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External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions

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Objective: In this article, we investigated the effects of external human-machine interfaces (eHMIs) on pedestrians' crossing intentions.

Background: Literature suggests that the safety (i.e., not crossing when unsafe) and efficiency (i.e., crossing when safe) of pedestrians' interactions with automated vehicles could increase if automated vehicles display their intention via an eHMI.

Methods: Twenty-eight participants experienced an urban road environment from a pedestrian's perspective using a head-mounted display. The behavior of approaching vehicles (yielding, nonyielding), vehicle size (small, medium, large), eHMI type (1. baseline without eHMI, 2. front brake lights, 3. Knightrider animation, 4. smiley, 5. text [WALK]), and eHMI timing (early, intermediate, late) were varied. For yielding vehicles, the eHMI changed from a nonyielding to a yielding state, and for nonyielding vehicles, the eHMI remained in its nonyielding state. Participants continuously indicated whether they felt safe to cross using a handheld button, and "feel-safe" percentages were calculated.

Results: For yielding vehicles, the feel-safe percentages were higher for the front brake lights, Knightrider, smiley, and text, as compared with baseline. For nonyielding vehicles, the feel-safe percentages were equivalent regardless of the presence or type of eHMI, but larger vehicles yielded lower feel-safe percentages. The Text eHMI appeared to require no learning, contrary to the three other eHMIs.

Conclusion: An eHMI increases the efficiency of pedestrian-AV interactions, and a textual display is regarded as the least ambiguous.

Application: This research supports the development of automated vehicles that communicate with other road users.

Keywords: Virtual reality, automated driving, pedestrians, decision-making, crossing, HMI

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INTRODUCTION

According to the European Commission (2015), 21% of fatal road traffic accidents concern pedestrians, and 69% of these accidents occur in urban areas. Automated vehicles (AVs) have the potential to reduce these fatalities. The adoption rate of AVs is expected to increase in the upcoming decades (Bansal & Kockelman, 2017). Consequently, traditional driver-pedestrian interactions such as eye contact and hand gestures may gradually disappear, and pedestrians may be unable to infer the intention of AVs. This may hamper efficient and safe interaction and may negatively affect the acceptance of AVs on public roads. Various surveys indicate that pedestrians would like to receive information about whether or not the AV is stopping (Dziennus, Schieben, Ilgen, & Käthner, 2016; Merat, Louw, Madigan, Wilbrink, & Schieben, 2018; Núñez Velasco, Rodríguez Palmeiro, Farah, & Hagenzieker, 2016).

Prior Research on the Communication of Vehicle State and Gap Acceptance

In the area of manual driving, a number of prototypes have been developed that use wireless communication to inform pedestrians whether it is safe to cross. Examples are permissive traffic alerts delivered via a cell phone app (Rahimian et al., 2016; Rahimian, O'Neal, Zhou, Plumert, & Kearney, 2018) and a vibrotactile wristband providing warning messages (Cœugnet et al., 2017).

Instead of using wireless communication, it is possible to deliver *direct* visual communication. In a field experiment, Rodríguez Palmeiro et al. (2018) examined the effects of "self-driving" signage on pedestrians' crossing decisions. Twenty-four participants were led to believe that they encountered self-driving vehicles while a human driver remained in control of the vehicle (Wizard of Oz method). The critical gap and self-reported stress levels did not differ significantly between vehicles with a static "self-driving" sign and a traditional vehicle. However, a questionnaire after the experiment indicated that most participants had noticed the differences in the appearance of the vehicles.

Apart from a passive sign, an external human-machine interface (eHMI) could be introduced to present dynamic information with the goal to enhance the safety and efficiency of pedestrian-AV encounters. Clamann, Aubert, and Cummings (2017) presented two eHMI concepts (a display with a walk/don't walk advisory symbol, and a display showing the vehicle speed) to 50 participants in a field experiment. These eHMIs had no statistically significant effects on the crossing decision times compared with having no eHMI. Interviews showed that, although 76% of participants reported having seen the eHMI, only 12% reported that the eHMIs influenced their decision to cross. Clamann et al. concluded that it is likely that participants had a crossing strategy that relied on gap distance and that this strategy was dominant over the effect of the eHMIs. Similarly, a virtual-reality study by Li, Dikmen, Hussein, Wang, and Burns (2018) found that the majority of pedestrians reported that they made their decision based on vehicle kinematics; the authors argued that eHMIs are a secondary information channel at best. The supposed limited efficacy of eHMIs has led some researchers to study vehicle motion itself as a mode of communication. Examples of *movement as gesture* are drivers stopping far before the stop line (to signal that they intend to wait and pedestrians can take right of way) or slowly rolling the car forward (to indicate that they will take right of way) (Risto, Emmenegger, Vinkhuyzen, Cefkin, & Hollan, 2017).

Several experimental studies have reached more positive conclusions about eHMIs. Lagström and Lundgren (2015) tested an eHMI in a field experiment with nine participants. The eHMI consisted of a LED-strip on the front, which showed whether the vehicle was decelerating or not. After a training session, participants were able to decode the meaning of the LED signals and expressed positive opinions about it. In a virtual reality experiment using a head-mounted display, Chang, Toda, Sakamoto, and Igarashi (2017) examined a concept where the car's headlights looked at the participant to indicate its intention to stop ("Eyes on a Car"). This eHMI decreased the mean decision-making time from 2.32 s (SD = 0.85) to 2.03 s (SD = 0.88). Finally, a virtual reality study with a head-mounted display by Böckle, Brenden, Klingegård, Habibovic, and Bout (2017) tested a yielding vehicle with LED strips in front. Results showed that 29 of 34 participants indicated that they felt safe to cross when the eHMI was on, compared with 13 of 34 participants when the eHMI was off.

The above studies show that AVs and eHMIs can affect vehicle-pedestrian interaction and perceived safety of pedestrians. However, there appears to be no consensus on the benefits of various eHMIs and relevant design parameters (Sandt & Owens, 2017).

Aim of This Research

In this study, we examined the effects of eHMIs on the crossing intentions of pedestrians. We explored four eHMI concepts and examined the effects on whether pedestrians felt safe to cross. Here, the eHMI should ensure efficiency (i.e., the pedestrian should cross when the vehicle is yielding) and safety (i.e., the pedestrian should not cross when the approaching vehicle maintains speed).

Two additional independent variables were included in the present experiment. First, we varied the timing of the eHMI in three levels: (1) early: the eHMI switched state before the AV started to decelerate, (2) intermediate: the eHMI switched state at the moment the AV started to decelerate, and (3) late: the eHMI switched state after the AV started to decelerate. Second, we varied the vehicle size. Current AVs are designed in different sizes (e.g., Waymo using a small vehicle vs. Uber using an SUV), which may have important effects on gap acceptance. Kadali and Vedagiri (2016) examined 5,890 safety margins of pedestrians at unprotected crosswalk locations, extracted from videos. The mean safety margin was 3.50 s for a truck, 3.04 s for a car, 2.69 s for a three-wheeled passenger cart, and 2.06 s for a two-wheeler. Terry, Charlton, and

Figure 1. A participant's view as seen via the head-mounted display. In this case, a BMW Z4 is approximately 35 m from the participant. The participant could look around and move a little less than a meter to the front and to the sides.

