Using an automated vehicle’s lateral deviation to communicate vehicle intent to the pedestrian

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by

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Acknowledgements

With this report, I finally complete the quest I embarked upon in August 2017, to obtain my Master's degree in Vehicle Engineering with a specialization in Human Factors. It has been a unique, enlightening, frustrating, and ultimately rewarding experience.

I would like to thank my supervisor Dr. ir. Joost de Winter, who has helped me at every step of this research, right from formulating and refining the research objectives to designing the experiment and understanding the results. I would also like to thank Dr. Pavlo Bazilinskyy, who helped ensure the study went along smoothly as planned. Special thanks to Dr. Dimitra Dodou for helping out in the design stages of the experiment.

During the final stage of the research, while preparations for the lab experiment were under-way, the unexpected occurrence of a global pandemic caused by the Coronavirus (COVID-19) led to a government-instituted lockdown of the country. This meant that we could no longer use our lab to conduct the experiment while also staying on schedule. Hence it was decided that the final experiment would be conducted online using the crowdsourcing platform Appen (known as Figure-Eight at the time of the experiment). The participants' task on the Appen platform was designed along the same lines as that of the lab experiment, and the data collected was also strictly filtered to ensure that the final results were of high quality. I would once again like to thank my aforementioned supervisors for helping me complete my research in such challenging conditions.

Abstract

Highly automated vehicles may lead to vehicle occupants getting distracted from driving-related tasks, so it may be necessary to look at newer modalities to achieve effective pedestrian-vehicle communication. This research proposes using the lateral deviation of the automated vehicle within its lane as a method to communicate if it is going to yield to the pedestrian. In a crowdsourced experiment, videos containing an approaching automated vehicle were shown to participants. The effect of 1) levels of deviation (no deviation, deviation of 0.4 m, 0.8 m and 1.2 m), 2) direction of deviation (towards pedestrian, away from pedestrian), 3) vehicle behaviour (yielding, not yielding), 4) onset of deviation (onset at a distance of 50 m and 30 m from the pedestrian), and 5) intended vehicle path (vehicle going straight, vehicle taking a turn) were studied. A between-subjects design was used to assign participants (total N = 945; and after filtering, N = 638) randomly to one of 4 groups based on 1) the deviation direction-behaviour mapping (deviation towards pedestrian was 'yielding' and away was 'non-yielding', deviation towards pedestrian was 'non-yielding', away was 'yielding') and 2) instructions at the experiment start (not informed of the vehicle deviation, informed of the deviation). Each participant viewed 28 videos, and the task was to press and hold a key as long as it felt safe to cross. The results showed that 1) vehicle deviation to indicate yielding led to a statistically significant improvement in willingness to cross, for all four groups 2) the magnitude of lateral deviation also had a statistically significant effect on crossing willingness when comparing the two extreme values (0.4 m and 1.2 m) for the yielding trials in two of four groups, 3) for one group there was a statistically significant difference in willingness to cross when the vehicle indicates that it intends to take a turn versus when it intends to go straight ahead. It is concluded that lateral deviation of the vehicle, when used to communicate yielding intent, affects the pedestrians' willingness to cross the road.

1. Introduction

1.1 Overview

Road crossing decisions by pedestrians are usually based on the motion of the approaching vehicle combined with driver communication signals such as eye-contact or physical gestures. For highly automated vehicles (HAVs) of SAE level 3 and above (SAE On-Road Automated Vehicle Standards Committee, 2014), even if a person is present in the driver's seat, he/she may not be in control of the vehicle or aware of its surroundings at all times. As a result, the effectiveness of driver-pedestrian communication might be reduced. A majority of pedestrians (84% according to a study by Sucha et al., 2017) seek to establish eye-contact with the driver when crossing. Pedestrians have also shown to be hesitant to cross the road when the person in the driver's seat is distracted from the driving task (Lagström and Lundgren, 2015; Rodriguez Palmeiro et al., 2018), which can be the case for HAVs. One of the strategies to increase the effectiveness of communication between pedestrians and HAVs is to add an external human-machine interface (referred to as eHMIs) on the vehicle that conveys the vehicle's intention to the pedestrian (e.g., De Clercq et al., 2019; Faas and Baumann, 2019; Hudson et al., 2018).

