Transportation Research Interdisciplinary Perspectives 23 (2024) 100990

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

Effects of a frontal brake light on pedestrians' willingness to cross the street

Daniel Eisele [1,*], Tibor Petzoldt [2]

Chair of Traffic and Transportation Psychology, Technische Universität Dresden, 01062 Dresden, Germany

ARTICLE INFO

Keywords:
Automated vehicle
AV
eHMI
Communication
Implicit
Interaction

ABSTRACT

Effects of a frontal brake light (FBL, a potential external human–machine interface for automated vehicles) on participants' self-reported willingness to cross a vehicle's path were investigated. In a mixed design online study (vehicles in the experimental group were equipped with FBLs, there were no FBLs in the control group), participants observed videos of a vehicle approaching at different speeds from the perspective of a pedestrian standing at the curb. The vehicles exhibited either yielding behavior (braking onset 55 m or 32 m before standstill in front of the pedestrian's position) or non-yielding behavior (approach speed was maintained). Participants specified their willingness to cross the vehicle's path at different distances. When the vehicle yielded (i.e., FBL was activated), willingness to cross was significantly higher in the experimental group than the control group. Notably, we further observed a significantly lower willingness to cross in the experimental group than the control group when the vehicle did not yield (i.e., FBL was deactivated). Novel external human–machine interfaces might therefore influence the interaction with vehicles not only when they are activated but also when they are deactivated.

Introduction

Along with the introduction of increasingly automated vehicles (AVs) on public roads, human-robot interactions are introduced to collaborative tasks which currently take place between humans. This has sparked a growing body of research investigating how AVs should interact with vulnerable road users. The goal is to ensure successful human-AV interactions in terms of safety, performance, and human satisfaction (Markkula & Dogar, 2022). A key step towards this goal is to find out how humans understand and react to the behavior and the communicative cues of AVs. This is especially important, as misunderstandings might lead to potentially fatal consequences. In order to explicitly inform surrounding road users about an AV's state and intentions, efforts have been made to develop prototypes of so-called external human–machine-interfaces (eHMIs). While the proposed designs vary considerably (Wilbrink et al., 2023), most use light-emitting displays to communicate their messages. The negotiation of the right-of-way is considered a central topic (Dey et al., 2020a, p. 8). Most prototypes communicate aspects of the AV's *intention* (e.g., "I intend to yield to you"). Notably, communicating aspects of the *current behavior* of an AV (e.g., "I am decelerating") has received little attention so far (Clamann et al., 2017; Wenjun et al., 2023).

A frontal brake light (FBL) which communicates that the vehicle is decelerating to road users ahead of (and potentially oblique to) the vehicle, can be a simple approach to support the human-AV interaction (Petzoldt et al., 2018). The FBL activates as soon as the vehicle begins decelerating, remains activated during the deceleration and deactivates as soon as the vehicle stops decelerating. The FBL itself does neither provide a reason for the deceleration nor communicate the AV's future intentions (e.g., whether it will continue decelerating and come to a standstill or start accelerating again). While such intentions could possibly be inferred from the situational context (e.g., when the FBL lights up, as an AV approaches a zebra crossing with a pedestrian waiting at the curb), the FBL lacks the certainty that messages like "I am yielding to you" can provide. However, in contrast to "I am yielding to you", the FBL does not require the vehicle to have a continuously reliable and comprehensive understanding of its surroundings in order to work. From a technological perspective, the FBL is as simple as the brake lights on the back of current motorized vehicles. Accordingly, it is not surprising that patents for similar ideas date back nearly a century (Douglass, 1924; Pirkey, 1925). Moreover, the FBL has the strength that its message holds true for any observer (including other drivers), in

* Corresponding author.
E-mail addresses: daniel.eisele@tu-dresden.de (D. Eisele), tibor.petzoldt@tu-dresden.de (T. Petzoldt).
[1] https://orcid.org/0000-0002-1751-3342
[2] https://orcid.org/0000-0003-3162-9656

https://doi.org/10.1016/j.trip.2023.100990
Received 22 August 2023; Accepted 5 December 2023
Available online 16 December 2023

contrast to messages such as "I am yielding to you", which have specific and exclusive addressees. The latter might lead to safety relevant misunderstandings if a road user incorrectly assumed to be the intended addressee (Tabone et al., 2021). The FBL therefore remains functional in complex everyday traffic scenarios with multiple road users present (see Dey et al., 2020b, Dey et al., 2021).

Effects of FBLs have been studied in few empirical studies so far. Recent evidence from a video based lab experiment suggests that an FBL helps to identify decelerations considerably earlier (Petzoldt et al., 2018). In another recent longitudinal field study, 102 (non-automated) vehicles on the apron of an airport were equipped with FBLs for 3.5 months. The surveyed staff members rated the FBL overall positively and stated that it improved communication and safety (Monzel, 2018). In an earlier study, participants used an FBL on their private vehicle for a month. They thought that the FBL had merit and were more willing to buy an FBL than participants from the control group who were not familiar with the concept of an FBL before being surveyed. The latter group also, in theory, saw merit in the concept of an FBL (Post & Mortimer, 1971). In conclusion, researchers have plausibly argued that attitudes towards the FBL are positive, both in theory and after real life experiences, and that it facilitates the perception of a vehicle's deceleration. It remains unclear, however, whether the FBL causes actual behavioral changes in interactions with vehicles (like crossing a street across their path) since the identification of deceleration can certainly play an important role in the decision making process but "is neither identical nor necessarily perfectly correlated with the actual initiation of a crossing" (Petzoldt et al., 2018, p. 4). Therefore, potential effects of the FBL on behavioral intent like a pedestrian's willingness to cross should be investigated in a next step.