Perrone (2008) similarly found that the time gap where participants started to yield was 7.27 s for trucks, 6.45 s for vans, and 5.83 s for cars. Accordingly, we expected that the total time that people felt safe to cross would increase with decreasing vehicle size.

The present experiments were conducted in a virtual reality environment using a head-mounted display. Virtual reality allows for the immersive, safe, and controlled examination of novel types of feedback (De Winter, Van Leeuwen, & Happee, 2012). In particular, the use of a virtual reality environment is advantageous as compared to questionnaires, which do not immerse a participant, and on-road tests, for which it is difficult to guarantee safety and to control the timing of the stimuli.

METHOD

This research complied with the tenets of the Declaration of Helsinki. Informed consent was obtained from each participant.

Participants

Twenty-eight participants (21 males, 7 females) with a mean age of 24.57 years ($SD = 2.63$) took part in the study. Only people from right-hand side driving countries were allowed to participate. Participants had five different nationalities: 22 German, one Swiss, three Italian, one Chinese, and one Spanish. They were all living in Germany at the time of the experiment. Two participants reported being color-blind. Nine people wore glasses, and two people wore contact lenses during the experiment.

Experimental Design

The participant experienced a traffic situation from the viewpoint of a pedestrian, using a head-mounted display in a virtual environment (see also Feldstein, Dietrich, Milinkovic, & Bengler, 2016). The pedestrian was standing on the pavement next to a two-lane two-way urban road in a European setting on a sunny afternoon (Figure 1). This type of interaction scenario is common in eHMI research (e.g., Clamann et al., 2017; Li et al., 2018). We chose not to use a zebra crossing, to increase the ambiguity for the participant. The presence of a zebra crossing would suggest that it is safe to cross, as in Germany approaching vehicles are obliged to stop when a pedestrian stands on the curb and is about to cross a zebra. Our experimental paradigm assumes that the AV can detect that a pedestrian is standing at the curb with the intention to cross, which seems a realistic assumption, considering that AVs are being developed to predict pedestrians' crossing intentions (Kooij, Schneider, Flohr, & Gavrila, 2014). Even if the pedestrian does not have right of way in this situation, future AVs (as well as human drivers) can be expected to

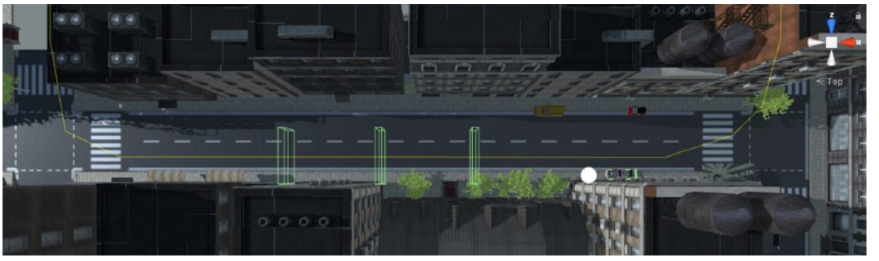

Figure 2. Top view of the virtual environment. The yellow line is the route that vehicles followed. The white circle is the location of the participant. The three boxes are the locations where the external human-machine interface (eHMI) switched state (50, 35, or 20 m). Yielding vehicles started decelerating at 35 m.

Figure 3. From left to right: Smart Fortwo, BMW Z4, Ford F150.

stop for pedestrians in such cases, for courtesy and safety reasons.

Vehicles driving at 50 km/h came around a corner at approximately 90 m on the left side of the participant and drove past the participant to disappear by turning left on a corner approximately 30 m away from the participant (see Figure 2 for a top-down view).

The research was of a within-subject design, with four independent variables. The first independent variable was the type of vehicle, consisting of three levels: (1) small (Smart Fortwo), (2) medium (BMW Z4), and (3) large (Ford F150), see Figure 3.

The second independent variable was the yielding behavior, consisting of two levels: (1) yielding and (2) not yielding. Yielding vehicles initiated braking at a distance of 35 m from the pedestrian. The deceleration of the vehicle was 3.5 m/s^2, and the vehicle came to a stop at a distance of 7.5 m from the pedestrian. The vehicle stood still for 3.5 seconds, after which it drove off again. Figure 4 shows the relationships between AV-pedestrian distance, elapsed time, vehicle speed, and time to arrival for yielding and nonyielding vehicles.

The third independent variable concerned the presence and type of eHMI: (1) baseline without eHMI, (2) front brake lights, (3) Knightrider animation, (4) smiley, and (5) text. The eHMIs consisted of lights or a screen implemented in front of the vehicle (Figure 5). Front brake lights are a concept that has been proposed before in different forms and formats (Antonescu, 2013;

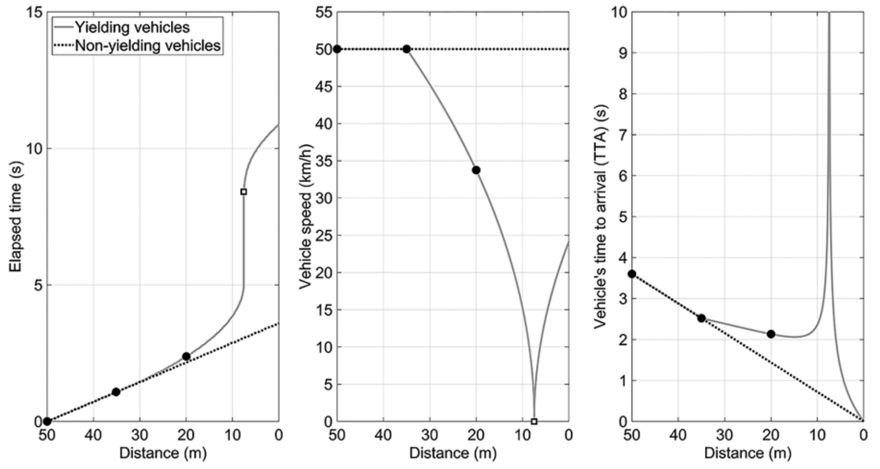

Figure 4. Three different depictions of the behavior of the approaching vehicle as a function of the distance to the pedestrian. In each figure, a distinction is made between yielding and nonyielding vehicles. Left: elapsed time, Middle: vehicle speed, Right: vehicle's time to arrival (TTA = speed / distance). The black circular markers indicate when the external human-machine interface (eHMI) changed from its nonyielding state to its yielding state (3 levels of timing are shown). The white square marker indicates when the eHMI changed back to its nonyielding state (see Figure 5 for yielding and nonyielding states).