However, some researchers have proposed that the vehicle motion alone could be the primary factor in making a crossing decision (Dey and Terken, 2017; Risto et al., 2017). In a field study, Dey et al. (2017) found that 96% of pedestrians do not make explicit gestures towards drivers in current traffic (and 100% of drivers did not gesture to pedestrians) when crossing the road at a crosswalk. Moore et al. (2019) also found no statistically significant differences in interaction quality for pedestrian-vehicle encounters at a crosswalk, with and without a driver.

The current research attempts to investigate if the vehicle behaviour itself, specifically, lateral deviation of the vehicle within its lane, can be used to improve intent communication, thereby preserving the existing modality of using vehicle behaviour as an indication of its intent. First, the literature is reviewed to explain why the conventional vehicle motion patterns seen in current traffic, while effective, might be insufficient as a means of actually improving pedestrian-vehicle communication.

1.2 Influence of vehicle parameters such as speed, time to collision (TTC), distance and deceleration on pedestrian behaviour

There have been several studies on what parameters can cause pedestrians to accept or reject an available gap in traffic. Simpson et al. (2003) found that pedestrian made fewer unsafe crossings (defined as crossings where there was either a collision with virtual vehicle or the vehicle was just 1.5s away from colliding) for trials with uniform inter-vehicle distance compared to trials with uniform vehicle speed and postulated that distance might be a bigger guiding factor in crossing decisions. Oxley et al. (2005) and Schmidt and Faerber (2009) measured accepted time gaps for different vehicle speeds. Oxley et al. (2005) found that distance to the vehicle as well as TTC had an effect on crossing decisions, but the influence of distance appeared to be higher. Schmidt and Faerber (2009) also found that TTC and distance had a significant effect on crossing decisions, but participants chose tighter gaps at higher speeds indicating that TTC information might not always be used when deciding to cross. When further exploring the influence of TTC on crossing, Petzoldt (2014) found that the mean accepted time gap was higher for vehicles approaching at 30 km/h compared to 50 km/h, suggesting that TTC is accounted for in the crossing decision. At the same time, pedestrians also incorrectly estimated higher TTC for vehicles approaching at 50 km/h compared to 30 km/h. When calculated based on the pedestrian estimations of TTC, the accepted time gaps were similar for both 50 km/h and 30 km/h trials, showing that the effect of TTC on accepted time gaps is reduced when the subjective TTC estimations of pedestrians are taken as a reference. The underestimation of TTC might be one explanation for why pedestrians appear to choose similar time gaps in the experiments of Simpson et al. (2003), Oxley et al. (2005), Schmidt and Faerber (2009) for different vehicle speeds (i.e., different TTC). In summary, pedestrians make systematic errors in estimating TTC.

A more recent study by Beggiato et al. (2017) that investigated preferences of pedestrians for braking behaviour of vehicles also found that participants across all ages showed a trend of accepting shorter time gaps at higher vehicle speeds. A second explanation for this trend of riskier behaviour offered by Beggiato et al. (2017) (in addition to the previously mentioned theory of Schmidt and Faerber (2009), that TTC information is not always used when crossing), was that pedestrians might have an expectation that if they actually enter the street, the vehicle would stop for them regardless of its speed, out of politeness or for safety reasons (Färber 2016).

A third possible explanation for choosing smaller time gaps at higher speeds is the incorrect estimation of vehicle speed. Visual perception research indicates that changes in speed can be distinguished reliably (even 5 to 7% changes in velocity can be detected, see McKee, 1981). According to the results from Sun et al. (2015), 40 km/h was found to be the upper limit for accurate speed perception of approaching vehicles by pedestrians in clear weather. Speeds higher than 40 km/h were underestimated, and the estimation error increased with increasing speeds. Hence there is a possibility that the actual value of vehicle speed is underestimated by pedestrians, leading to TTC overestimation and to the acceptance of a riskier time gap. Furthermore, the concept of ‘Tau’ that has been proposed as a mechanism for TTC calculations (Lee, 1976) has also been shown to have limited applicability when the vehicle velocity is not constant (Tresilian, 1995) or when cognitive workload is higher (Delucia and Novak, 1997). Further research is needed to confidently state if the incorrect estimation of speed itself is the root cause of errors in TTC estimation in the results from the gap acceptance studies. Nonetheless, the acceptance of shorter time gaps with increasing speeds is a well-established trend.

Pedestrian demographics also have a strong influence on the accepted gaps in all the aforementioned studies. The trend of older pedestrians choosing more conservative gaps than their younger counterparts is mentioned by Tournier et al. (2016) in their review of the literature. Pedestrians also attempt to compensate for riskier gap selections, if any, by increasing their crossing speed (Ishaque and Noland, 2008), which is again a function of their mobility and demographics. When combining these demographic differences with the perceptual issues mentioned above, it appears that speed of the vehicle may not be a reliable parameter to convey the intent of the vehicle due to inaccurate estimation of its speed as well as TTC.

