again sooner compared to other eHMI conditions. The data reveal that the *Bumper+PB* condition does not perform significantly better than the single-fire *Bumper* eHMI except during the last second before a complete stop. The pairwise comparisons are also reported in Table 4c.



(a) The variation of pedestrians’ willingness to cross as a function of the time-to-stopping of the yielding vehicle for different eHMI conditions.

Condition	F	Sig.	Effect size (r)
eHMI	22.46	<0.001	0.49
TTS	64.63	<0.001	0.37
eHMI * TTS	5.64	<0.001	0.07

(b) Test statistics of the effects of eHMI, Time-to-Stop, and their interaction on pedestrians’ willingness to cross.

TTS	F	Sig.	$\eta_p^2$	Pairs of significant differences
9.0	0.228	0.876	0.032	
8.5	0.211	0.888	0.029	
8.0	0.886	0.465	0.112	
7.5	3.01	0.053	0.301	
7.0	1.881	0.164	0.212	
6.5	5.227	<b>0.007</b>	0.427	(1,4)
6.0	7.847	<b>0.001</b>	0.529	(1,3), (1,4)
5.5	12.098	<b>&lt;0.001</b>	0.633	(1,3), (1,4), (2,3)
5.0	10.444	<b>&lt;0.001</b>	0.599	(1, 2), (1, 3), (1, 4), (2, 3)
4.5	13.142	<b>&lt;0.001</b>	0.652	(1, 3), (1, 4), (2, 3)
4.0	14.061	<b>&lt;0.001</b>	0.668	(1, 2), (1, 3), (1, 4), (2, 3), (3, 4)
3.5	14.42	<b>&lt;0.001</b>	0.673	(1, 2), (1, 3), (1, 4), (2, 3), (3, 4)
3.0	14.045	<b>&lt;0.001</b>	0.667	(1, 2), (1, 3), (1, 4), (2, 3), (3, 4)
2.5	11.874	<b>&lt;0.001</b>	0.629	(1, 2), (1, 3), (1, 4), (2, 3), (3, 4)
2.0	12.673	<b>&lt;0.001</b>	0.644	(1, 2), (1, 3), (1, 4), (2, 3), (3, 4)
1.5	12.858	<b>&lt;0.001</b>	0.648	(1, 2), (1, 3), (1, 4), (2, 3)
1.0	9.084	<b>&lt;0.001</b>	0.565	(1, 3), (1, 4), (2, 4)
0.5	5.55	<b>0.006</b>	0.442	(1, 3), (1, 4)
0.0	4.686	<b>0.012</b>	0.401	(1, 3), (1, 4)

**Legend**

- 1 – No eHMI
- 2 – Bumper
- 3 – Bumper+SA
- 4 – Bumper+PB

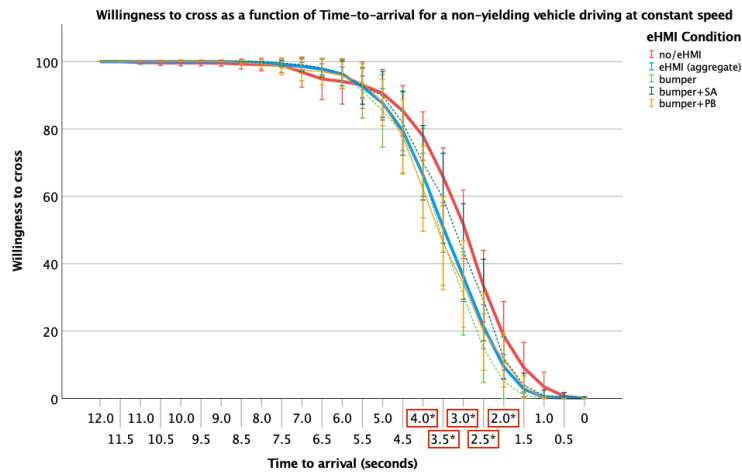
(c) Main effects of different eHMIs across different Time-to-stop (TTS) measuring points for a yielding vehicle. The TTS points where the eHMI had a significant effect are highlighted in bold and the corresponding significant differences from pairwise comparisons are reported.

Figure 4: Performance of different eHMI concepts when the vehicle is yielding.