Jandron, 1998; O'Sullivan, 1994; Petzoldt, Schleinitz, & Banse, 2018; Tracy, 2008; Veach, 2005; Walton, 1999). In our case, this display featured a green lamp when the vehicle was maintaining speed, which turned to a light cyan when the vehicle was yielding. The Knightrider was an animation: A bar repeatedly went from left to right (from the pedestrians' perspective) in about 0.5 s to indicate that it is safe to cross. This concept resembles various other concepts in the literature, which used an LED strip at the front of the car (Habibovic, 2018; Lagström & Lundgren, 2015; Mahadevan, Somanath, & Sharlin, 2018). The smiley was inspired by Semcon (2017); this anthropomorphic concept was claimed to be "readily understood by everyone." The text eHMI was based on Fridman et al. (2017), where 200 participants provided their opinion on about 30 eHMI concepts through an online survey, and where a text WALK was regarded as the least ambiguous. The contrasts and the sizes of the eHMIs were verified using a pilot study in which the eHMIs were found to be distinguishable from a distance smaller than 50 m. We used light cyan because cyan (or turquoise) is a neutral color that is not occupied by traffic rules and is salient in virtual reality (whereas white may not be visible when illuminated; Dietrich, Willrodt, Wagner, & Bengler, 2018; Werner, 2018).

The fourth independent variable was the timing of the eHMI, consisting of three levels: (1) early (50 m), (2) intermediate (35 m), and (3) late (20 m). The timing refers to when the yielding vehicles changed state; nonyielding vehicle eHMIs never changed state. For yielding vehicles, the eHMI switched back to its nonyielding state when the vehicle started moving again (i.e., when the elapsed time, as indicated in Figure 4 left, was 7.5 s).

Each participant encountered approximately 340 vehicles in a period of about 30 min. 45 of these vehicles (5 eHMIs × 3 vehicle sizes × 3 timing levels) were yielding, and 45 (5 eHMIs × 3 vehicle sizes × 3 repetitions) were nonyielding. The rest were "filler" vehicles driving with random time gaps. The vehicles were divided into five blocks of nine waves (i.e., 45 waves in total). A different eHMI condition was presented per block. After each block of nine waves, the participant was asked to take a break of about 2 min. Filler vehicles did not yield and showed the

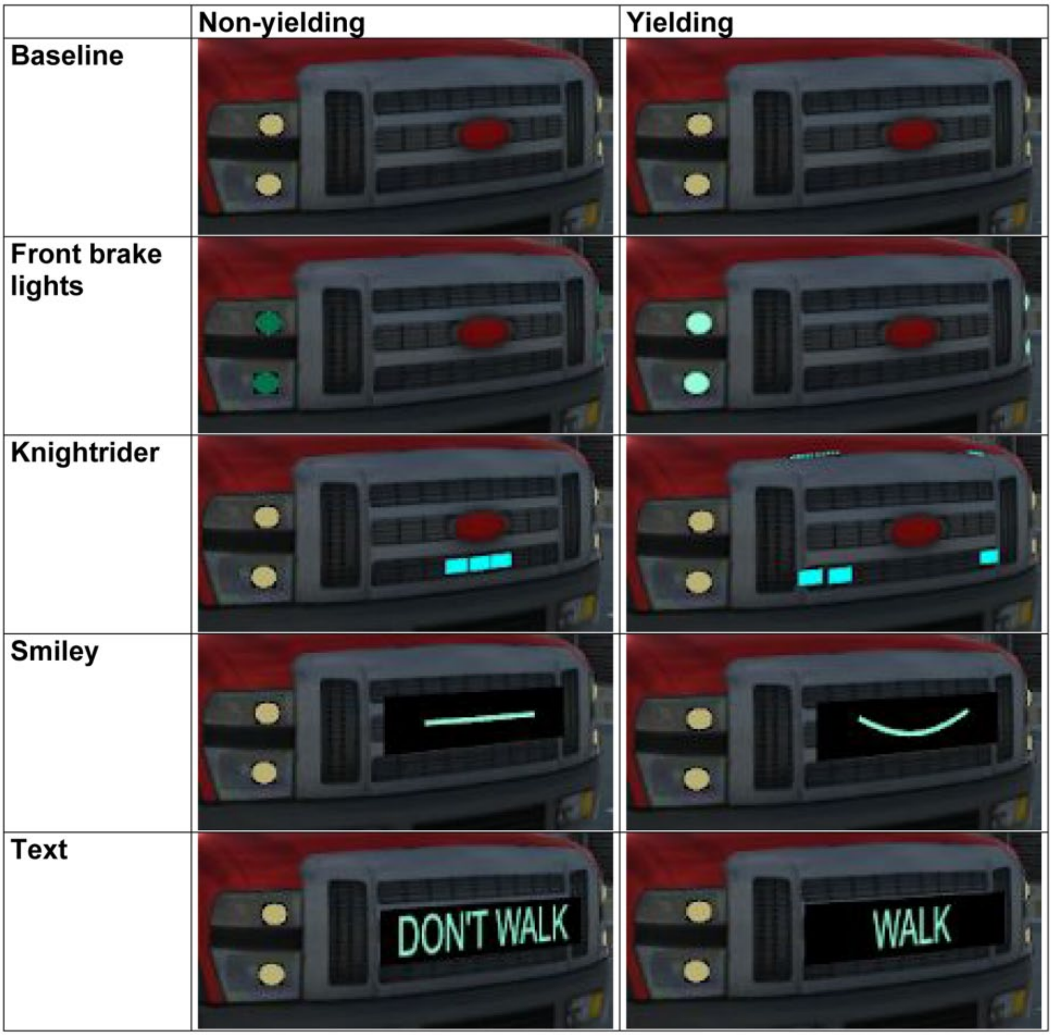

Figure 5. From top to bottom: (1) baseline, (2) front brake lights, (3) Knightrider (in the yielding state, the bar moved from left to right, from the perspective of the participant), (4) smiley, and (5) text.

same eHMI as the nonyielding vehicles in that block. The total experiment, including consent form, practice session, breaks, and questionnaires took about 1 hr per participant.

Each wave consisted of one yielding vehicle, one nonyielding vehicle, and five or six filler vehicles (Figure 6). Thus, one out of seven or eight vehicles yielded. The nonyielding vehicles and “filler” vehicles drove 50 km/h without slowing down, except for the last two filler vehicles, which slowed down in response to the yielding vehicle. While approaching around the corner (i.e., before slowing down), the time gap to the preceding vehicle was 4.0 s for yielding or nonyielding vehicles, and a randomized value between 1.5 and 3.5 s for filler vehicles. The time gaps between waves of a block were about 15 s.

