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Sripada, Anirudh; Bazilinskyy, Pavlo; de Winter, Joost

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Automated vehicles that communicate implicitly: examining the use of lateral position within the lane

Anirudh Sripada, Pavlo Bazilinskyy and Joost de Winter

Department Cognitive Robotics, Delft University of Technology, Delft, The Netherlands

ABSTRACT

It may be necessary to introduce new modes of communication between automated vehicles (AVs) and pedestrians. This research proposes using the AV's lateral deviation within the lane to communicate if the AV will yield to the pedestrian. In an online experiment, animated video clips depicting an approaching AV were shown to participants. Each of 1104 participants viewed 28 videos twice in random order. The videos differed in deviation magnitude, deviation onset, turn indicator usage, and deviation-yielding mapping. Participants had to press and hold a key as long as they felt safe to cross, and report the perceived intuitiveness of the AV's behaviour after each trial. The results showed that the AV moving towards the pedestrian to indicate yielding and away to indicate continuing driving was more effective than the opposite combination. Furthermore, the turn indicator was regarded as intuitive for signalling that the AV will yield.

Practitioner Summary: Future automated vehicles (AVs) may have to communicate with vulnerable road users. Many researchers have explored explicit communication via text messages and led strips on the outside of the AV. The present study examines the viability of implicit communication via the lateral movement of the AV.

Abbreviations: AV: automated vehicle; eHMI: external human-machine interface

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Automated driving; implicit communication; vehicle movement; vulnerable road users; crowdsourcing

Introduction

Road crossing decisions by pedestrians are usually based on the approaching vehicle's motion, also referred to as implicit communication. Sometimes, implicit communication is combined with explicit signals such as eye contact or hand gestures (e.g., Sucha, Dostal, and Risser 2017). For automated vehicles (AVs) of SAE Level 3 and above, the person in the driver's seat may not be aware of the vehicle's surroundings, as a result of which explicit communication might be compromised.

One of the strategies to restore explicit communication between pedestrians and AVs is to add explicit communication in the form of an external human-machine interface (eHMI). An eHMI could convey the AV's intentions or provide instructions to the pedestrian (e.g., De Clercq et al. 2019; Faas and Baumann 2019; Hudson et al. 2018). Literature indicates that as many as 70 eHMI concepts have been proposed so far, each of which allows the AV to send explicit signals to other road users (Dey et al. 2020).

Several researchers have argued that implicit communication (i.e., vehicle motion) is more important than explicit signs and gestures. In a field study, Dey and Terken (2017) found that 96% of pedestrians did not make explicit gestures towards drivers (and 100% of drivers did not gesture to pedestrians) when crossing the road at a crosswalk. Moore et al. (2019) made a case against eHMIs and reported that implicit cues are dominant; they reported no significant differences in interaction quality for pedestrian-vehicle encounters at a crosswalk, with and without a driver. Several other studies concur that implicit communication is a more important cue than explicit signs, gestures, or other vehicle features (Clamann, Aubert, and Cummings 2017; Dey et al. 2019; Lee et al. 2020; Nuñez Velasco et al. 2020; Rothenbücher et al. 2016).

Instead of using eHMIs that communicate explicitly, it may prove fruitful to let AVs communicate implicitly

CONTACT Joost de Winter j.c.f.dewinter@tudelft.nl Department Cognitive Robotics, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands.

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via adjustments in their approach speed and distance. Research has shown that speed and distance, and the composite measure time-to-arrival (TTA, i.e., the time gap), strongly affect the likelihood that a road user will cross (De Winter et al. 2009; Oxley et al. 2005; Schmidt and Färber 2009; Simpson, Johnston, and Richardson 2003). Dietrich et al. (2019) investigated the effect of different deceleration patterns (baseline: constant deceleration, defensive: braking hard and early, and aggressive: braking hard and later) coupled with different values of vehicle pitch (none, normal pitch proportional to vehicle deceleration, boosted normal pitch, and premature pitch which preceded vehicle deceleration) on the crossing behaviour of pedestrians. The results showed that defensive deceleration patterns led to earlier initiation of crossing. Generally, participants disliked the artificial pitch (none, boosted, premature), stating that they expected the pitch to be proportional to the vehicle's deceleration. Other studies have also suggested that automated vehicles could use early versus late stopping to communicate intent (Ackermann et al. 2019; Risto et al. 2017; Schmidt et al. 2019).

A limitation of using longitudinal cues for communicating intent is that pedestrians have an imperfect perception of these variables. For example, a video-based study by Beggiato et al. (2017) showed a trend of accepting shorter time gaps at higher vehicle speeds, i.e., pedestrians initiated riskier crossings when the vehicle approach speed was higher. Similarly, Petzoldt (2014) found that the mean accepted time gap was higher for vehicles approaching at 30 km/h compared to 50 km/h. However, when calculated based on the pedestrians' own estimates of the time gap, the accepted time gaps were similar for 30 and 50 km/h trials, suggesting that pedestrians have a biased perception of time gaps. Furthermore, visual perception research indicates that speed differences can be distinguished with limited accuracy (e.g., a 5% change in velocity could be detected; McKee 1981). According to Sun et al. (2015), speeds higher than 40 km/h are underestimated, with the estimation error increasing with increasing speed. In addition to speed and distance, vehicle deceleration plays a role in crossing decisions. Visual perception research indicates that humans do not perceive acceleration directly (Benguigui, Ripoll, and Broderick 2003; Brenner et al. 2016) but 'reverse-engineer' it via first-order estimates of the speed of an object at different points in time (Brouwer, Brenner, and Smeets 2002). In Schmidt et al. (2019), the task of pedestrians was to make a crossing decision as soon as possible for an approaching vehicle. In their study, most participants correctly detected whether the vehicle was decelerating in trials with low vehicle speeds (15 km/h) and close distances (later deceleration onset) but failed to do so in trials with higher vehicle speeds (40 km/h) and farther distances (early deceleration onset).