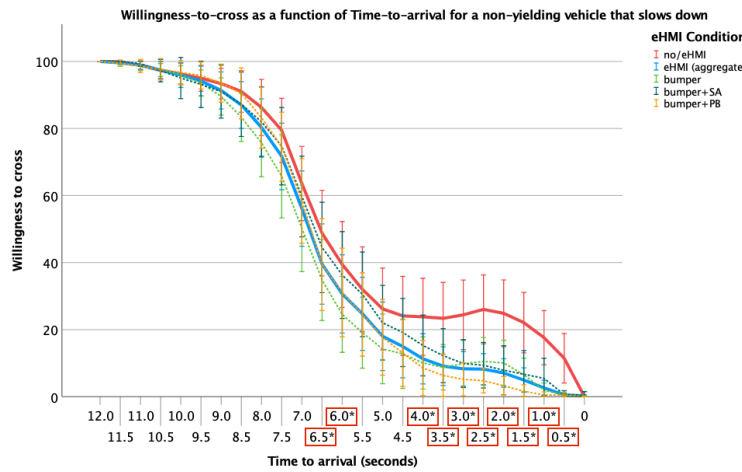
4.1.2 *Not yielding.* As we focus on effective communication methods in eHMIs for a yielding message, we only present a condensed analysis of the data for non-yielding behaviors. For each of the two non-yielding behaviors (1) maintaining a constant speed of 50 km/h and (2) slowing down from 50 km/h to a constant speed of 20 km/h the participants experienced the AV with and without eHMIs. In

contrast to the three eHMI concepts for the yielding conditions (*Bumper*, *Bumper+SA*, and *Bumper+PB*), the eHMI remains the same when the vehicle does not yield (the light band on the bumper glows continuously). Since we used the non-yielding behavior as control conditions for each eHMI concept, we took measurements for the same non-yielding eHMI concept across the blocks for each





(a) The variation of pedestrians’ willingness to cross as a function of the time-to-arrival for a non-yielding vehicle driving at constant speed of 50 km/h.



(b) The variation of pedestrians’ willingness to cross as a function of the time-to-arrival for a non-yielding vehicle which slowed down from 50 km/h to 20 km/h and continued at this speed.

	F	Sig.	Effect size (r)
<i>Constant speed</i>			
eHMI	6.18	0.021	0.46
TTA	464.60	<0.001	0.73
eHMI * TTA	4.001	0.007	0.09
<i>Slowing</i>			
eHMI	18.32	<0.001	0.67
TTA	147.62	<0.001	0.51
eHMI * TTA	3.27	0.033	0.09

(c) Test statistics of the effects of eHMI, time to arrival, and their interaction on pedestrians’ willingness to cross for the two non-yielding conditions.

Figure 5: Participants’ responses of their willingness to cross for the non-yielding cases. The responses for the 3 eHMI conditions have been aggregated under one (bold blue) ‘eHMI’ line and contrasted with the (bold red) ‘No eHMI’ line. The responses for the individual eHMI conditions are shown in dotted lines. The TTA measurements where the eHMIs have a statistically significant effect on willingness to cross are marked with an asterisk and highlighted in red.

eHMI condition (see Figure 3b). Therefore, to analyze these data for each non-yielding behavior we averaged the non-yielding eHMI

data per participant (see Figure 5). Subsequently, we conducted a repeated-measures ANOVA for each non-yielding behavior between the No eHMI and eHMI conditions every 0.5 s from 9 seconds of Time-to-Arrival (TTA) until 0 seconds (front bumper next to the pedestrian), and the test statistics are shown in Figure 5c.

As shown in Figure 5a, the willingness to cross for the eHMI condition is significantly lower than for the No-eHMI condition between the a TTA of 4.0 s and 2.0 s for the non-yielding condition at 50 km/h. This indicates that in these TTA measurements, the eHMI helps pedestrians to know more conclusively that the vehicle does not intend to stop and therefore be more decisive earlier about their decision to not cross. For the non-yielding condition with reduced speed, Figure 5b shows an interesting pattern: In the No-eHMI condition, the willingness to cross drops as the car approaches, but rises again as it slows down – pedestrians assumed that the slowing behavior meant that the vehicle was yielding to them. Only later, when they realized that the vehicle continues to drive, did they abruptly decide that they could no longer cross. In comparison, the pedestrians' willingness-to-cross was significantly lower in the eHMI condition from the TTA measurements of 6.5 s and 6.0 s, and stayed consistently lower from the TTA measurement of 4.0 s onward. In the presence of the eHMI, despite the slowing behavior of the car, there was no more confusion whether the car was yielding to them. Instead, the eHMI elucidates the car's intention to keep driving.