Latin squares with $n = 5$ were used for varying the order of the eHMIs. Latin squares with $n = 9$ were used for varying the order of the type of vehicle and the timing of the eHMI. This means that all participants were exposed to one eHMI with each timing (3 levels) and each vehicle (3 levels).

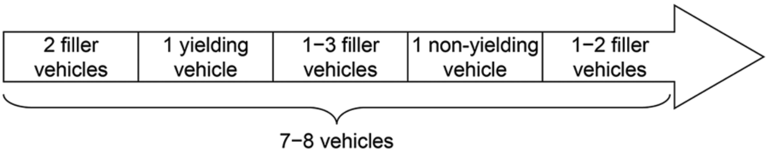

Figure 6. Each wave consisted of seven or eight vehicles. All vehicles showed the same external human-machine interfaces (eHMI) type in a block of nine waves. The timing of the eHMI (50 m, 35 m, or 20 m) varied for the yielding vehicles. The type of vehicle (small, medium, large) varied for all the vehicles. Distances between filler vehicles were randomized. The time gap for yielding and nonyielding vehicles was always 4.0 s. The nonyielding vehicle always preceded the yielding vehicle. Filler vehicles never yielded.

Participant's Task

A handheld remote was used to measure when the participant felt safe to cross at any moment of time. The task was described as follows in the consent form: *Each time you feel safe to cross, please do the following: (1) Press the button on the remote. (2) Keep pressing the button as long as you feel safe. (3) When you do not feel safe to cross anymore, release the button.* The task was practiced in a session of 3 min without eHMI, and was repeated after the preexperiment questionnaire.

Materials and Equipment

The experiment ran on a desktop with Intel(R) Xeon(R) CPU E5-1620 v4 (@ 3.5 GHz) processor, 16 GB RAM, NVIDIA Quadro M5000 graphics card, and Windows 10 Enterprise operating system. Unity version 5.5.0f3 Personal, combined with the Oculus Rift CV1 head-mounted display, integrated headphones, and a constellation tracking camera were used for providing the virtual environment at a resolution of 2,160 × 1,200 pixels.

Background noise and driving sounds were implemented. The driving sounds were the same for each vehicle. The frequency and the volume of the driving sound depended on distance and velocity.

Procedure

A consent form was signed before starting the experiment. A general questionnaire containing demographic questions and a Brief Sensation Seeking Scale (Hoyle, Stephenson, Palmgreen, Lorch, & Donohew, 2002) were administered on a laptop using Google Forms.

The use of head-mounted displays can cause nausea, headache, or other discomforts, and use longer than 1 hr is not advised (Karner, 2017). The participant was asked to indicate his/her well-being using the single-item misery scale (MISC; Emmerik, De Vries, & Bos, 2011) during the breaks of the experiment, to ensure that the experiment was done in a safe and responsible manner, and to monitor simulator discomfort.

After the experiment, a questionnaire for measuring the understanding and preferences of the interfaces was provided. The participants were asked if they felt safe to cross for screenshots of each interface in each state. The presence questionnaire of Witmer, Jerome, and Singer (2005) was used to measure the fidelity of the virtual experience. In addition, a NASA-TLX (Hart & Staveland, 1988) for measuring workload was provided after the experiment. The NASA-TLX included six items: (1) mental demand, (2) physical demand, (3) temporal demand, (4) performance, (5) effort, and (6) frustration, which in this version were answered on a 21-point scale from "very low" ("perfect" for the performance item) to "very high" (failure for the performance item). The scores were transformed to percentages, and a composite score was obtained by taking the mean of the six scores (Byers, Bittner, & Hill, 1989).

Analysis of Button Press Data

The button state (pressed or not pressed) was recorded at a frequency of about 45 Hz. First, we made descriptive plots of the mean number of trials in which the button was pressed as a function of the distance between the pedestrian and the AV. This allows for inferring when participants felt safe to cross as a function of vehicle distance, yielding behavior, and eHMI state (cf. Figure 4).

Subsequently, we tested the effects of the independent variables on the extent to which participants felt safe to cross. For this purpose, we calculated for each trial the “feel safe” percentage, defined as the total time that the button was pressed divided by the driving period. More specifically, for yielding vehicles, the feel-safe percentage was calculated over the 8.42 s period where the vehicle was at a distance between 50 and 7.5 m, that is, up until the vehicle started driving again and the eHMI switched back from its yielding to its nonyielding state. For nonyielding vehicles, the feel-safe percentage was calculated over the 3.62 s period where the vehicle drove between 50 and 0 m. We did not calculate the button-press behavior for the filler vehicles, because these vehicles featured inhomogeneous behaviors and randomly varying gap sizes.

For nonyielding vehicles, we tested the effects of vehicle size and eHMI type on the feel-safe percentage using a two-way repeated-measures analysis of variance (ANOVA; with the three repetitions per condition averaged). For yielding vehicles, we tested the effects of vehicle size, eHMI type, and eHMI timing using a three-way repeated-measures ANOVA. For testing the effect of eHMI timing, we excluded the baseline condition because the eHMI timing did not apply to this condition.

RESULTS

The results of the MISC scale indicated that discomfort was overall low, with most participants reporting “no symptoms” or “slight symptoms.” The level of discomfort increased over the course of the experiment, but all participants completed the experiment. Boxplots of the MISC scores per session are provided in the online supplementary materials.

Nonyielding Vehicles

Initially, approximately half of the participants felt safe to cross (distance of 50 m), and all participants released the button when the vehicle got closer, see Figure 7. Around 0 m, the button press percentage increased again, as it became safe to cross the road once the vehicle passed the participant.

The mean (*SD*) feel-safe percentages were 18.9 (17.6), 18.5 (18.6), 16.7 (19.2), 16.8 (17.4), and 20.1 (19.3) for the baseline, front brake lights, Knightrider, smiley, and text, respectively. The mean (*SD*) feel-safe percentages for the Smart, BMW, and Ford were 20.3 (18.2), 18.8 (18.9), and 15.5 (17.1), respectively.

According to a two-way full-factorial repeated-measures ANOVA, the effect of eHMI type was not significant, $F(4,108) = 1.61$, $p = .176$, $\eta_p = .056$, whereas the effect of vehicle size was, $F(2,54) = 7.74$, $p = .001$, $\eta_p = .223$. There was no statistically significant vehicle size × eHMI interaction, $F(8, 216) = 1.40$, $p = .197$, $\eta_p = .049$.

Pairwise comparisons (i.e., paired *t* tests) showed significant differences between the Smart and the Ford, $t(27) = 3.39$, $p = .002$, and between the BMW and the Ford, $t(27) = 3.02$, $p = .005$. There was no significant difference between the Smart and the BMW, $t(27) = 1.20$, $p = .241$.