As pointed out above, pedestrians rely on implicit communication in terms of approach speed and distance, but they do not have a veridical perception of these variables. As an alternative, we propose to use lateral distance as an implicit cue for communicating yielding intent. An object's spatial distance is considered an effective nonverbal cue that can be perceived even by infants (Leslie 1982). The effect of interpersonal distance on people's expectations of behaviour has been previously explored by Hall (1966). He proposed four distance zones (intimate, personal, social, public) and mentioned that interactions are based on where other people are located within these zones. For example, the social zone (between four to twelve feet away) is the range within which there is an expectation of social interaction. Similar effects of distance are seen in human-robot interaction studies (Hoffman and Ju 2014; Mumm and Mutlu 2011) and studies about the tendency of humans to assign intentions to movements for animate and inanimate objects (Baldwin and Baird 2001; Meltzoff et al. 2001). Spatial proximity may also prove to be an effective communication cue in traffic, as suggested by Fuest et al. (2018). In their study, drivers were asked to communicate to pedestrians through driving behaviour that they were not going to stop, and most of them chose to do so by laterally moving 0.5 metres within their lane in a direction away from the pedestrian. Furthermore, when pedestrians had to wait, they preferred the vehicle driving at a greater lateral distance from them.

Research question

As pointed out above, lateral deviation of the AV may be a promising implicit communication cue. In the present study, the effect of lateral deviation of the AVs within its lane was investigated. The primary research question was which deviation mapping (towards/away from pedestrian) of the vehicle is more intuitive when trying to communicate yielding and non-yielding intent. On the one hand, it may be argued that a yielding AV should move towards pedestrians to indicate they can safely cross (e.g., 'the AV moves towards me to stop for me') and that a non-yielding vehicle should move away from pedestrians ('the AV keeps a safe distance from me'). On the other hand, perhaps a non-yielding vehicle should move towards pedestrians to communicate that they should not cross ('the AV threatens me by moving towards me').

In addition to the effects of lateral deviation mapping, the effects of the magnitude of the lateral deviation and its onset timing were studied in conditions with and without turn indicator signal. The inclusion of onset timing was based on De Clercq et al. (2019) and Eisma et al. (2019). These studies found that pedestrians were willing to cross if the vehicle intent was communicated before the vehicle began to decelerate. Equivalently, it might be useful to investigate if an early onset of the lateral deviation helps pedestrians initiate crossings earlier.

The turn signal was included because it is a commonly used and highly familiar signal by means of which road users judge an approaching vehicle's intended lateral motion (e.g., Lee and Sheppard 2016). It can be expected, however, that the use of the turn signal may cause confusion if paired with lateral motion.

Finally, it can be argued that it is important to examine whether pedestrians need to be told that the AV's lateral motion is informative of the AV's yielding behaviour, or whether they can figure this out themselves. Therefore, in our experiment, half of the participants were provided with information about the meaning of lateral deviation, and the other half were not.

Method

Video stimuli

In the experiment, participants viewed clips showing a vehicle (Smart Fortwo) approaching the participant from the left along a 5-m wide lane of a two-lane straight road. The video clips were recorded in a Unity3D environment previously used by De Clercq et al. (2019) and Kooijman, Happee, and De Winter (2019). The experiment was created using jsPsych, a JavaScript library for running behavioural experiments in a web browser (De Leeuw 2015). The same approach was previously used to study reaction times for multimodal stimuli (Bazilinskyy and De Winter 2018) and to study the effects of different eHMI configurations on pedestrians' perceived safety (Bazilinskyy et al. 2021).

All videos were 10.0 s long, had a frame rate of 60 fps, and a resolution of 1280 × 720 pixels. Each video started with a 1 s black frame to make transitions between the trials less abrupt. There was no sound in the videos, and the driver's seat was empty. For all trials, the initial velocity of the AV was 39 km/h, and the initial distance (i.e., upon the disappearance of the black frame) was approximately 85 m.

Independent variables

The independent variables were: (1) deviation level (within-subject), (2) deviation mapping (between-subjects), (3) information provision about the deviation (between-subjects), (4) vehicle yielding (within-subject), (5) onset of deviation (within-subject), and (6) turn indicator (within-subject). Details about these independent variables are provided in Table 1. Illustrations for the different deviation levels (Independent Variable 1) and deviation onsets (Independent Variable 5), for yielding and non-yielding vehicles with and without turn indicator (Independent Variables 4 & 6) are shown in Figure 1. Additionally, Figure 2 depicts what the AV looked like from the pedestrian's perspective for two deviation levels.

Experimental design

Participants viewed 24 different trials with lateral deviation (3 levels of nonzero deviation × 2 onset points of deviation × 2 turn indicator states × 2 yielding behaviours) plus 4 baseline trials without lateral deviation (2 yielding behaviours × 2 turn indicator states). Each participant viewed the 28 different trials twice, so 56 videos in total. As pointed out above, there were four groups of participants (2 deviation mapping groups × 2 information groups). The trials were shown in random order, and the participants were randomly allocated to one of four groups.

Participants and recruitment

The research was approved by the Human Research Ethics Committee of the TU Delft (no. 1116) The crowdsourcing service Appen (https://appen.com) was used to recruit 2000 participants. The participants were informed of this research when they logged in to one of the channel websites (e.g., https://www.ysense.com) where this experiment would show up in the list of available projects. Each participant was allowed to complete the experiment only once. A payment of USD 0.35 was offered for participating in the experiment.

Table 1. Independent variables of the experiment.