## 4.2 User Experience Questionnaire

We used a repeated-measures ANOVA to test the effects of the different eHMI conditions for each of the six UEQ scales (measured in a 7-point Likert scale from -3 to +3) to determine the overall user experience of each eHMI solution. We also included the *No-eHMI* condition in the analysis as we also wanted to evaluate the overall experience of the approaching car as a baseline. As the assumption of sphericity was violated for some of these tests, we uniformly report the multivariate tests as they do not assume sphericity and are more conservative [16, 17].

The tests of the main effects (Figure 6a) show that the effect of the different eHMI conditions is significant for each of the six UEQ scales. The effects are also shown in Figure 6b. The post-hoc tests (pairwise comparison of the main effects of the different eHMI conditions with Bonferroni confidence interval adjustment) are summarized in Figure 6c. Results show that the *No eHMI* condition performs significantly worse than any of the eHMIs in almost all of the six scales (except perspicuity). When a baseline *Bumper* eHMI is augmented with additional contextual windshield displays (*Bumper+SA*, and *Bumper+PB*), the perception of dependability, stimulation, and novelty are significantly increased. There is no statistically significant difference between the two different kinds of contextual windshield displays.

## 4.3 Subjective Ranking

To analyze the ranking data of the participants, we employed the non-parametric Friedman's ANOVA. The results show that there is a statistically significant order of preference for the different kinds of eHMIs ( $\chi^2(3) = 49.94, p < 0.001$ ).

Pairwise comparisons (Wilcoxon signed rank tests) were performed with a Bonferroni correction for multiple comparisons. Statistical significance was accepted at the  $p < .008$  level. The *No eHMI* condition ranks statistically significantly lower than all the other three conditions (*Bumper* > *No eHMI*:  $p < .001$ ; *Bumper+SA* > *No eHMI*:  $p < .001$ ; *Bumper+PB* > *No eHMI*:  $p < .001$ ). The baseline *Bumper* eHMI concept also ranks lower than both contextual enhanced eHMI concepts using the windshield in addition (*Bumper+SA* > *Bumper*:  $p < .001$ , *Bumper+PB* > *Bumper*:  $p < .001$ ). Although the median rank of *Bumper+PB* is higher than *Bumper+SA*, this difference is not statistically significant. Summarizing the subjective ranking, the *No eHMI* condition consistently performs worst, followed by the baseline *Bumper* eHMI, and the two contextual eHMIs with windshield displays are the most preferred.

## 4.4 Qualitative Feedback

In addition we collected qualitative feedback through semi-structured interviews at the end of the experiment to gain insights from the subjective reasoning of the participants. This section outlines insights from the thematic analysis applied to the qualitative data, furnished with selected participant quotes.

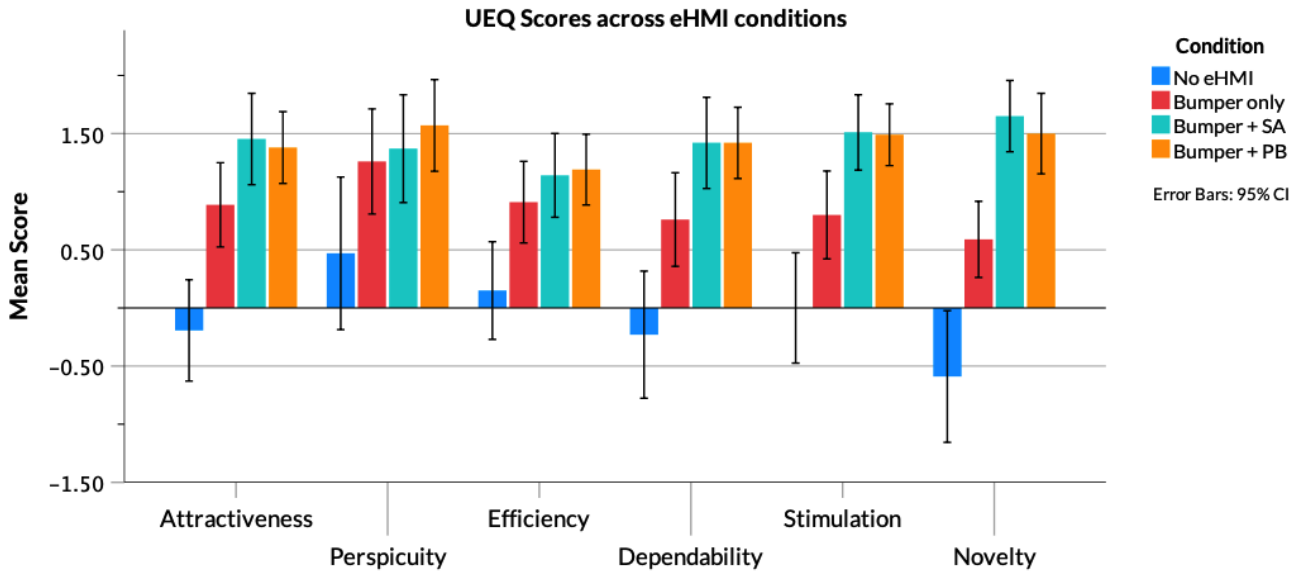
**4.4.1 eHMIs help pedestrians to feel more confident about their crossing decisions.** Participants remarked that in general, the presence of any eHMI helped them feel more comfortable about the interaction with the car. When the eHMI activated, participants saw that as a confirmation of their assumptions about the car's intention [P4] and felt more confident to cross [P7]. Some participants also mentioned that the eHMI made the interaction more comfortable for them [P26].