Yielding Vehicles

As with the nonyielding vehicles, initially (i.e., for a distance of 50 m) about half of the participants felt safe to cross (Figure 8). In the baseline condition, the percentage of participants who felt safe to cross as a function of distance exhibits a clear U-curve pattern, dropping below 10% around 20 m and then increasing again (Figure 8). This can be explained because crossing is safe when the vehicle is still far away, then becomes unsafe as the vehicle approaches, and then becomes safe again as the vehicle clearly slows down to a stop. With eHMI, this drop in perceived safety is hardly present (for early eHMI timing, at 50 m) or reduced (for eHMI timings of 35 and 20 m). Furthermore, Figure 8 illustrates that participants responded *after* the moment the eHMI changed state (this moment is designated by the vertical dotted line).

The mean (*SD*) feel-safe percentage for the Smart, BMW, and Ford were 73.7 (12.9), 73.0 (13.0), and 72.2 (12.9), respectively. These

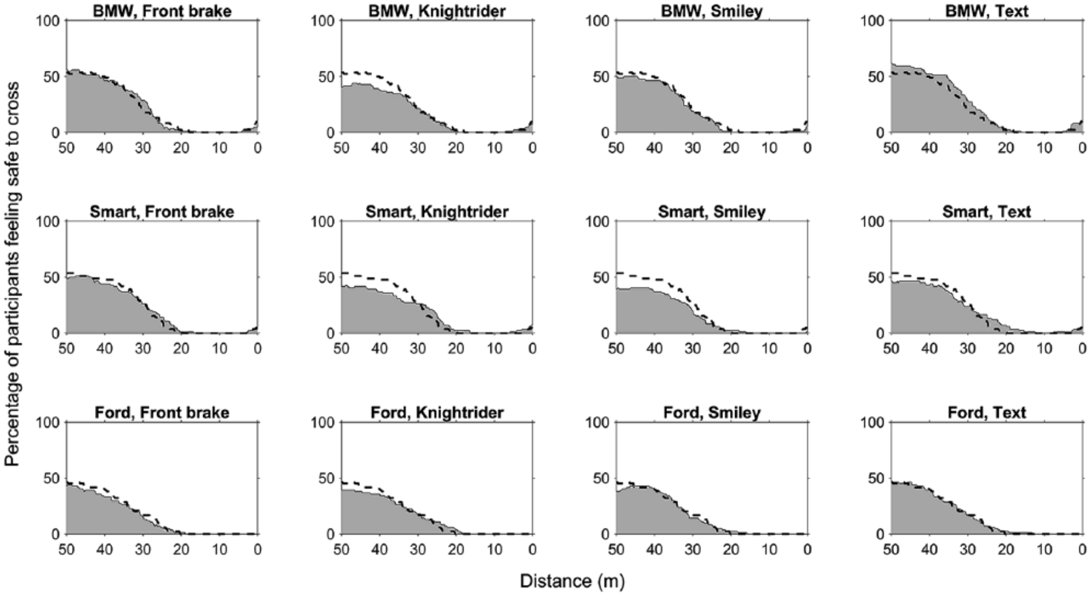

Figure 7. Nonyielding vehicles: percentage of participants feeling safe to cross (*y*-axis) as a function of the distance between the pedestrian and the vehicle (*x*-axis). The dashed line represents the baseline without external human-machine interface (eHMI) for that vehicle size (Smart, BMW, or Ford). The percentage was calculated across 84 trials (28 participants × 3 repetitions).

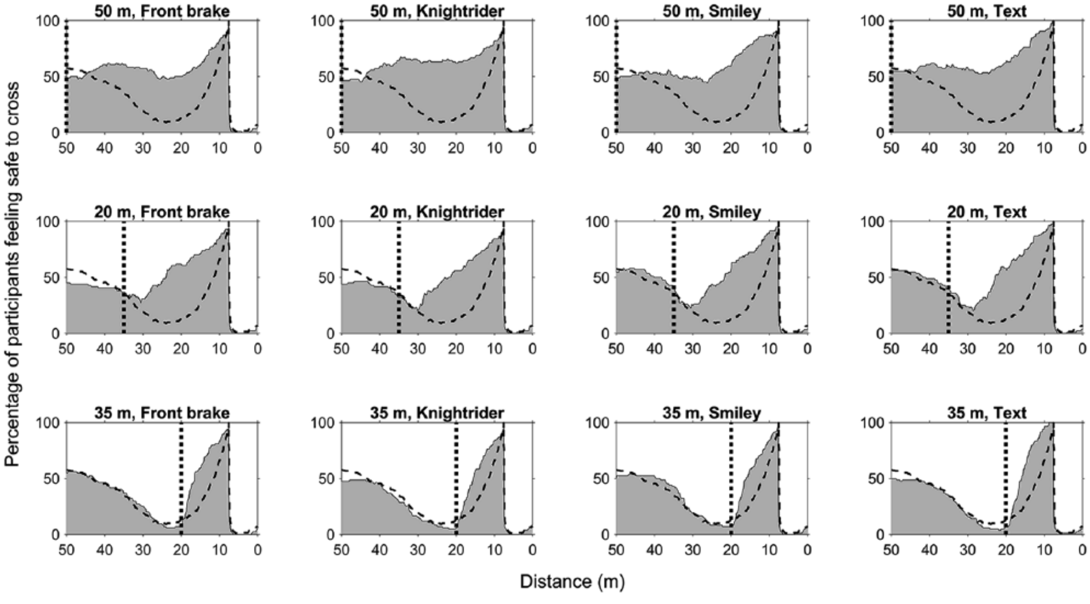

Figure 8. Yielding vehicles: percentage of participants feeling safe to cross (*y*-axis) as a function of the distance between the pedestrian and the vehicle (*x*-axis). Columns show the four external human-machine interfaces (eHMIs) and rows show the eHMI timing (50 m, 35 m, 20 m). The percentage was calculated across 84 trials (28 participants × 3 vehicle sizes; the three vehicle sizes were combined, because vehicle size had only a small effect). The dashed line represents the baseline without eHMI. The baseline percentages were calculated across 252 trials (28 participants × 3 vehicle sizes × 3 repetitions). The vertical dotted line represents the eHMI timing, that is, the moment that the eHMI changed state from nonyielding to yielding.

differences were in the expected direction (i.e., larger vehicles yielding lower feel-safe percentages). It can be seen in Figure 8 that the eHMIs had clear and substantial effects on whether participants felt safe to cross. To illustrate, in the baseline condition, or with late timing, only 1 to 5 of 28 participants (3.6% to 17.9%) pressed the button when the distance was 20 m. However, with eHMIs with early or intermediate timing, between 11 and 20 (39.3% and 71.4%) participants pressed the button (see supplementary materials for an overview of all combinations of conditions). The mean (*SD*) feel-safe percentages were 65.3 (13.2), 74.0 (15.0), 74.4 (14.8), 74.8 (13.1), and 76.2 (12.6) for baseline, front brake lights, Knightrider, smiley, and text, respectively. The mean (*SD*) feel-safe percentages (excluding the baseline condition) were 79.3 (14.6), 75.8 (14.1), and 69.5 (11.4) for the early, intermediate, and late timing, respectively.