Of course, the detection of a deceleration (vehicle decelerates: yes/no), which is facilitated by an FBL, is just one factor in pedestrians' decision-making on whether to cross. It has been shown that variations in vehicle behavior like its deceleration rate and approach speed, the distance from the pedestrian at braking onset, and the remaining physical distance between vehicle and pedestrian influence street-crossing greatly (Dey et al., 2019; Ezzati Amini et al., 2019). The FBL and other eHMIs that have been proposed so far are meant to only communicate certain aspects of a vehicle's state, behavior or intention explicitly while the vast majority of cues remains implicit. Findings from prior studies point to the ongoing importance of implicit cues that are communicated by the vehicle's kinematics when eHMIs are present (e.g., Domeyer et al., 2020; Lee et al., 2022). It has been argued that they will remain the basis for on-road communication and should be augmented by eHMIs whenever they provide an advantage (de Winter & Dodou, 2022). It seems plausible that effects on pedestrian behavior caused by an eHMI can interact with the effects caused by a vehicle's (implicit) kinematic cues. Therefore, such interactions should be considered in eHMI development in order to predict possible ramifications caused by the introduction of an eHMI as precisely as possible.

It should be noted that the effects of eHMIs might go beyond situations in which they are actually activated. The fact that actively communicating yielding intent via an eHMI has effects on crossing decisions (e.g., Faas et al., 2020) raises the obvious question of how, in similar scenarios, road users would respond to vehicles that are equipped with an eHMI, but don't communicate that message. It seems plausible to assume that knowing a vehicle is equipped with a certain eHMI from prior interactions can also influence interactions in situations in which the eHMI is not activated / an eHMI is completely absent. Indeed, in a condition of mixed traffic (some vehicles braking with FBL activated, some vehicles braking without), observers were slower to identify deceleration for non-FBL vehicles compared to a condition in which none of the vehicles was equipped with any eHMI (Petzoldt et al., 2018). It seemed as if pedestrians were waiting for some explicit information on deceleration, potentially resulting in more cautious decisions when this explicit information is not available. As such possible secondary effects can be undesirable, they should also be considered in eHMI development.

Based on the above considerations, we designed a study in which both the presence of the FBL (i.e., the explicit information on the fact that the vehicle is braking and when/where the braking onset begins) and kinematic cues (approach speed and deceleration rate) were manipulated in order to study their effects on pedestrian's willingness to cross. We considered situations in which the FBL is active (i.e., vehicle brakes) as well as non-active (i.e., vehicle does not brake). Based on prior research, we expected a dominant effect of the vehicle's kinematics on willingness to cross. We further expected effects of the FBL on willingness to cross. During decelerations, we hypothesized to observe a higher willingness to cross in front of a vehicle with an FBL than without. We further assumed that knowing about the concept of an FBL and interacting with it might lead to a lower willingness to cross when the FBL is not activated (i.e., when the vehicle does not decelerate).

Methods

Design

To answer whether an FBL influences pedestrians' willingness to cross, we conducted a randomized online study with a mixed design featuring two groups. Participants were shown videos (from the perspective of a pedestrian standing at the curb) of approaching vehicles on a straight one-lane street. Following Dey et al. (2019), the videos ended at different points in time, when the vehicle's physical distance from the observer was either 45, 30, 15, 5 or 1.5 m. Within groups, we varied the vehicle's initial approach speed (30/50 km/h, both common speeds in German urban traffic) and the vehicle's behavior (non-yielding/yielding). In non-yielding conditions, the approach speed was maintained until the vehicle passed the observer's position. In yielding conditions, the vehicle decelerated for either 55 or 32 m and came to a standstill at the observer's position. We refer to this variable as *braking onset*. The combination of the factor levels resulted in 28 unique variations. Each of these was shown twice (to better estimate the "true" willingness to cross in the respective variation) in randomized order, amounting to 56 videos per participant. Whether vehicles were equipped with an FBL, was varied between groups. In the experimental group (EG) all vehicles were equipped with an FBL. In the control group (CG), vehicles were not equipped with an FBL and there was no mention of the existence of FBLs. Table 1 provides an overview over the factors and factor levels.

The participants' task was to specify their willingness to cross on a Likert scale ranging from 1 (very low) to 10 (very high) at the moment the video ended. In Germany, where the experiment was conducted, it is the driver's decision whether to yield to a pedestrian intending to cross in places where this is not explicitly regulated. There is no obligation to do so. However, of course, for a pedestrian, (safely) crossing an approaching vehicle's path is generally permitted and common in

Table 1
Overview over factors and factor levels.

Between Subjects	Within Subjects		
Presence of FBL on vehicle	Approach speed	Yielding Behavior	Distance from Pedestrian when video cut off
FBL present	50 km/h	no yielding, approach speed maintained	1.5 *m*
FBL absent	30 km/h	yielding, braking onset 55 m from pedestrian	5 *m*
		yielding, braking onset 32 m from pedestrian	15 *m*
			30 *m*
			45 *m*

everyday traffic.

Participants

50 German residents took part in the study. Initially, a convenience sample was recruited from the first author's personal network. To achieve the aspired sample size, additional participants were recruited through Prolific, an online platform, which distributes online experiments to paid research participants for a service fee (Prolific, 2022). These participants received 4 GBP as a compensation. Screenings revealed no significant differences regarding street-crossing willingness between the two subsamples. The experimental software (Labvanced, 2022) randomly assigned 30 participants to the EG and 20 to the CG. Two participants (one in each group) were excluded from analysis based on their unsystematic, inconsistent ratings regarding their willingness to cross. The remaining 48, (27f, 21 m) were between 20 and 69 years of age ($M = 31.6$, $SD = 11.5$).