**4.4.2 Pedestrians prefer additional contextual information on the windshield.** Most participants commented that the presence of the windshield display aided their decision making. Having additional contextual information helped the comprehension of the intent of the car with greater confidence regarding what it means for their own safety in a road-crossing situation. Participants mentioned that the additional information on the windshield made them feel more secure about the car's intention [P3] and resolved their hesitation regarding if the car was indeed stopping for them [P7]. One participant [P21] even mentioned that they actually disliked the *Bumper* eHMI compared to the other eHMIs – “For me, it was almost like it added confusion to my existing precaution. If it just says that it is stopping without making it specific, it feels like now I should try to understand what the light is saying instead of just focusing on the car's speed and looking for the gap.”

**4.4.3 Preferences regarding contextual information differ.** In comparing the different contextual concepts Progress Bar (distance to stopping position) and Situation Awareness (visualizing the pedestrian's presence) we found individual differences. Of the 25 participants tested, 13 had a preference for the Progress Bar concept over the Situation Awareness concept, while 12 indicated their preference as the other way round. There were specific reasons behind why some people preferred one over the other:

Attractiveness	$F(3,22) = 14.25, p < .001, \eta_p^2 = .660$
Perspicuity	$F(3,22) = 3.13, p = .046, \eta_p^2 = .299$
Efficiency	$F(3,22) = 5.74, p = .005, \eta_p^2 = .439$
Dependability	$F(3,22) = 11.76, p < .001, \eta_p^2 = .616$
Stimulation	$F(3,22) = 11.01, p < .001, \eta_p^2 = .600$
Novelty	$F(3,22) = 16.82, p < .001, \eta_p^2 = .696$

(a) Test results of main effects of eHMI condition across the six dimensions of UEQ.



(b) Mean score of each of the six UEQ dimensions clustered over the different eHMI conditions.

		Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
No eHMI	Bumper	<b>p &lt; .001</b>	p = .201	p = .026	p = .030	p = .007	p < .001
	Bumper+SA	<b>p &lt; .001</b>	p = .131	p = .006	p < .001	p < .001	p < .001
	Bumper+PB	<b>p &lt; .001</b>	p = .029	p = .002	p < .001	p < .001	p < .001
Bumper	Bumper+SA	p = .081	p = 1.000	p = 1.000	p = .010	p = .011	p < .001
	Bumper+PB	p = .068	p = .683	p = .561	p = .035	p = .016	p = .002
Bumper+SA	Bumper+PB	p = 1.000	p = 1.000	p = 1.000	p = 1.000	p = 1.000	p = 1.000

(c) Pairwise comparisons of positive difference between eHMI conditions for each of the six dimensions of UEQ. The statistically significant differences are highlighted in bold font.

Figure 6: Results of the UEQ analysis.

*Preference for situation awareness:* Some participants preferred the situational awareness display (*Bumper+SA*) because they liked getting the specific acknowledgement from the vehicle that they were being yielded by, as opposed to the progress bar (*Bumper+PB*) because they could not gauge how long it would take for the car to actually stop [P4]. Others mentioned that when they realized that the “car saw them” and moved “as a person would turn their face to look at me”, they had full trust in the system [P7]. One participant specifically mentioned that simply the slowing down of the car is not enough of a cue for them, since it can slow down for any number of reasons – they feel the need for acknowledgement, and the *Bumper+SA* concept felt as a specific and personal communication, which they liked [P21]. Yet another participant reflected that with the *Bumper+PB* concept, it was hard for them to understand where

exactly the car would stop, while in contrast, when the car “mapped to [them], it helped” and they felt more comfortable than trying to figure out the stopping moment [P23].