According to a three-way full-factorial repeated-measures ANOVA, the effect of vehicle size was not statistically significant, $F(2,54) = 2.67$, $p = .079$, $\eta_p = .090$, the effect of eHMI was significant, $F(4,108) = 16.19$, $p < .001$, $\eta_p = .375$, and the effect of eHMI timing (excluding the baseline condition) was significant as well, $F(2,54) = 44.54$, $p < .001$, $\eta_p = .622$. There was no significant vehicle size × eHMI timing interaction, $F(4, 108) = 1.31$, $p = .272$, $\eta_p = .046$, nor a significant vehicle size × eHMI type interaction, $F(8, 216) = 1.41$, $p = .195$, $\eta_p = .049$. There was also no significant eHMI timing × eHMI type interaction, $F(6, 162) = 1.68$, p = .130, $\eta_p = .058$ (the baseline condition was excluded from calculating this interaction).

Because the eHMI timing and vehicle size were ordinal variables, we also performed tests of within-subjects linear contrasts. Results showed that the effect of vehicle size was significant, $F(1, 27) = 4.28$, $p = .048$, $\eta_p = .137$, and that the effect of eHMI timing was significant as well, $F(1, 27) = 58.33$, $p < .001$, $\eta_p = .684$.

Pairwise comparisons showed that participants' feel-safe percentages were significantly ($p < .001$) higher when they encountered an eHMI instead of no eHMI, $t(27) = 5.54$, 5.18, 5.98, and 7.02 for baseline versus front brake light, Knightrider, smiley, and text, respectively. There were no significant differences between the four eHMIs (all $p > .190$ for the six paired comparisons). The timing conditions differed significantly from each other ($p < .001$ between the three pairs of eHMI timing).

Learning Behavior

The experiment consisted of five blocks, and within each block, one eHMI type was presented in nine waves of vehicles. The feel-safe percentages within a block are shown in Figure 9 for yielding vehicles. A learning effect can be distinguished, with the percentage increasing as a function of wave number. Figure 9 also provides illustrative learning curves, which were fit using the following function: $y = 1/(a + b*\exp(-c*x))$. Here, y is the mean feel-safe percentage, x is the wave number, and a, b, c are the fitted parameters. The fits are provided for the baseline condition (showing a low feel-safe percentage, and no learning), the text condition (showing a high feel-safe percentage, and little learning), and the average of the other three eHMI conditions (showing an initially low feel-safe percentage, and a high feel-safe percentage after learning).

We performed post hoc tests to examine the degree of learning. First, we compared the feel-safe percentage between the first and the last wave, for each eHMI condition. Paired *t* tests showed significant differences between the first and last wave for three of the five eHMI conditions; baseline: $t(27) = 0.02$, $p = .982$, front brake lights: $t(27) = 3.16$, $p = .004$, Knightrider: $t(27) = 5.24$, $p < .001$, smiley: $t(27) = 3.86$, $p < .001$, text: $t(27) = 0.91$, $p = .370$. There was no statistically significant learning for the baseline condition, as evidenced by the fact that the feel-safe percentage remained relatively low (Figure 9). There was also no statistically significant learning for the text eHMI, which was already relatively high in Wave 1.

Second, we compared differences between eHMI conditions for the feel-safe percentages in Wave 1, that is, when participants first encountered the particular eHMI. When selecting Wave 1, the differences between the text and the other four eHMI conditions were statistically significant: $t(27) = 2.35$, $p = .026$ for text vs. baseline, $t(27) = 2.23$, $p = .035$ for text vs. front brake light, $t(27) = 2.55$, $p = .017$ for text vs. Knightrider, and $t(27) = 3.01$, $p = .006$ for text vs. smiley. In other

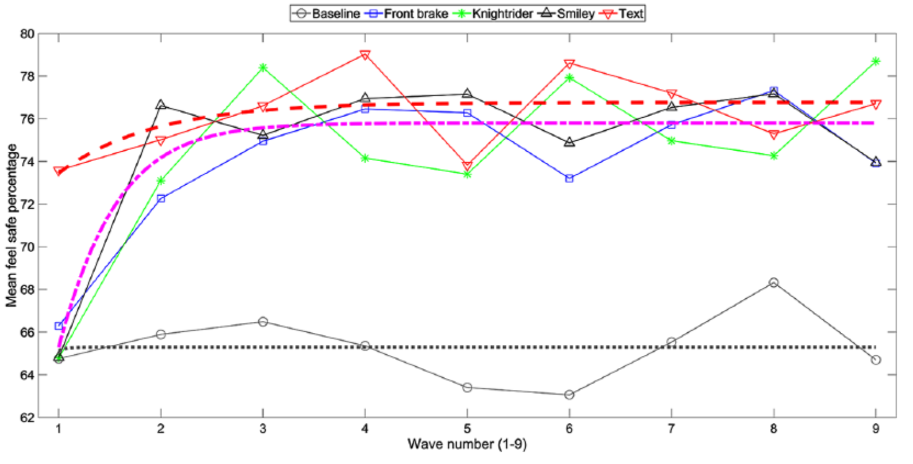

Figure 9. Mean feel-safe percentages for yielding vehicles as a function of the wave number in a block. The experiment consisted of five blocks, with a different external human-machine interface (eHMI) per block. Each wave contained one yielding vehicle. The smooth lines represent learning curve fits for baseline (dotted, gray), text (dashed, red), and the three other eHMIs averaged (dashed-dotted, magenta).

words, although there were no statistically significant differences in the feel-safe percentage between the four eHMI types when averaged across the nine waves (see Section 3.2), the effects were significant for the first wave.

Subjective Experience

After conducting the experiment, the participants were asked whether they felt safe to cross while showing screenshots of the vehicles with the eHMIs in the yielding and nonyielding state. The results (Table 1) show that the text was regarded as the least ambiguous among the four eHMIs.

Participants also completed a questionnaire asking them to order the eHMIs according to their preferences. The results (Table 2) showed that the baseline was selected last by more than 80% of the participants. There were no clear differences between the four eHMIs, although the smiley and Knightrider were ranked somewhat higher than the front brake lights and the text.

Results from the presence questionnaire indicated that participants were well able to adjust to the virtual environment and gave high ratings to the sounds. Relatively low scores (4.25 on the scale from 1 *not at all* to 7 *completely*) were obtained for being able to control events. This can be explained because participants in our experiment could not cross the road. Relatively low ratings, yet still toward the positive end of the scale (4.50 on a scale from 1 *prevented task performance* to 7 *not at all*), were also obtained for the extent to which visual quality interfered with task performance. The full responses of the presence questionnaire are provided in the supplementary material (Table S3).