Material

The videos of a vehicle approaching the camera perspective were rendered using the VICOM Editor (2021). The perspective was set to an average German eye-height of 1.6 m (Windel, 2019). The top part of Fig. 1 illustrates the different behaviors of the vehicle. The different lines depict the vehicle's speed (y-axis) relative to the physical distance from the pedestrian (x-axis). Every clip started when the vehicle was 100 m away from the pedestrian. The vehicle either maintained its speed continuously (horizontal lines) or started to decelerate in a linear fashion at the two marked points (dashed lines) until it came to a standstill at the participant's position. This corresponded to deceleration rates between 0.6 m/s^2 and 3.0 m/s^2, which cover the spectrum of service braking in manual driving (i.e., everyday braking, no emergency maneuvers) according to Schnabel and Lohse (2011) as well as preferred rates in automated vehicles (Scherer et al., 2016). Apart from being of theoretical interest, the differences in the vehicle's kinematics made the vehicle's behavior less predictable for the participants. At standstill, we left enough space between the vehicle and the viewer's perspective to convey the impression that a pedestrian could cross in front of the vehicle's hood. The dotted lines in Fig. 1 mark the five points where the different video segments were cut.

Apart from the vehicle's behavior (and the FBL in the experimental group), there was no difference in the video clips. The FBL was added using DaVinci Resolve (2022). Fig. 2 shows screenshots from a sample clip (top: control group, bottom: experimental group). The FBL's color (magenta; RGB 225, 0, 225) was chosen for pragmatic reasons, as it is unusual in German traffic and was well visible (Werner, 2019). The stimuli were purely visual; there was no audio track. The clips were presented in 50 fps and a maximum resolution of 1920 x 1080 px.

Procedure

Participants received a link to the experiment via e-mail or the Prolific platform and used their own hardware to take part. Smartphones and devices with a screen resolution lower than 1280 × 720 pixels were excluded from participation. After they gave informed consent, they were familiarized with the traffic situation by a screenshot from the stimuli and the following text (in German): "You are a pedestrian on the sidewalk of a one-way street. You are standing at the curb, as you intend to cross the street. You have a clear destination. You are on the way to your workplace/university. You are not in a hurry. This experiment includes several video clips in which a vehicle will approach you. The camera's perspective depicts your visual field as the pedestrian. These videos will stop at predefined points in time." The participants in the EG were further explicitly informed about the FBL's functionality and messages: "You have surely noticed the magenta-colored light on the vehicle's grill. This is a frontal brake light. It indicates that the vehicle is braking. It activates as soon as the vehicle begins to brake, it continuously remains activated as long as the vehicle is braking and deactivates at the moment the vehicle stops braking. So, the frontal brake light works just as ordinary brake lights at the rear of a motorized vehicle do." After watching a group-specific example video of a vehicle braking to standstill, their task (specify their willingness to cross on a Likert scale ranging from 1 to 10 at the moment the video ended) was explained. They then had the opportunity to practice the task three times, before

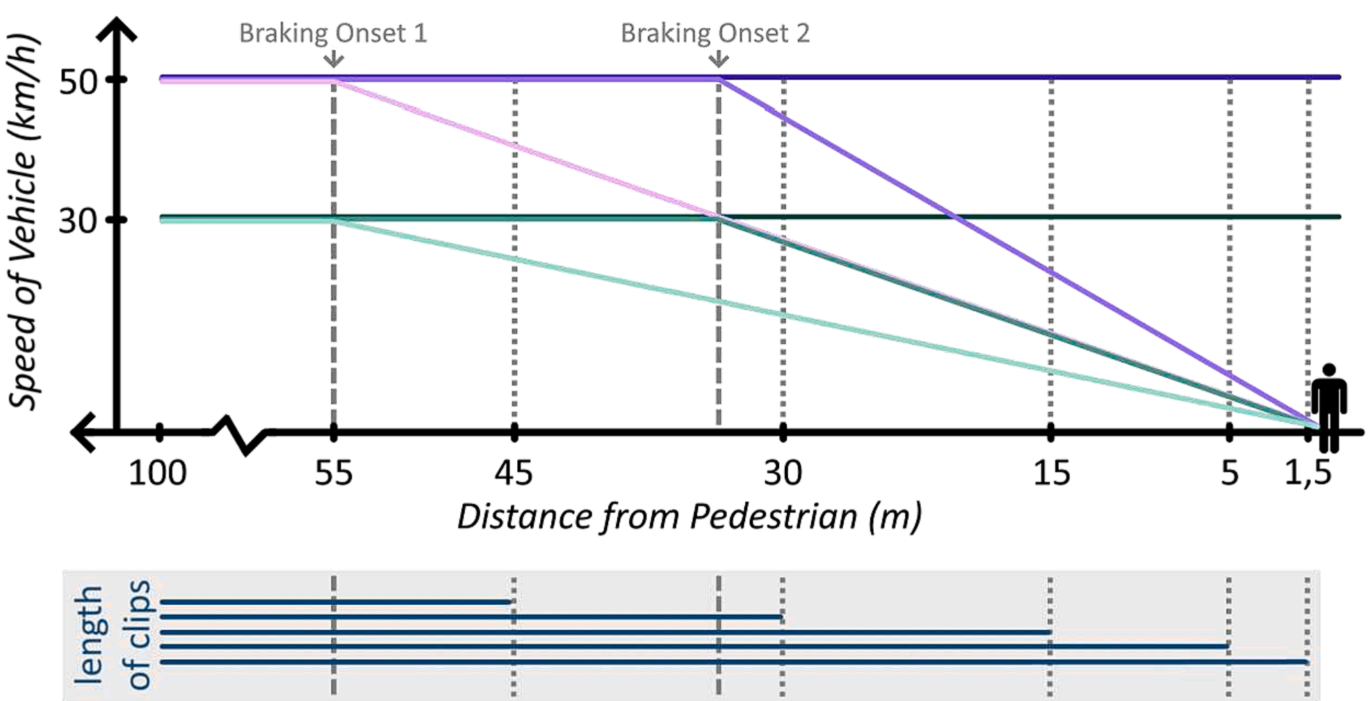

Fig. 1. The different behaviors of the vehicle represented by its speed at different distances from the pedestrian (top) and the distances from the pedestrian's position at which the different segments ended (bottom).