Independent variable	Levels
1. Deviation level (within-subject) The lateral deviation levels were loosely based on Fuest et al. (2018), who used a deviation of 0.5 m, and the maximum to which the AV could deviate while staying within the lane. The deviation values were equally spaced. The vehicle controller asset used in Unity3D has an inherent trade-off between the accuracy of vehicle path followed and the speed of the vehicle. Accordingly, a target deviation in the vehicle's path cannot be achieved instantly; it requires time to stabilise its trajectory, and the vehicles, therefore, follow a curvilinear path (Figure 1).	• No deviation. • Deviation of 0.4 m from lane centre. • Deviation of 0.8 m from lane centre. • Deviation of 1.2 m from lane centre.
2. Deviation mapping (between-subjects) Half of the participants viewed trials where a deviation towards them meant the vehicle was yielding and away from them meant the vehicle was not yielding (mapping 'Towards'). The opposite mapping was implemented for the other half of the participants (mapping 'Away'). A between-subjects design was used to prevent carryover effects from one mapping to the other.	• Deviating towards pedestrian when yielding & deviating away from the pedestrian when not yielding (Towards group). • Deviating away from the pedestrian when yielding & deviating towards pedestrian when not yielding (Away group).
3. Information provision about the deviation (between-subjects) Before the experiment, half of the participants were informed that the vehicle would deviate in its lane to communicate if it would stop, while the other half were not informed about this.	• Informed. • Uninformed.
4. Vehicle yielding (within-subject) Yielding behaviour, together with the deviation direction, allowed for investigating the main research question of which yielding-deviation mapping is preferred.	• Yielding: onset of braking 30 m from the pedestrian (6.1 s into the video), and full stop 8.5 m from the pedestrian (10.0 s into the video, i.e., at the end of the video). The deceleration was 2.74 m/s^2. The video ended right after the AV came to a stop. • Not yielding: constant speed of 40 km/h. The video ended 1.1 s after the AV had disappeared from the screen. • In case the turn indicator was on: deceleration to 20 km/h, in which case the video ended 0.1 s after the AV had disappeared from the screen.
5. Onset of deviation (within-subject) The AV began its deviation at a distance of 50 m from the pedestrian (i.e., before deceleration onset) or 30 m from the pedestrian (i.e., same moment as the deceleration onset).	• Early: Deviation started 50 m from the pedestrian (4.2 s into the video). • Late: Deviation started 30 m from the pedestrian (6.0 s into the video).
6. Turn indicator (within-subject) For a vehicle going straight ahead, deceleration is usually only needed if there is an intention to yield to the pedestrian, but when taking a turn, vehicles tend to decelerate in general, and the turn indicator is usually on. In this study, it was investigated whether a lateral deviation is interpretable in the presence of the turn indicator. When the turn indicator was on, non-yielding AVs decelerated moderately as the aim was to mimic realistic turning behaviour.	• Right turn indicator off. • Right turn indicator on (6.2 s into the video). Furthermore, in the case of non-yielding trials: the AV vehicle decelerated at 1.54 m/s^2 to 20 km/h as it passed the pedestrian.

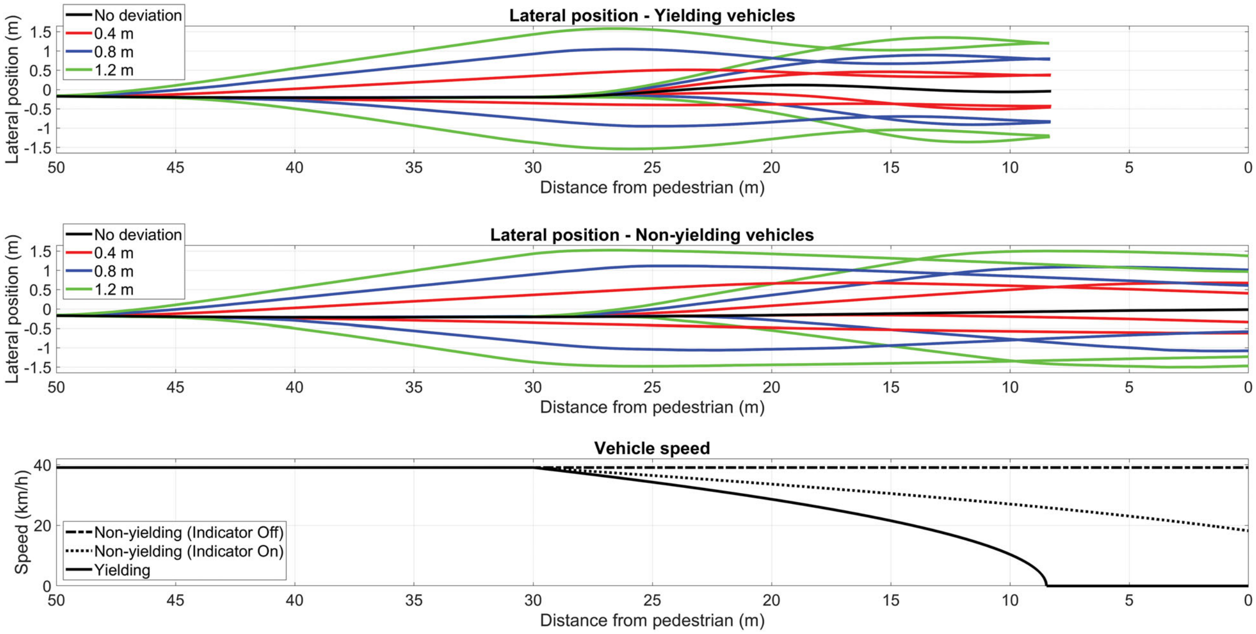

Figure 1. Top: Lateral position in non-yielding trials. Middle: Lateral position in yielding trials. Bottom: Vehicle speed in yielding and non-yielding trials. The vehicle's lateral deviation onset occurred at 50 m (4.2 s into the video) or at 30 m (6.0 s into the video). At a distance of 8.5 m (10.0 s into the video), the vehicle came to a full stop.

Figure 2. Screenshots depicting a lateral deviation of 1.2 m within the lane ($t = 7.70$ s, non-yielding vehicle, late deviation onset, indicator off).