Participants had the opportunity to provide a textual response to the question *Do you have any comments or notes about the experiment?* Eleven of 28 participants provided an answer. Four participants reported that the resolution of the head-mounted display was low. Three of these participants reported that this made the text display hard to read at a larger distance. The participants commented on the simplicity or monotony of the experiment: “It would be good to have traffic on the other street side,” “A bit dull toward the end,” and “The time slot between cars that let you walk was pretty similar throughout the experiment. That’s why sometimes I was already expecting the car to let me walk without realizing the signs.” Two participants commented that the front brake lights should feature a dynamic component: “Blinking car lights might be a clearer signal to cross the street instead of just switching them on” and “I would prefer flashing upper beams over ‘just’ switching it on.”

TABLE 1: Number of Participants per Response Option to the Question "Do You Feel Safe to Cross?"

Condition	Yes	Not sure	No	Total
Baseline	3	12	13	28
Front brake lights, nonyielding	7	5	16	28
Knightrider, nonyielding	4	5	19	28
Smiley, nonyielding	1	7	20	28
Text, nonyielding	1	1	26	28
Front brake lights, yielding	18	7	3	28
Knightrider, yielding	17	8	3	28
Smiley, yielding	22	6	0	28
Text, yielding	27	1	0	28

Note. eHMI = external human-machine interface. When asked the question, participants were shown a screenshot of the eHMI.

TABLE 2: Number of Participants per Response Option to the Question "Which Interface Would You Prefer the Most?"

Condition	Mean Rank	First Choice (Most Preferred)	Second Choice	Third Choice	Fourth Choice	Fifth Choice (Least Preferred)	Total
Baseline	4.61	1	1	1	2	23	28
Front brake lights	2.79	5	9	2	11	1	28
Knightrider	2.46	8	5	9	6	0	28
Smiley	2.25	7	11	8	0	2	28
Text	2.89	7	2	8	9	2	28

Correlational Analysis

Table 3 shows the results of an exploratory correlation analysis among individual participant characteristics and feel-safe percentages. It can be seen that the feel-safe percentages did not correlate substantially with age, gender, workload, or sensation seeking scores. However, the feel-safe percentages for the eHMIs were strongly correlated with the feel-safe percentages without eHMI (i.e., baseline condition), r = .85 for yielding scenarios, and r = .90 for nonyielding scenarios. These findings indicate that there are reliable individual differences in the extent to which participants felt safe to cross. In other words, for yielding vehicles, participants felt overall safer to cross with eHMI (74.9%) as compared with the baseline condition (65.3%), but there were stable individual differences (*SD* of about 13%).

DISCUSSION

Main Findings

This study investigated the effects of four eHMIs on participants' crossing intentions using a virtual reality set up with head-mounted display.

For nonyielding vehicles, perceived safety was unaffected by the presence of an eHMI: Participants felt equivalently safe to cross when confronted with no eHMI (baseline condition) and an eHMI that did not switch state. This finding can be explained because the baseline condition and the four eHMIs provided the same information, in the sense that the eHMIs did not change state while the vehicle was approaching. Future research could examine eHMIs that change from a neutral state into a cue that the vehicle will *not* yield (e.g., a smiley turning from neutral into a sad state).

TABLE 3: Pearson Correlation Matrix Among Variables

	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Age (years)														
2	Gender (1 = female, 2 = male)	.10													
3	Safe to cross, yielding, no eHMI (%)	.16	.14												
4	Safe to cross, yielding, eHMI (%)	.15	.30	.85											
5	Safe to cross, no yielding, no eHMI (%)	.23	.27	.66	.59										
6	Safe to cross, no yielding, eHMI (%)	.11	.34	.59	.52	.90									
7	TLX mental demand (%)	–.15	.08	–.10	–.11	.00	.00								
8	TLX physical demand (%)	–.33	–.08	–.01	–.07	.30	.18	.42							
9	TLX temporal demand (%)	–.24	.13	–.12	–.25	.16	.17	.53	.39						
10	TLX performance (%)	–.37	–.21	–.06	–.16	.12	.13	.49	.43	.52					
11	TLX effort (%)	–.41	–.09	.21	.11	.26	.20	.58	.43	.70	.70				
12	TLX frustration (%)	–.48	–.13	.01	–.05	.08	.10	.43	.51	.56	.71	.68			
13	TLX total (%)	–.42	–.06	–.02	–.11	.20	.16	.74	.68	.79	.82	.87	.82		
14	Sensation seeking score (%)	.04	–.07	.15	.14	.18	.07	–.19	–.05	.19	–.24	.19	–.06	–.04	
	Mean	24.6	1.75	65.3	74.9	18.9	18.0	41.1	20.2	36.4	27.5	29.8	19.5	29.1	55.1
	SD	2.6	0.44	13.2	13.1	17.6	18.0	19.5	19.2	18.8	18.8	19.1	18.4	14.9	16.5

Note. eHMI = external human-machine interface. Correlations are among age, gender, mean feel-safe percentages, self-reported workload (NASA-TLX), and self-reported sensation seeking score ($N = 28$).

For yielding vehicles, participants felt safer to cross (i.e., higher button press percentages) with all four eHMIs. The feel-safe percentages were about 10% lower for the baseline condition than for the four eHMIs. Although a difference of 10% seems uncompelling, it should be noted that this value represents an average of the entire 8.42-s period of approaching and standing still. When zooming in at specific parts of the approach phase, the differences were substantially stronger: In the baseline condition, about 10% of participants felt safe to cross when the vehicle was close, whereas this was about 60% for the eHMIs with early and intermediate timing. Figure 8 showed that participants who were presented with an early timing (distance of 50 m) eHMI were more likely to press the button *before* the vehicle started to slow down (distance of 35 m). The results are in line with Chang et al. (2017) and Böckle et al. (2017), who showed that pedestrians do respond to cues provided by an eHMI. The effect sizes for eHMI timing were strong, indicating that the earlier the eHMI switched state, the earlier participants felt safe to cross. Thus, with an eHMI indicating that the AV intends to stop, more pedestrians are expected to cross before the AV. Hence, eHMI can enhance traffic efficiency.

Learning Behavior and Perspective Taking

Over a sequence of nine exposures to the same eHMI, only text appeared to require no significant learning. In essence, the smiley, front brake light, and Knightrider provided the same information as the text, as the eHMIs changed state at the same moment. However, the nontextual eHMIs (front brake light, Knightrider, and smiley) provided no explicit instruction to the participants. For example, when the smiley changes to “sad,” this could mean several things: A participant may think that the sad face pertains to him/herself (an egocentric perspective) or to the vehicle (an allocentric perspective). Research suggests that switching from an egocentric to an allocentric visual perspective absorbs cognitive processing time (Martin et al., 2018). In particular, young children (Ampofo-Boateng & Thomson, 1991; Epley, Keysar, Van Boven, & Gilovich, 2004; Piaget & Inhelder, 1956) and older persons appear to have difficulty in taking another agent’s perspective (Martin et al., 2018).