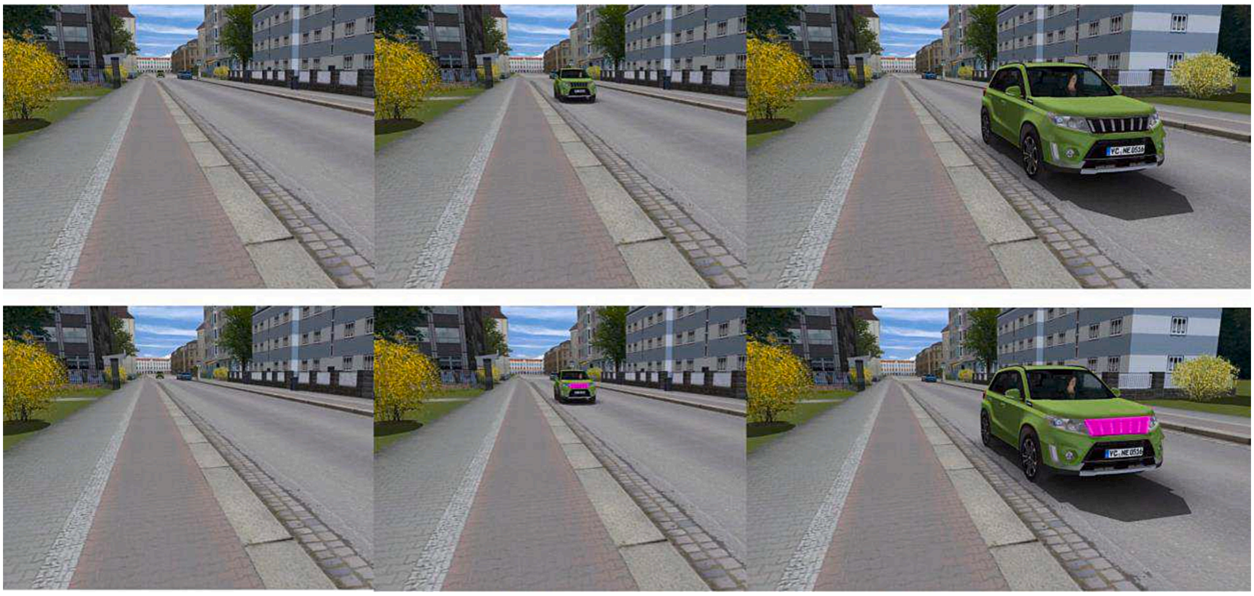

Fig. 2. Screenshots of a video clip in the control group (top) and experimental group (bottom).

the 56 experimental trials began. Afterwards, they rated the FBL on the short version of the User Experience Scale (UEQ-S, Schrepp et al., 2017), which measures user experience on a pragmatic and hedonic dimension and provides an overall score. They then rated their level of (dis-) agreement with several statements regarding the potential usefulness and safety effects of the FBL on a 5 point Likert scale (Petzoldt et al., 2018). At the end, they indicated their age and gender. After finishing, they had the opportunity to download a debriefing that explained the experimental mechanics of the two groups and the goal of the study. The experiment took an average of 16 min to complete. This study complied with the tenets of the Declaration of Helsinki (a set of ethical principles for experiments involving human subjects).

Analysis

Two Mixed RMANOVAs were calculated in Jasp Team (2022) to analyze the variances in the yielding and the non-yielding conditions separately. Whether the vehicles were equipped with an FBL was the between-subjects factor. Within-subject factors were the vehicle's approach speed, the distance when deceleration began (braking onset) and the vehicle's physical distance from the pedestrian at the time the video ended. Willingness to cross was the dependent variable. The distance 45 m was excluded from the analysis of yielding conditions, as yielding vehicles were not yet decelerating at that point when the braking onset was 32 m. This does not apply to non-yielding conditions, where all distances were analyzed.

An inspection of the data subsets revealed violations of the RMANOVA's assumptions. Where Mauchly's test indicated a violation of sphericity, Huynh-Feldt corrected F-Statistics are reported for yielding data (ε was above 0.75) and Greenhouse-Geisser corrected values for non-yielding data (ε was below 0.75), following Field (2017). Levene's test revealed heteroscedasticity in half of the yielding conditions (which seems to be a desirable effect of the FBL, discussed below). Following Pituch and Stevens (2016), we assume our ANOVAs remained robust despite this violation, as our group size ratio falls within the commonly referred to cutoff. Ratings of the FBL on the UEQ-S were analyzed using the tool provided by its authors (Schrepp, 2018).

Results

Yielding conditions (FBL active in experimental group)

Fig. 3 depicts willingness to cross relative to the different distances between vehicle and pedestrian during the yielding process. Values of the two groups are depicted separately. As one would expect, willingness to cross was highest at the furthest distance in both groups. Willingness decreased at closer distances and rose again at the smallest distance, shortly before the vehicle came to a standstill. This difference between distances was significant, $F(3, 282) = 11.8$, $p < .001$, $\eta_p^2 = 0.11$.