Procedure and instructions

Participants started with a questionnaire entitled '*Measuring pedestrian's willingness to cross in front of an automated vehicle*'. The questionnaire mentioned that participants had to be at least 18 years old and that their details would remain anonymous. The questionnaire collected basic demographics (age, gender, etc.) and driving behaviour information and informed participants that they would see multiple videos of a vehicle approaching them and that they would have to press and hold a key when they felt safe to cross the road. Participants had to click a link to leave Appen and go to the page with the videos.

Before the videos were shown, task information was presented. The text for participants who received information about vehicle deviation was: *'The purpose of this experiment is to determine if the movement of an automated vehicle can be used to communicate if it is going to stop for a pedestrian. In the following videos, you will see an automated vehicle deviate within its lane as it approaches you. The direction of the deviation indicates whether it intends to stop or keep going. Your task will be to hold a response key if you feel safe to cross.'* In other words, before the experiment, participants in the Informed group received information about the meaning of the deviation, but not about which deviation direction means what.

The text for participants who received no information about vehicle deviation was: '*The purpose of this experiment is to determine your willingness to cross in front of an automated vehicle. In the following videos, you will see an automated vehicle approaching you*'. In other words, participants in the Uninformed group received no information about the vehicle deviation.

For both groups, it was further mentioned: '*You will view 56 animations. Press and HOLD 'F' when you feel safe to cross the road in front of the car. You can release the button and then press it again as many times as you want during the video. After each 10 videos you will be able to take a small break. The window of your browser should be at least 1300px wide and 800px tall. Press 'C' to start the first video*'. Below each video, it was mentioned: '*Start by HOLDING the 'F' key. Release the key when it becomes unsafe to cross; press again when safe to cross*'.

The participants were given the option to take a break after every 10 videos via the following text: '*You have now completed 10 [20, 30, 40, 50] videos out of 56. When ready press 'C' to proceed to the next batch.*' After each video, participants answered the following statement using a slider bar: '*The behaviour of the car in the previous video was intuitive for signalling that the car stopped or did not stop (0 = completely disagree, 100 = completely agree)*'.

The last page of the experiment contained a question on the preference of the mapping adjusted to the mapping shown to that particular participant. For example, participants in the Towards mapping groups were asked '*In the current study, the car went towards you when stopping, and away from you when it continued driving. Do you prefer this mapping, or would you prefer the opposite mapping: away from you when stopping, and towards you when it continued driving?*' The participant had to click on one of two radio buttons. Each participant received a unique code at the end of the experiment, which had to be entered in the questionnaire to receive the remuneration.

Dependent variables and analysis

From the elapsed times in the data recordings, it was determined whether there were issues with the playback of the 60-fps videos, for example, due to a slow computer of the participant. Trials that were estimated to last longer than 12 s (where 10 s was expected based on video duration) were removed. For the remaining trials, the observed key response times were divided by the estimated video duration and multiplied by 10 s to ensure that the maximum possible response time was 10 s.

The first dependent variable was the percentage of participants who pressed the key between 7.5 and 8.5 s into the video. This period was selected for maximal sensitivity; in the 7.5–8.5 s interval, the AV had started its lateral deviation, but had not come to a full stop yet. The second dependent variable was the intuitiveness rating on a scale from 0 to 100%.

Means and standard deviations were computed for these variables per experimental condition, and statistical significance was inferred from non-overlapping 95% confidence intervals for within-subject designs. The confidence intervals were computed by first subtracting the participant mean score (for details of this method, see Morey, 2008).

Results

Two-thousand people completed the study between 12 June 2020 and 11 July 2020. The study received an overall satisfaction rating of 4.3 on a scale of 1 (very dissatisfied) to 5 (very satisfied), based on 92 people who completed an optional satisfaction survey that was offered by the crowdsourcing platform. If people participated more than once from the same IP address or used the unique code more than once (suggesting cheating), only their first completed study was kept. Furthermore, people who indicated they did not read the instructions or who faced technical issues with data storage or video playback were removed. If, for a participant, less than 75% of the trials were completed within 12 s (where 10 s was expected based on video duration), this participant was removed.

In all, 1,104 participants were included in the analysis. The questionnaire and experiment took a median of 33.1 min to complete (25th percentile = 25.2 min, 75th percentile = 47.9 min). The variability in the survey completion time can be explained by the fact that the participants were free to take a break after each video. There were 281 participants in the Informed & Towards group, 267 participants in the Uninformed & Towards group, 282 participants in the Informed & Away group, and 274 participants in the Uninformed & Away group. The participants were from 66 different countries, with the highest number coming from Venezuela ($n = 475$), followed by the USA ($n = 77$), and India ($n = 57$). There were 744 male and 354 female respondents (6 indicated 'I prefer not to respond'), with the overall mean age being 36.5 years ($SD = 11.3$). A total of 59,978 out of a maximum possible of 61,824 trials (1104 participants × 56 videos per participant) were included in the analysis.

Figures 3 and 4 show the percentages of participants pressing the response key as a function of time for yielding and non-yielding trials, respectively. As the