*Preference for progress bar:* In contrast, other participants stated that with the *Bumper+SA* concept, they could not be certain if the car was really tracking them, and speculated that it would be even more difficult on a busy street where they were not the only pedestrian present [P3, P18] – for them, knowing a stopping distance was more useful [P3, P10]. Yet another participant mentioned that it is not important for them to know whom the car will stop for, but rather information about where it will stop helps them make a judgment about crossing the road [P11].

## 4.5 Evaluation of Hypothesis

Quantitative results from all three measures show an improvement in pedestrians' road-crossing decision-making as well as a strong preference towards the two eHMI concepts where additional contextual data were provided at a closer distance (*Bumper+SA*) and (*Bumper+PB*) compared to (*Bumper*) where no additional information clarifying the context was present. The qualitative feedback corroborates this finding. Combining insights from all the different analyses, we accept hypothesis H1 and infer that *adding distance or time-to-arrival based proximal contextual information has potential to make interactions between AVs and pedestrians more efficient.*

## 5 DISCUSSION

Our results show that distance-based information clarifying the context of the AV's intent enhances pedestrians' comprehension and perception of the vehicle's intention. We reflect on the findings of our study to improve the design of future eHMIs and how distance-dependent contextual eHMIs can benefit the effectiveness and user experience of AV-pedestrian interaction.

### 5.1 The effect of eHMI

All eHMI conditions performed subjectively and objectively better than using no eHMI, which is in line with previous findings [5, 20, 21, 25]. While the effect of eHMIs holds true for all three behavioral conditions (yielding, not yielding/ constant speed, and not yielding/ slowing down), we take a deeper look particularly at the non-yielding condition when the vehicle slowed down. In this case, pedestrians only had the behavior of the vehicle to identify its intention when there was no eHMI. At this point, when the vehicle slowed down, pedestrians took that as an indication that the vehicle was yielding to them, and their willingness to cross increased. Only later when it became clear that the vehicle did not intend to yield did their willingness to cross go down. In contrast, in the presence of an eHMI, even though the vehicle slowed down, pedestrians responded to the message of the eHMI that the vehicle did not intend to yield, and their willingness to cross did not go up when the vehicle slowed down. This shows that the eHMI plays an active role in modulating pedestrians' understanding of the vehicle intent and they do not solely depend on the vehicle's movement patterns in determining whether the vehicle would yield to them. This ties in with previous research showing that the vehicle's movement patterns are enough for expressing the intentions of a vehicle and that further communications may not be necessary [11, 29, 30]. We posit that while vehicle movement patterns may be enough for many common and ordinary situations, an eHMI has the potential to clarify the intention of the vehicle and reduce ambiguity.

### 5.2 The effect of contextual information

The findings from the quantitative analyses show that the contextual information provided in terms of the vehicle's situational awareness of the pedestrian (*Bumper+SA* eHMI) perform significantly better than all other eHMI conditions. When the contextual information was presented in terms of the vehicle's stopping time using a progress bar (*Bumper+PB*), objective willingness-to-cross results show that it did not clarify the vehicle's yielding intention much better than the regular *Bumper* eHMI without any further

contextual information until the very last moment. This is interesting when considered in conjunction with the self-reported UEQ scores and subjective ranking. For 3 out of the 6 constructs of the UEQ (*Dependability*, *Stimulation*, and *Novelty*), the two eHMIs with added contextual information perform better than the eHMI without contextual information. However, there is no significant difference between the two eHMIs with contextual information. An identical pattern applies to the subjective ranking results.

We found that contextual information has an effect on pedestrians' understanding of the vehicle's intention in creating confidence on its yielding intention, and this translates to making more efficient road-crossing decisions. Earlier research shows that equipping AVs with additional displays is not preferred by pedestrians and eHMIs must be simple and easily comprehensible [27]. However, we show that additional contextual information, when provided in a timely and expected manner, can help pedestrians in their decision-making process.

### 5.3 Challenges of contextual information

Each of the two contextual eHMI concepts has its own unique design challenges and implications in communication. For the *Bumper+PB* concept, a recurring difficulty is that it is hard for the pedestrians to map the abstract visualization on the windshield (even with a 'full windshield' indicating the moment of a complete stop) to an actual point on the road or a precise moment in time. While it provides a rough estimate of how close the vehicle is to a complete stop as a correspondence to how 'full' the windshield was, a lot is left to guessing and estimation, and this is not foolproof.