Fig. 3 further shows that there was a between-groups difference in willingness to cross. At every distance, willingness to cross was higher in the experimental group (active FBL) than the control group (no FBL), suggesting a main effect of the FBL on willingness to cross in yielding conditions. This effect was indeed significant, $F(3, 282) = 11.8$, $p < .001$, $\eta_p^2 = 0.11$. Simple main effects indicated that the difference was

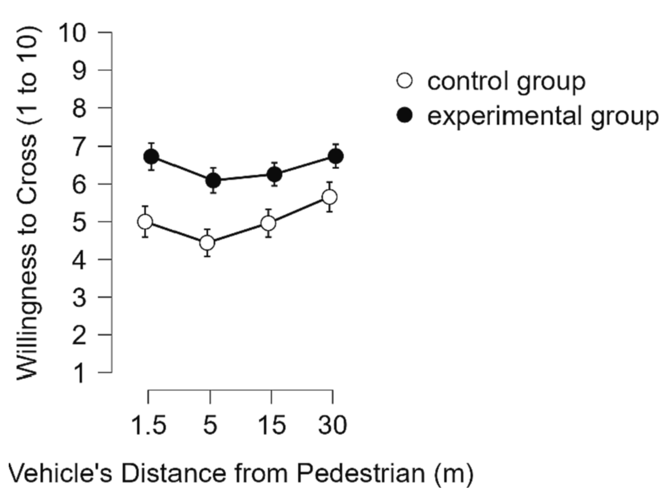

Fig. 3. Yielding Conditions: Willingness to cross relative to physical distance between vehicle and pedestrian, split by groups. Note. Values are averaged across approach speeds (30/50 km/h) and braking onsets points (32/55 m); see Table 2 for detailed descriptive values. As the vehicle was braking in these conditions, the FBL was active in the EG; there was no FBL in the CG. Error bars display the normalized 95 % confidence interval of the mean (Morey, 2008).

significant at every distance (every $p < .008$). There was no significant interaction between distance and group membership. An inspection of the descriptive values showed that the variances in the experimental group in 30 km/h conditions were consistently smaller than those in the control group (see *SDs* in Table 2). These differences were indeed significant in 7 of 8 conditions (every $p < .03$). The differences in conditions with an approach speed of 50 km/h were only significant at a distance of 1.5 m ($p = .02$).

As one would expect, we observed significantly lower willingness to cross in trials with a 50 km/h than 30 km/h approach speed ($F(1,94) = 228.7$, $p < .001$, $\eta_p^2 = 0.71$) and a lower willingness in trials with the 32 m than the 55 m braking onset, $F(1,94) = 70.4$, $p < .001$, $\eta_p^2 = 0.43$. There was no interaction between group membership and these factors. Descriptive values of willingness split by approach speed, distance and group membership are supplied in Table 2.

Non-yielding conditions (FBL inactive in experimental group)

Fig. 4 depicts willingness to cross relative to the vehicle's distance from the pedestrian in non-yielding conditions (i.e., the approach speed was maintained). Values of the two groups are depicted separately. As one would expect, willingness to cross was highest when the vehicle was the furthest from the pedestrian and decreased at closer distances, suggesting a main effect of distance on willingness to cross. This effect was significant, $F(2.5, 236.9) = 169.9$, $p < .001$, $\eta_p^2 = 0.64$. Bonferroni-corrected post-hoc tests showed that the stepwise differences between 45 m and 5 m were significant (every $p < .001$). The difference between 5 m and 1.5 m was not significant.

We again observed a between-groups difference, pointing to an effect of the FBL in non-yielding conditions. Fig. 4 shows that willingness to cross was lower in the experimental group than the control group (in contrast to yielding conditions, see Fig. 3), a difference that, although comparatively small, was found to be significant, $F(1, 94) = 4.1$, $p = .045$, $\eta_p^2 = 0.04$. There was no interaction between group membership and distance.

As one would expect, we observed a significantly lower willingness to cross at a speed of 50 km/h than 30 km/h, $F(1,94) = 383.7$, $p < .001$, $\eta_p^2 = 0.43$. There was no interaction between group membership and speed. Descriptive values of willingness to cross split by approach speed, distance and group membership are provided in Table 3.

Subjective ratings of the FBL

Overall, participants in the experimental group reported a positive view of the FBL. With regards to user experience (as measured by the UEQ-S, possible values range from −3 to + 3) the pragmatic quality received an average rating of 2.3 ($SD = 0.7$), which is labeled "excellent" on the UEQ-S benchmark. The hedonic quality was 1.4 ($SD = 0.9$), which corresponds to "good". This amounts to an "excellent" overall rating of 1.8 ($SD = 0.7$).

Table 4 shows the participants' assessment of the frontal brake light as measured by agreement to general statements. Most participants liked the general idea of an FBL. They also felt that the FBL might contribute to road safety, while they were less (but still somewhat) optimistic regarding its potential to increases traffic efficiency.

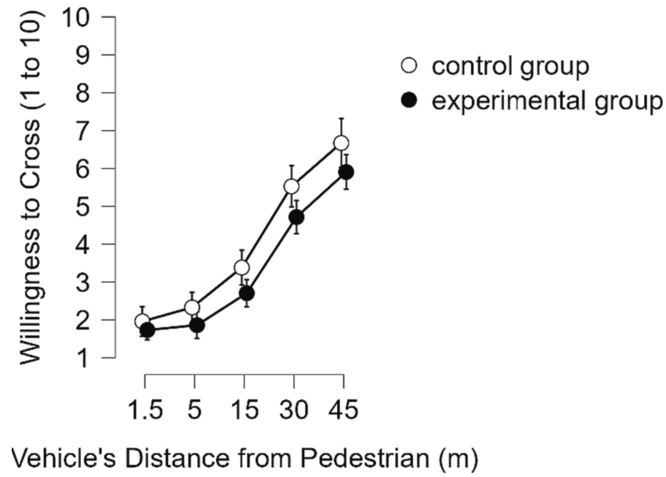

Fig. 4. Non-yielding conditions: Willingness to cross relative to physical distance between vehicle and pedestrian, split by groups. Note. Values are averaged across approach speeds (30/50 km/h); see Table 3 for detailed descriptive values. As the vehicle was not braking in these conditions, the FBL was inactive in the EG; there was no FBL in the CG. Error bars display the normalized 95 % confidence interval of the mean (Morey, 2008).

Table 3
Willingness to cross (M, SD) in non-yielding conditions at different distances split by vehicle behavior (approach speed) and group.