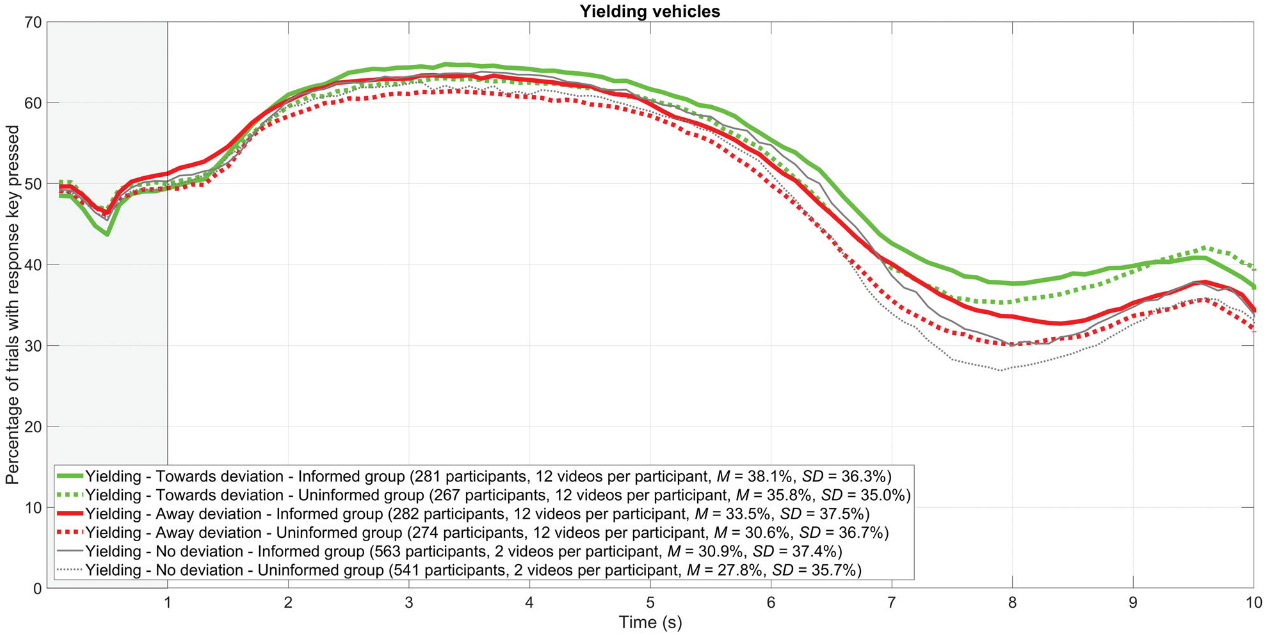

Figure 3. Percentage of trials in which the response key was pressed for the Informed and Uninformed groups in the yielding trials. The mean and standard deviation (*SD*) at the level of participants for the 7.5–8.5 s interval are shown in parentheses. The lateral deviation started at 4.2 s (early onset) or 6.0 s (late onset). The vehicle decelerated from 6.1 s to 10 s.

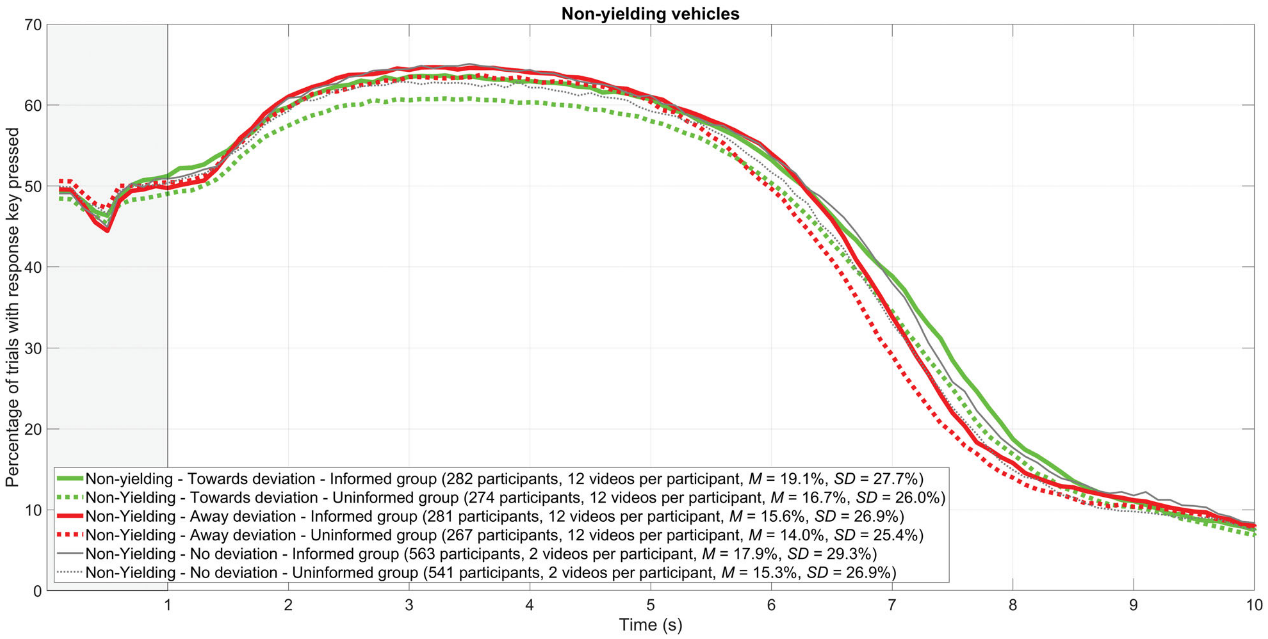

Figure 4. Percentage of trials in which the response key was pressed for the Informed and Uninformed groups in the non-yielding trials. The mean and standard deviation (*SD*) at the level of participants for the 7.5–8.5 s interval are shown in parentheses. The lateral deviation started 4.2 s (early onset) or 6.0 s (late onset) into the video.

vehicle approached, the keypresses began to decrease. Braking started 6.0 s into the video and the vehicle came to a stop 10.0 s into the video for yielding trials, which explains the increase in keypresses towards the end. For non-yielding trials, on the other hand, the keypresses continuously decreased after 6 s into the video.

Figure 3 also shows that a lateral deviation in yielding trials (especially a deviation towards the pedestrian) made participants think it was safe to cross the road compared to no deviation. The effect of deviation was smaller for non-yielding trials (Figure 4) than for yielding trials (Figure 3).