The front brake was green when the vehicle was maintaining speed. Our choice of green is consistent with a survey study by Zhang, Vinkhuyzen, and Cefkin (2017), which found that respondents associated green with a moving vehicle. However, our color coding may still have been confusing for the participants. The literature appears to provide no consistent answer regarding the type of color coding to use: Antonescu (2013) and Jandron (1998) proposed red front brake lights; Walton (1999) proposed blue lights, whereas Barry and Fraser (1938) and Petzoldt et al. (2018) opted for green ones. Petzoldt et al. (2018) motivated their choice of green for yielding vehicles by stating that the front brake light “has no warning function, but rather indicates that a safe crossing in front of the vehicle might be possible.” We argue that the nontextual eHMIs—such as the smiley and front brake light—can only be interpreted after having learned that a change of state implies that the vehicle will yield. Participants encountered AVs for one of the first times in their lives. It is possible that pedestrians start to feel safer when having more experience and knowledge about AVs, as pointed out by Núñez Velasco et al. (2016).

The results of the learning curves were consistent with the results from the postexperiment questionnaire, where 27 out of 28 participants felt safe to cross with the text WALK (Table 1). Our findings also provide confirmation of online questionnaire research by Fridman et al. (2017), who found that text was among the least ambiguous symbols and that colored lights were regarded as ambiguous. More generally, research indicates that language-based interfaces have high potential in automated driving (Politis, Brewster, & Pollick, 2015). Thus, we conclude that the use of an eHMI increases the total time that pedestrians feel safe to cross, and text is regarded as the least ambiguous. Future research is needed to evaluate whether text-based eHMIs are feasible, as they require knowledge of the conveyed language and messages might not be readable from larger distances.

Effects of Vehicle Size

Our results showed that vehicle size had effects that were consistent with the literature (e.g., Kadali & Vedagiri, 2016) in that larger vehicles were deemed less safe. Effect sizes were small, however: For nonyielding vehicles, the mean feel-safe percentages were 20.3, 18.8, and 15.5 for the large, medium, and a small vehicle, respectively, whereas for yielding vehicles, the corresponding percentages were 73.7, 73.0, and 72.2.

Advantages and Limitations of Our Experimental Paradigm

The presence questionnaire indicated that the simulation was regarded as realistic and immersive, which supports the idea that virtual environments are a suitable alternative to field tests (Brade et al., 2017). However, some participants indicated that the screen resolution was low and that this may have affected their performance when looking further away. Furthermore, no avatar was implemented in the environment (e.g., no feet or legs were shown), and participants did not actually cross the road. Instead, our experiment used a remote-control button to measure whether the participant felt safe to cross. The advantage of our approach, as compared with crossing the road, is that we collected continuous "feeling safe" measurements as a function of distance (see Figures 7 and 8) as opposed to a single crossing decision per encounter. Future research could be conducted by instructing participants to cross the road. The advantage of actually crossing would be increased realism and the possibility to extract information from the bodily measurements, such as hesitative stepping onto the road and walking speed.

All participants finished the experiment, and the MISC did not reveal large discomforts. Therefore, it can be concluded that head-mounted displays can be used safely in the conditions of our experiment, that is, no translation through the virtual environment, young participants, and taking a break approximately every 5 min. Even though the experiment can be regarded as rather monotonous, participants did not perceive the task to be highly taxing. This is as evidenced, for example, by the low score on the frustration item of the NASA TLX (19.5% on a scale from very low to very high). Our experiment did not investigate crossing behavior when an eHMI does not work properly, and the topic of errors of omission and errors of commission deserves further investigation (cf. Skitka, Mosier, & Burdick, 1999). Furthermore, our experiment used university participants and an unambiguous European environment with clear weather. In the United States, pedestrians are not supposed to cross the road midblock. This would limit the generalizability of our findings to European contexts. Also, the idea that AVs should stop for pedestrians standing at the edge of the roadway is debatable, as it may be a hard problem for AVs to determine the intent of the pedestrian (Kooij et al., 2014; Vinkhuyzen & Cefkin, 2016).

Text may be poorly visible on rainy days and may have to be complemented with a universal color or symbol to support all pedestrians, including children. A questionnaire study by Charisi, Habibovic, Andersson, Li, and Evers (2017) showed that a stop sign, a red stopping light, and a walk signal were correctly interpreted by children, whereas a walking figure, an anthropomorphic animation, and a projected zebra crossing were not (see also Fridman et al., 2017, for a variety of ambiguous and nonambiguous eHMIs). Another issue with text is that it requires focused attention to read; it may therefore be unsuitable for quickly extracting information in a brief glance or from peripheral vision (Cefkin, 2018). Research in visually demanding scenarios, such as road crossings where AVs approach from multiple directions, may be a suitable test case for text-based eHMIs. Future research could investigate behaviors of groups of pedestrians (cf. Jiang et al., 2018) or children (cf. Chihak, Grechkin, Kearney, Cremer, & Plumert, 2014). Finally, future research could also explore the effectiveness of automated vehicles that provide auditory cues to pedestrians (Mahadevan et al., 2018; Matthews, Chowdhary, & Kieson, 2015; Merat et al., 2018).

CONCLUSIONS

In conclusion, eHMIs increase the efficiency of pedestrians' crossing decisions, in the sense that pedestrians feel safe to cross when it is indeed safe to do so. Furthermore, we showed that certain types of eHMIs (smiley, front brake lights, Knightrider LED strip) require learning, whereas a textual display is understood directly. In the postexperiment questionnaire, participants rated having an eHMI as preferable over having no eHMI. Currently, car manufacturers are proposing various types of prototypes, including LED strips and external lights. Our findings indicate that the design of eHMIs may require standardization and regulation, as it is impractical—and potentially dangerous—to have a variety of eHMIs on future roads.

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KEY POINTS

- Participants were immersed in a virtual environment and encountered approaching vehicles with different eHMIs.
- The eHMIs increased efficiency, that is, the time that participants felt safe to cross when the vehicle was yielding.
- A textual eHMI (WALK / DON'T WALK) was regarded as least ambiguous, as evidenced by learning curves and self-reports.
- It is viable to communicate the intention to yield before the vehicle initiates the yielding maneuver.

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SUPPLEMENTARY MATERIAL

Supplementary material is available for this article at https://doi.org/10.4121/uuid:622905c5-d760-49e9-96c2-b116a679ec33

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