Distance	Vehicle Behavior			
	30 km/h		50 km/h	
	EG	CG	EG	CG
1.5 *m*	2.1 (2.0)	2.5 (2.7)	1.4 (1.0)	1.5 (1.2)
5 *m*	2.2 (2.6)	2.8 (2.5)	1.5 (1.5)	1.9 (1.7)
15 *m*	3.7 (2.4)	4.2 (2.7)	1.8 (1.2)	2.6 (2.0)
30 *m*	5.6 (2.6)	6.6 (3.0)	3.8 (2.3)	4.5 (2.4)
45 *m*	6.4 (2.4)	7.3 (3.0)	5.4 (2.7)	6.1 (2.3)

Note. EG = experimental group; CG = control group. SDs are in brackets.

Discussion

In this experiment, effects of a frontal brake light and different vehicle behaviors on pedestrians' willingness to cross the street across the vehicle's path were studied. We focused on main effects of the FBL and possible interactions with vehicle behavior.

Findings and conclusions

The results of our investigation show that the use of an FBL can

Table 2
Willingness to cross (M, SD) in yielding conditions at different distances split by vehicle behavior (approach speed, braking onset) and group.

Distance	Vehicle Behavior							
	30 km/h				50 km/h			
	32 *m*		55 *m*		32 *m*		55 *m*	
	EG	CG	EG	CG	EG	CG	EG	CG
1.5 *m*	7.7 (2.1)	5.7 (3.6)	8.6 (2.5)	6.6 (3.6)	5.7 (3.1)	4.5 (3.1)	4.9 (3.1)	3.3 (2.4)
5 *m*	6.8 (2.6)	5.2 (3.5)	8.1 (2.5)	6.6 (3.6)	4.2 (2.5)	3.3 (2.2)	5.2 (3.0)	3.7 (2.5)
15 *m*	6.5 (2.6)	5.7 (3.2)	8.2 (2.2)	8.6 (3.2)	4.7 (2.5)	3.3 (2.4)	5.7 (2.7)	4.2 (2.5)
30 *m*	7.1 (2.3)	5.8 (2.7)	8.4 (2.0)	7.1 (3.0)	5.4 (2.3)	4.3 (2.1)	6.0 (2.5)	5.4 (2.2)

Note. EG = experimental group; CG = control group. SDs are in brackets.

Table 4
Participants' general assessment of the FBL by agreement to a set of statements, relative frequencies in %.

The frontal brake light…	completely disagree	disagree somewhat	neither nor	agree somewhat	completely agree
… is a good idea	0	0	3.5	41.4	55.2
… can facilitate getting ahead in traffic	0	17.2	34.5	24.1	24.1
… can make traffic safer	0	0	6.9	48.3	44.8

influence the willingness to cross. This extends on prior research that pointed to its potential in speeding up the decision to cross, as it leads to considerable improvements in the identification of a vehicle decelerating (Petzoldt et al., 2018). In particular, we observed a higher willingness to cross in front of a yielding vehicle in participants who saw vehicles equipped with an FBL than those who were neither introduced nor exposed to the FBL. Notably, the variance in willingness to cross when the vehicle was yielding was lower in the subjects who saw the FBL. The willingness to cross of those not exposed to the FBL was significantly more dispersed. Interestingly, this was only observed at the lower approach speed of 30 km/h. These observations suggest that eHMIs can not only help to raise the overall probability of a certain behavioral reaction to an AV (in our case a higher willingness to cross in reaction to the FBL) but also cause more uniformity in reactions (in our case a lower interindividual variability in willingness to cross when the FBL was present).

Perhaps our most important finding was that the FBL also influenced interactions with a vehicle in situations where it was not activated. Those who knew about the concept and had interacted with the FBL in prior trials, were more conservative in their willingness to cross when the vehicle did not yield (i.e., when the FBL was inactive, as there was no braking) than those who did know about the FBL. We argue this finding is important in the broader sense, as it shows that introducing vehicles equipped with novel eHMIs into traffic potentially influences interactions with these vehicles not exclusively in situations the eHMI is activated in (which has been the main goal and focus of research so far) but also in situations they are not activated in (in a possibly unintended manner).

In line with prior research (e.g., Dey et al., 2019; Ezzati Amini et al., 2019; Tian et al., 2023; Zach Noonan et al., 2023), vehicle kinematics greatly influenced willingness to cross in our study. When the vehicle maintained its approach speed, the willingness to cross was highest at the furthest distance between vehicle and pedestrian and decreased as the distance decreased. At the higher approach speed, willingness to cross was consistently smaller than at the lower speed. When the vehicle was yielding on the other hand, willingness to cross also decreased as the vehicle came closer, starting at an initially higher value. In contrast to non-yielding behavior however, willingness to cross started to increase again when the vehicle was very close. Dey et al. (2019) plausibly argue that although the vehicle is decelerating, the situation is conceived as ambiguous, which causes willingness to cross to go down from a certain distance. As soon as the vehicle has nearly come to a standstill close to the pedestrian however, it seems more certain that it will indeed yield to the pedestrian - which increases willingness to cross. As one would expect, we found that willingness was lower both when the initial approach speed was higher and braking onset was later. This observation corroborates the notion that early braking can be used as a communicative system, both on its own and in combination with an eHMI (Dey et al., 2020a). This would simultaneously result in lower braking intensities which are preferred by passengers in AVs (de Winkel et al., 2023). These findings add to the body of evidence that vehicle kinematics (which are intuitively understandable), are an important factor for the interaction with (automated) vehicles. The effects of vehicle kinematics were independent from whether participants were subjected to the FBL in the course of the experiment. It is possible therefore that the FBL has a consistent effect across different vehicle kinematics.

Regarding subjective ratings, the participants reacted positively to the FBL. They mostly agreed that the FBL is a good idea and can enhance traffic safety. With regards to user experience, it is not surprising that our participants rated the pragmatic value of the FBL highly in a scenario where the FBL's message always indicated that the vehicle would yield to the pedestrian. Interestingly, they also ascribed a good hedonic quality to the FBL. These positive reactions are in line with prior studies (Monzel, 2018; Petzoldt et al., 2018; Post & Mortimer, 1971). However, as our study only investigated one very simple scenario, this positive reaction cannot be generalized to all possible interactions with FBLs in traffic.