Figures 3 and 4 also show that the differences between the Informed and Uninformed group were very small, and because the information provision was a between-subjects variable, statistical power was low. According to a power analysis, 8,724 participants would be needed to detect an effect of $d = 0.06$ (corresponding to a difference of 2% for a standard deviation of 33%; alpha = 0.05, 1-beta = 0.80, two-tailed). To illustrate, the percentage of trials in which participants pressed the response key between 7.5 and 8.5 s in the yielding trials for the Towards mapping was 38.11% for the Informed group ($n = 281$) and 35.79% for the Uninformed group ($n = 267$), a non-significant effect according to a *t*-test at the level of participants, $t(546) = 0.76$, $p = 0.448$. Because of the minor and non-significant differences between the Uninformed and Informed groups, these groups were merged in subsequent analyses.

Intuitiveness ratings

After each trial, participants responded to the statement of whether the behaviour of the car was intuitive for signalling that the car stopped or did not stop, on a scale from 0 (*completely disagree*) to 100 (*completely agree*).

Figure 5 (left top) shows that yielding AVs that moved towards the pedestrian were associated with a higher intuitiveness rating than no deviation, and that the higher the deviation, the higher the intuitiveness. This trend was present for both turn indicator states. In the same vein, for yielding AVs that moved away from the pedestrian (right top figure), a high lateral deviation tended to yield lower intuitiveness ratings compared to no deviation.

The results for non-yielding AVs that moved towards the pedestrian (right bottom figure) were consistent with those for yielding AVs. That is, non-yielding AVs that moved towards the pedestrian (i.e., especially for 1.2 m deviation, the largest deviation) resulted in low intuitiveness ratings. For non-yielding AVs that moved away from the pedestrian (left bottom figure), the effects of lateral deviation were only small.

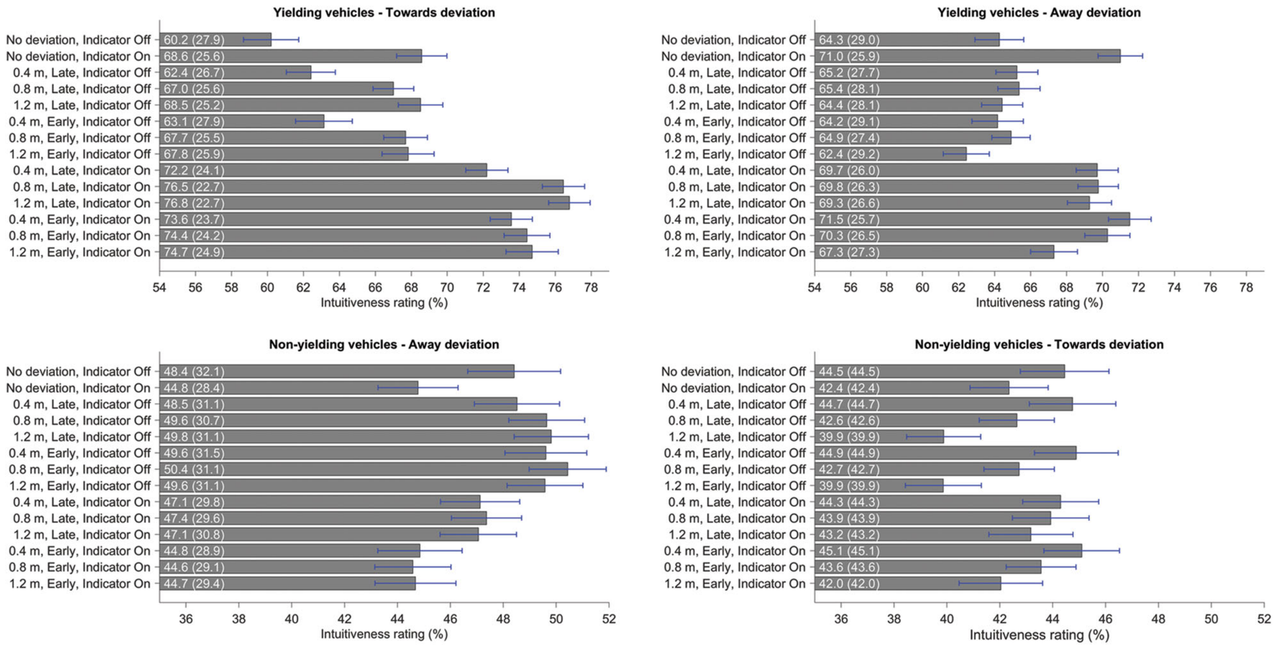

Figure 5. Mean intuitiveness ratings for yielding and non-yielding vehicles deviating towards and away from the participant. Error bars represent standard 95% confidence intervals at the level of participants. The intuitiveness rating is the response to the statement 'The behaviour of the car in the previous video was intuitive for signalling that the car stopped or did not stop', on a scale from 0 (*completely disagree*) to 100 (*completely agree*), entered using a slider bar. Each bar also shows the mean (standard deviation across participants in parentheses) in numeric form.

Additionally, it was found that, for yielding AVs (left and right top figures), the turn indicator had a positive effect on the intuitiveness ratings compared to the turn indicator off scenarios. For non-yielding AVs that moved away from the pedestrian (left bottom figure), the turn indicator had a negative effect on intuitiveness compared to the turn indicator off scenarios.

From all videos of yielding AVs, the highest intuitiveness rating was obtained for a late 1.2 m deviation towards the pedestrian with the turn indicator on (76.8%). From all videos of non-yielding AVs with the turn indicator off, the highest intuitiveness rating was obtained for an early 0.8 m deviation away from the pedestrian (39.9%). Thus, overall, it was found that yielding vehicles should move towards the pedestrian, and non-yielding vehicles should move away from the pedestrian.

Keypress results

Participants were asked to press the response key 'F' when they thought it is safe to cross. For increased sensitivity, only keypresses between 7.5 and 8.5 s were taken into consideration. Figure 6 shows the results of the keypress rates.

For yielding AVs that moved towards the pedestrian (left top figure), lateral deviations resulted in a higher keypress rate than no deviation, and the higher the deviation, the higher the keypress rate. These effects were present for both turn indicator states (left top figure). No clear patterns were observed for yielding AVs that moved away from the pedestrian (right top figure). For non-yielding AVs (bottom figures), the effects of lateral deviation on keypress rates were generally small.