On the other hand, many participants liked the (*Bumper+SA*) concept that mirrors the presence and location of the pedestrian on the windshield. Previous research has shown that in general pedestrians like the idea of a moving light cue [27] and our study corroborates this finding. However, the biggest challenge of this implementation is that while it works for one individual, or even a group of co-located individuals sharing the same intent in traffic, it may start to lose efficacy as it scales up in a busy, dynamic situation with multiple pedestrians having different intentions. Such an eHMI is able to show individual pedestrians at a fairly low resolution (since windshield space is limited, and with an increasing number of pedestrians to uniquely represent in the display, the distinction between individuals starts to blur). As a result, groups of pedestrians will likely be piled together in the visualization. This might cause further confusion regarding 'whom' the eHMI has 'seen'. In the inability of the eHMI to distinctly acknowledge everyone individually, pedestrians might need to start to fill the gap in the information – whether a particular light element refers to a particular pedestrian or someone else. This has potential to cause further confusion, and therefore must be tested in the context of dynamic and busy traffic scenarios to test its scalability.

Another insight was regarding the moment of the activation of the contextual information on the windshield eHMI. As explained, the windshield eHMI activates at distance of 25 m from the pedestrian as earlier research indicates that at this point pedestrians start fixating the windshield – likely to seek additional information from the driver [12]. However, two participants [P7, P26] noted that they would like the contextual information to come sooner: For them,

doubt regarding the vehicle's yielding intention had already set in before the confirmatory contextual information was provided. More research needs to investigate the ideal point of providing contextual information in different traffic scenarios. Knowing that in general there is a hesitation and mistrust towards automated driving [2, 33], it is possible that the knowledge that the vehicle was automated stimulated participants to err on the side of caution compared to a manually driven vehicle. This may be the reason why they wanted more information earlier, although this theory needs to be tested because other research also suggests that pedestrians' willingness to cross in front of automated vehicles does not differ significantly from ordinary, manually driven vehicles [9, 24].

#### 5.4 Limitations and Future Work

In order to limit confounding factors, we conducted the experiment in a simplified traffic scenario involving only one vehicle and one pedestrian on a straight and empty road devoid of any other traffic. Our findings provide the first results regarding the benefit of contextual information in such a baseline scenario. Prior research also shows the effect of vehicle behavior in 'implicit communication' of vehicle intent [11, 29, 30, 36]. Future work needs to validate the results across different vehicle behaviors in different traffic situations and in more dynamic scenarios involving multiple vehicles and pedestrians.

In our study, we offered stimuli as video clips to participants. It is possible that due to a lack of potential physical harm, participants exhibit a more risk-taking behavior. However, we chose this setup to ensure a high level of control in the environment and ensure the participants' safety. In addition the video-based approach allows for a simple and cheap proof-of-concept validation. Previous research shows that time-to-arrival estimates hold between video and real-life situations [35], which retains the ecological validity of this study.

Finally, while we drew insights about the merits of certain contextual information in this experiment, it is important to consider that we explored them in the context of windshield displays. There may be other ways of providing the same kind of contextual information, and results may vary. Our findings showed that people found it difficult to map the progress bar on the windshield to an actual on-road stopping location of the vehicle. It is possible that if the stopping point is shown as a projection on the ground, it would have been more comprehensible and the results would be different. Thus, although this study reveals that pedestrians benefit from knowing more contextual information about the vehicle's yielding intention, more work is needed to identify the ideal ways of displaying such contextual information.

## 6 CONCLUSION

This study presents a video-based experiment that explored the benefits of distance or time-to-arrival based contextual information provided on the vehicle windshield in addition to generic information about the vehicle's intent provided by the external Human-Machine Interface (eHMI) of an Automated Vehicle (AV). Our results show that additional contextual information helps pedestrians to be more confident about the vehicle's yielding intent and take more comfortable road crossing decisions. While subjective opinions are

split about the kind of contextual information that is most beneficial, quantitative results show that being acknowledged as 'seen' by an AV has a higher impact over information about the vehicle's stopping time or location when presented as windshield displays in resolving ambiguity regarding a pedestrian's safety to cross. We believe that our empirical insights may be crucial in the development of an effective eHMI system.

## ACKNOWLEDGMENTS

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