Taken together, our findings suggest that the FBL has the potential to influence a pedestrian's likely response to an AV's behavior in a predictable manner. If it can be ensured that the response can be influenced in a desirable way in every conceivable traffic constellation, the frontal brake light (or similar eHMIs that communicate aspects of a vehicle's current behavior) might help in achieving intended interaction outcomes. This can be regarded as a central goal in research on vehicle automation (Markkula & Dogar, 2022).

Limitations

While our methods enabled us to answer whether the FBL can influence pedestrians' willingness to cross, it is important to point out the study's scope and limitations. We made use of a simple controlled setting in which the pedestrian interacted with one vehicle at a time. This does obviously not portray the complexity of real traffic. Potentially undesirable effects of the FBL (e.g., when falsely understood as a yielding signal when a vehicle is braking but has no yielding intent) are beyond the scope of this study. Furthermore, while we did manipulate the vehicle's kinematics which are regarded as central in crossing decisions, we made the conscious decision to forgo other factors in order to maintain the desired level of experimental control. We did not consider factors like vehicle characteristics (e. g., size, appearance) or heuristics which influence our decision-making like illumination of a traffic scene (e.g., day vs. night), the social environment including other traffic participants, and the traffic infrastructure and formal traffic rules, which likely influence the reactions to an eHMI.

We realize the video-based apparatus (as opposed to a real-world investigation) limited both the possible physical dynamics of both actors as well as the physical danger that would arise from actual crossing behavior. However, we argue that the required level of experimental control (and safety) over conditions and participants would have been difficult to achieve in the field. One might argue that a simulation setup with a higher ecological validity should have been used. However, recent evidence suggests that participants perceive street-crossing situations in video-based online experiments similarly to those in a CAVE setup that allows for a higher level of immersion and more natural interactions with the environment (Tabone et al., 2023). As Recarte et al. (2005) showed that estimated arrival time of a vehicle in video material is highly equivalent to vehicles experienced in real life, the chosen method seems to be suitable for our purpose.

Future research

In a next empirical step, possible undesirable effects of a frontal brake light in more complex scenarios should be investigated (e.g., situations in which the reason for braking is not clear or confusing to an observer) to allow weighing its pros and cons. Additionally, we propose that future research should consider (possibly undesirable) effects of eHMIs in situations in which the eHMIs are not activated and investigate the interaction with vehicles that are not equipped with these eHMIs (e.g., in mixed traffic).

Funding

This work was supported by the German Federal Ministry of Education and Research (BMBF) as part of the project CADJapanGermany: HF [funding number 16ES1035].

CRediT authorship contribution statement

Daniel Eisele: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Tibor Petzoldt:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

We thank our research assistant Carla Bernadette Bubeck for supporting the realization of this study.

References

Clamann, M., Aubert, M., & Cummings, M. L. (2017). Evaluation of vehicle-to-pedestrian communication displays for autonomous vehicles. Transportation Research Board 96th Annual Meeting, Washington DC.

de Winkel, K.N., Irmak, T., Happee, R., Shyrokau, B., 2023. Standards for passenger comfort in automated vehicles: Acceleration and jerk. Appl. Ergon. 106, 103881 https://doi.org/10.1016/j.apergo.2022.103881.

de Winter, J., Dodou, D., 2022. External human–machine interfaces: Gimmick or necessity? Transportation Research Interdisciplinary Perspectives 15, 100643. https://doi.org/10.1016/j.trip.2022.100643.

Dey, D., Matviienko, A., Berger, M., Pfleging, B., Martens, M., & Terken, J. (2020). Communicating the intention of an automated vehicle to pedestrians: The contributions of eHMI and vehicle behavior. It - Information Technology, 0(0), 000010151520200025. https://doi.org/10.1515/itit-2020-0025.

Dey, D., Martens, M., Eggen, B., Terken, J., 2019. Pedestrian road-crossing willingness as a function of vehicle automation, external appearance, and driving behaviour. Transport. Res. F: Traffic Psychol. Behav. 65, 191–205. https://doi.org/10.1016/j.trf.2019.07.027.

Dey, D., Habibovic, A., Löcken, A., Wintersberger, P., Pfleging, B., Riener, A., Martens, M., Terken, J., 2020a. Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. Transportation Research Interdisciplinary Perspectives 7. https://doi.org/10.1016/j.trip.2020.100174.

Dey, D., van Vastenhoven, A., Cuijpers, R.H., Martens, M., Pfleging, B., 2021. Towards Scalable eHMIs: Designing for AV-VRU Communication Beyond One Pedestrian. In: 13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, pp. 274–286. https://doi.org/10.1145/3409118.3475129.

Domeyer, J.E., Lee, J.D., Toyoda, H., 2020. Vehicle automation–other road user communication and coordination: theory and mechanisms. IEEE Access 8, 19860–19872. https://doi.org/10.1109/ACCESS.2020.2969233.

Douglass, S. F. (1924). Motor vehicle signal (United States Patent Office Patent 1,519,980).

VICOM Editor (1.11). (2021). [Computer software]. TÜV | DEKRA arge tp21 GbR. www.vicomeditor.de.

Ezzati Amini, R., Katrakazas, C., Antoniou, C., 2019. Negotiation and decision-making for a pedestrian roadway crossing: A literature review. Sustainability 11 (23), 6713. https://doi.org/10.3390/su11236713.

Faas, S. M., Kao, A. C., & Baumann, M. (2020). A Longitudinal Video Study on Communicating Status and Intent for Self-Driving Vehicle – Pedestrian Interaction. 14.

Field, A., 2017. Discovering statistics using IBM SPSS statistics, (5th edition). SAGE Publications.