From all videos of yielding AVs, the best performance (i.e., highest keypress rate) was obtained for an early 1.2 m deviation towards the pedestrian with the turn indicator on (42.4%). From all videos of non-yielding vehicles with the turn indicator off, the best performance (i.e., lowest keypress rate) was obtained for an early 0.4 m deviation away from the pedestrian (12.3%).

Question about preferred mapping

For the question about the preferred mapping, the percentage of participants choosing the 'Towards' mapping for stopping was 82.4%, 84.8%, 49.2%, and 53.7% for the Informed & Towards group, Uninformed & Towards group, Informed & Away group, and Uninformed & Away group, respectively. In other words, participants preferred the Towards mapping for yielding vehicles after having experienced this mapping.

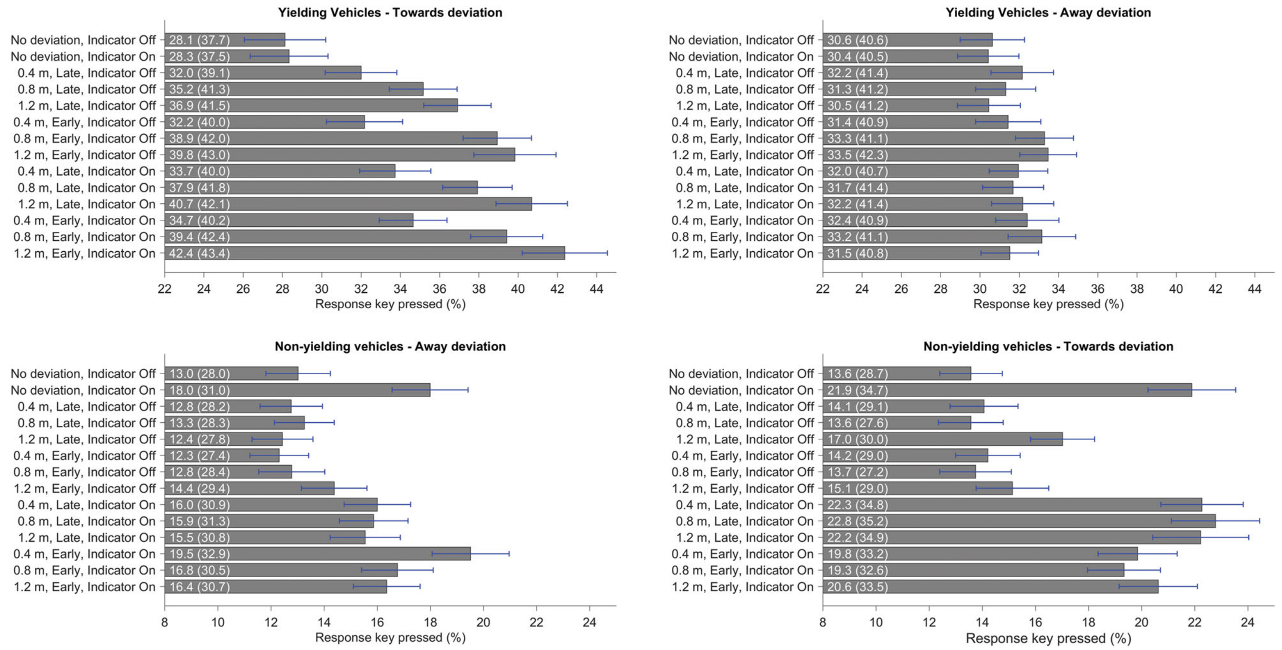

Figure 6. Keypress percentage in the 7.5–8.5 s interval for yielding and non-yielding vehicles deviating towards and away from the participant. Error bars represent 95% confidence intervals at the level of participants. Each bar also shows the mean (standard deviation across participants in parentheses) in numeric form.

National differences

The present study was conducted using a cross-national sample. An important question is whether the results are generalisable between participants from the different countries involved. Figure 7 shows the results for the three most highly represented countries (Venezuela, USA, India) for the condition Yielding Vehicles: Towards (i.e., the results that were presented in the left top of Figures 5 and 6). In this condition, we found that the higher the lateral deviation towards the pedestrian, the higher the percentage of participants pressing the key (Figure 6), and the higher the mean intuitiveness rating (Figure 5). Figure 7 shows that this trend also holds for participants from different countries. Of note, at the aggregate level, the correlation coefficient between lateral deviation (0, 0.4, 0.8, 1.2 m) and the percentage of participants pressing the key was 0.985, the correlation between lateral deviation and the mean intuitiveness rating was 0.965, and the correlation between the percentage of participants pressing the key and the mean intuitiveness rating was 0.995.

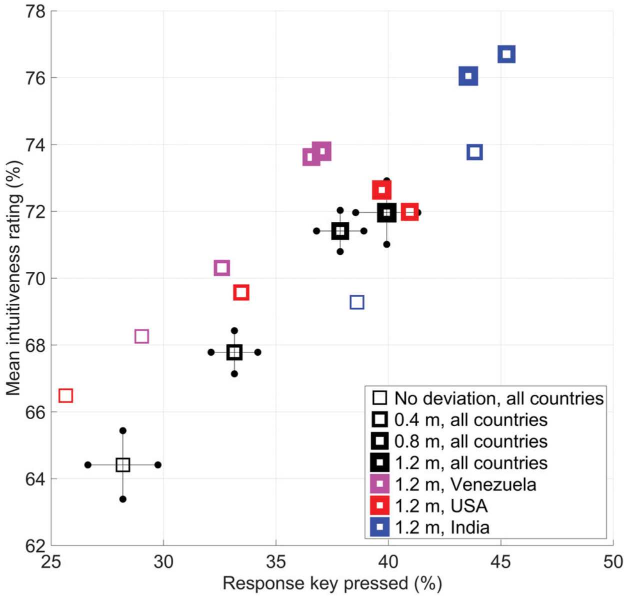

Figure 7. Mean intuitiveness rating versus the keypress percentage in the 7.5–8.5 s interval for yielding vehicles in the 'Towards yielding' condition, for four levels of lateral deviation (mean of 2 videos for no deviation, mean of 4 videos for the other deviation levels). A distinction is made between all participants ($n = 548$), participants from Venezuela ($n = 227$), USA ($n = 42$), and India ($n = 25$). The error bars represent 95% confidence intervals at the level of participants (depicted for 'all participants').