Jasp Team. (2022). JASP (0.16.4) [Computer software]. https://jasp-stats.org.

Labvanced., 2022. Computer software. Scicovery GmbH. https://www.labvanced.com.

Lee, Y.M., Madigan, R., Uzondu, C., Garcia, J., Romano, R., Markkula, G., Merat, N., 2022. Learning to interpret novel eHMI: The effect of vehicle kinematics and eHMI familiarity on pedestrian'crossing behavior. J. Saf. Res. 80, 270–280.

Markkula, G., Dogar, M., 2022. How accurate models of human behavior are needed for human-robot interaction? For Automated Driving? arXiv:2202.06123, arXiv. http://arxiv.org/abs/2202.06123.

Monzel, M., 2018. Feldstudie zur Erprobung einer Vorderen Bremsleuchte am Flughafen Berlin-Tegel. Zeitschrift Für Verkehrssicherheit 64, 210–218.

Morey, R.D., 2008. Confidence intervals from normalized data: a correction to cousineau (2005). Tutorials in Quantitative Methods for Psychology 4 (2), 61–64. https://doi.org/10.20982/tqmp.04.2.p061.

Petzoldt, T., Schleinitz, K., Banse, R., 2018. Potential safety effects of a frontal brake light for motor vehicles. IET Intel. Transport Syst. 12 (6), 449–453.

Pirkey, O. S. (1925). Signal for automobiles (United States Patent Office Patent 1,553,959).

Pituch, K.A., Stevens, J., 2016. Applied multivariate statistics for the social sciences: Analyses with SAS and IBM's SPSS, (6th edition). Routledge/Taylor & Francis Group.

Post, D.V., Mortimer, R.G., 1971. Subjective evaluation of the front-mounted braking signal. University of Michigan, Highway Safety Research Institute.

Prolific. (2022). [Computer software]. https://www.prolific.co.

Recarte, M.Á., Conchillo, Á., Nunes, L.M., 2005. Estimation of arrival time in vehicle and video. Psicomthema 17 (1), 112–117.

DaVinci Resolve (Version 18). (2022). [Computer software]. Blackmagicdesign. https://www.blackmagicdesign.com/de/products/davinciresolve.

Scherer, S., Schubert, D., Dettmann, A., Hartwich, F., & Bullinger, A. C. (2016). Wie will der „Fahrer" automatisiert gefahren werden? Überprüfung verschiedener Fahrstile hinsichtlich des Komforterlebens. In VDI Wissensforum GmbH (Ed.), Fahrerassistenz und Integrierte Sicherheit 2016 (pp. 299–310). VDI Verlag. https://doi.org/10.51202/9783181022887-299.

Schnabel, W., & Lohse, D. (2011). Grundlagen der Straßenverkehrstechnik und der Verkehrsplanung. 1: Straßenverkehrstechnik (3., vollst. überarb. Aufl). Beuth.

Schrepp, M., Hinderks, A., Thomaschewski, J., 2017. Design and evaluation of a short version of the User Experience Questionnaire (UEQ-S). International Journal of Interactive Multimedia and Artificial Intelligence 4 (6), 103. https://doi.org/10.9781/ijimai.2017.09.001.

Schrepp, M. (2018). UEQ-S Data Analysis Tool [Computer software]. https://www.ueq-online.org/Material/Short_UEQ_Data_Analysis_Tool.xlsx.

Tabone, W., de Winter, J.C.F., Ackermann, C., Bärgman, J., Baumann, M., Deb, S., Emmenegger, C., Habibovic, A., Hagenzieker, M., Hancock, P.A., Happee, R., Krems, J., Lee, J.D., Martens, M., Merat, N., Norman, D., Sheridan, T.B., Stanton, N. A., 2021. Vulnerable road users and the coming wave of automated vehicles: expert perspectives. Transportation Research Interdisciplinary Perspectives 9, 100293. https://doi.org/10.1016/j.trip.2020.100293.

Tabone, W., Happee, R., Yang, Y., Sadraei, E., García, J., Lee, Y. M., Merat, N., & de Winter, J. (2023). Immersive Insights: Evaluating Augmented Reality Interfaces for Pedestrians in a CAVE-Based Experiment. https://www.researchgate.net/publication/370160064_Immersive_Insights_Evaluating_Augmented_Reality_Interfaces_for_Pedestrians_in_a_CAVE-Based_Experiment.

Tian, K., Tzigieras, A., Wei, C., Lee, Y.M., Holmes, C., Leonetti, M., Merat, N., Romano, R., Markkula, G., 2023. Deceleration parameters as implicit communication signals for pedestrians' crossing decisions and estimations of automated vehicle behaviour. Accid. Anal. Prev. 190, 107173 https://doi.org/10.1016/j.aap.2023.107173.

Wenjun, P., Li, F., Xiang, J., 2023. Effect of vehicle external acceleration signal lights on pedestrian-vehicle interaction [Preprint]. In Review. https://doi.org/10.21203/rs.3.rs-2900757/v1.

Werner, A., 2019. New colours for autonomous driving: an evaluation of chromaticities for the external lighting equipment of autonomous vehicles. Colour Turn 1–14. https://doi.org/10.25538/TCT.V0I1.692.

Wilbrink, M., Cieler, S., Weiß, S.L., Beggiato, M., Joisten, P., Feierle, A., Oehl, M., 2023. Principles for external human-machine interfaces. Information 14 (8), 463. https://doi.org/10.3390/info14080463.

Windel, A., 2019. Kleine Ergonomische Datensammlung, (17th ed.). TÜV Rheinland.

Zach Noonan, T., Gershon, P., Domeyer, J., Mehler, B., Reimer, B., 2023. Kinematic cues in driver-pedestrian communication to support safe road crossing. Accid. Anal. Prev. 192, 107236 https://doi.org/10.1016/j.aap.2023.107236.