Discussion

In their questionnaire study on pedestrians' impressions of AVs in a shared space, Merat et al. (2018) found that pedestrians would like to receive information about the AV's intended path in addition to whether the AV has successfully detected them. As of present, over 70 eHMI concepts have been proposed (Dey et al. 2020), many of which are thought to enhance the interaction with pedestrians via explicit instructions or by showing the AV's state and intentions. In the current study, we sought a different approach by examining whether communication in the form of lateral deviation of the AV is a useful communication channel. More specifically, our research question was which yielding/deviation-direction mapping would result in the highest intuitiveness ratings and performance, i.e., crossing in yielding trials and not crossing in non-yielding trials.

The results, which consisted of post-trial intuitiveness ratings, pedestrian yielding intentions derived from a continuous keypress task, and a post-experiment question, unequivocally indicated that yielding vehicles should move towards the pedestrian and non-yielding vehicles should move away from the pedestrian. These findings are in line with a field study by Fuest et al. (2018), which concluded: 'If the AV does not yield, it should drive at constant speed with a lateral offset towards the centre of the road'.

Previous studies using eHMIs (De Clercq et al. 2019; Eisma et al. 2019) demonstrated that the communication of yielding intent *before* the onset of vehicle deceleration stimulates pedestrians to cross the road. The present study did not report clear differences between early and late lateral deviation (cf. Figure 6). This can be explained by the fact that we focussed our analysis on the 7.5–8.5 s interval in the videos, i.e., when the lateral deviation was already manifest for early deviation (starting at 4.2 s) and late deviation (starting at 6.0 s). A supplementary analysis (Supplementary Figure S1) showed that early deviation towards the pedestrian made participants think it is safe to cross earlier in time, which is consistent with the literature on eHMIs (De Clercq et al. 2019; Eisma et al. 2019).

Our study also showed that participants regarded the turn indicator as an intuitive signal for indicating that the car would yield, even though the turn indicator was not actually informative of the AV's yielding behaviour in our experiment. A possible explanation is that the turn indicator is a salient and familiar signal, which is used by drivers to indicate that they are about to park at the roadside. Accordingly, the turn indicator may be subjectively preferred compared to the unfamiliar or more suggestive lateral motion, see also May, Dondrup, and Hanheide (2015), who found that a turn indicator is a powerful navigation intent cue for a mobile robot. It should also be noted that for non-yielding AVs that moved away from the pedestrian, the turn indicator reduced intuitiveness ratings compared to indicator off scenarios. In this scenario, the car moved to its left, while signalling to the right, which may have caused confusion about the intention of the vehicle.

In the present study, half of the participants were notified about the meaning of the lateral deviation, and all participants were asked after each trial whether they found the vehicle behaviour intuitive for signalling that the car yielded or not yielded. As a result, participants may have quickly figured out that this study involved lateral vehicle motion that was mapped to yielding behaviour. After the experiment, we asked participants: '*In the experiment, the car sometimes steered to the left or right. Why did the car do that? Please elaborate. (required)*'. Our analysis of the responses to this question showed that about 34% of participants correctly understood that lateral deviation was a signal of yielding intent and 9% gave a semi-correct answer, without a clear difference between the Informed and Uninformed groups. An interesting observation was that in many of the answers (7%), participants assumed the vehicle was reacting to their presence or the presence of hypothetical other pedestrians, instead of proactively communicating with them. For example, some participants assumed that the AV's deviation for non-yielding trials meant the AV was trying to avoid a collision with them. Yet other participants (10%) thought that the lateral deviation was a technical or driver problem. In a previous pilot study ($n = 630$; Sripada 2020), using the same videos and information provision, we did not use the post-trial intuitiveness question, and found that only 7% of participants correctly understood the meaning of the lateral deviation, whereas 23% thought the vehicle reacted to a pedestrian. These findings suggest that training is required for participants to understand this new form of implicit communication.

A limitation of this study was that for non-yielding trials, the AVs were programmed to exhibit different behaviour when not using the turn indicator versus when using the turn indicator. As a result, non-yielding trials with the turn indicator on could not be compared with non-yielding trials with the turn indicator off. Future research could use a wider range of vehicle deceleration behaviours with and without turn indicator. In the present study, participants could not look around to judge for what reason (e.g., traffic lights, intersection, stop line) the AV was yielding. It would be interesting to replicate the current study, which was performed online, in a virtual reality or on-road setting. When using different hardware, such as a head-mounted display, participants will be able to look around to judge the traffic situation. Fuest, Schmidt, and Bengler (2020) cautioned that pedestrians' crossing intentions obtained from different research methods (video, virtual reality, Wizard of Oz) are comparable to a limited extent only, whereas Bhagavathula et al. (2018) found differences in presence ratings between real and virtual environments. On the other hand, Agarwal (2019) found strong congruence in pedestrians' distance and speed perception between a virtual reality environment and an on-road environment.

In conclusion, this study showed that the 'Towards yielding' mapping is more effective and intuitive than the 'Away yielding' mapping. Furthermore, the turn indicator is regarded as intuitive for indicating that the vehicle will yield.

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ORCID

Pavlo Bazilinskyy http://orcid.org/0000-0001-9565-8240
Joost de Winter http://orcid.org/0000-0002-1281-8200

Data availability statement

Raw keypress and questionnaire data, MATLAB code used for analysis, and questions asked in the survey are available at https://doi.org/10.4121/14046107.

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