In addition to speed and distance, detection and estimation of vehicle deceleration also plays a key role in making the crossing decision. Previous visual perception research indicates that acceleration values might not be directly perceived by humans (Benguigui et al., 2003; Benguigui and Bennett., 2010; Brenner et al., 2016), but 'reverse-engineered' by making first-order estimates of the speed of an object at different points in time (Brouwer et al., 2002).

For decelerations in vehicles, Fuest et al. (2018) found that pedestrians correctly interpreted if the vehicle was slowing down and yielding in 95.3 % of total trials in their study. A study by Ackermann et al., (2019) found that only 4 % of participants completely missed the detection of a braking manoeuvre by the vehicle, and Schneemann and Gohl (2016) reported that pedestrians correctly perceived a deceleration of the vehicle in 75 % of the trails. Hence, it is reasonable to assume that pedestrians are good at detecting vehicle deceleration and more specifically, if the vehicle is decelerating to yield. The efficiency of detection (how soon can the deceleration be detected) seems to be affected by vehicle speeds, deceleration and onset of deceleration. Ackermann et al. (2019) measured deceleration detection times as a result of different speeds, deceleration onset times and deceleration rates. The results showed that low speeds and higher decelerations had the shortest detection times. The detection times were also lower for a later onset of deceleration (TTC of 2 to 3 s before reaching the target) compared to an early onset (TTC of 3.5 to 4.5 s). A similar trend can be seen in the study of Schmidt et al. (2019), where the task of the pedestrians was to make a crossing decision as soon as possible for an approaching vehicle. Most participants in the study could correctly detect 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). However, trying to decelerate quickly at closer distances from the pedestrian would be considered unsafe behaviour from the drivers, and studying natural on-road interactions between drivers and pedestrians (Risto et al., 2017) shows that pedestrians feel comfortable to cross the road when drivers start deceleration early, decrease speed considerably and stop significantly short of the crosswalk. Research thus indicates that conditions in which most efficient detection of deceleration occurs are in conflict with conditions that are actually considered comfortable for crossing. In order to enhance pedestrian-vehicle communication, it might be worth investigating other vehicle motion parameters that can still be manipulated while staying within the paradigm of 'desirable' braking behaviour (i.e., deceleration pattern) that is prescribed by Risto et al. Overall, it can be seen that accurately identifying and accounting for vehicle parameters like speed, acceleration and TTC in the longitudinal direction during crossing can be performed by pedestrians only when these parameters fulfil specific conditions mentioned above. Hence reliable communication of HAV intent through its motion might require cues whose detection is less dependent on the aforementioned parameters.

1.3 Intent communication using vehicle behaviour in the context of HAV-pedestrian interaction

The ability to program specific behaviour for HAVs gives greater flexibility in choosing what type of vehicle cues are used to communicate with the pedestrian. As a result, we have opportunities to explore motion parameters beyond just velocity and deceleration, both of which are currently used by human drivers as communication cues for a crossing scenario. Dietrich et al. (2019) investigated the effect of different deceleration patterns – baseline (constant deceleration), defensive (braking hard and early), aggressive (braking hard and later) coupled with different values of vehicle pitch – none, normal pitch (proportional to deceleration), boosted pitch (amplified normal pitch), premature pitch (precedes deceleration) on crossing behaviour of pedestrians. The results showed that defensive deceleration patterns led to earlier initiation of crossings (similar to the results of Risto et al. (2017)). Pitch values had a low effect, and the participants also disliked the artificial pitch (boosted, premature) exhibited by the vehicle, stating that they expect the pitch to be in proportion to the perceived kinematic behaviour.

The lateral deviation of the vehicle is another parameter proposed as a possible behavioural cue for HAVs. In a study by Fuest et al. (2018), when drivers were asked to communicate to pedestrians through driving behaviour that they were not going to stop, they chose to do so by laterally moving 0.5 metres within their lane in a direction away from the pedestrian. When the vehicle appeared to drive autonomously past the pedestrians, this non-yielding behaviour was rated higher than the baseline non-yielding behaviour with no deviation, indicating the lateral deviation might be a viable option for intent communication.

De Clercq et al. (2019) and Eisma et al. (2020) conducted studies involving the use of an external interface and found that pedestrians were willing to cross if the vehicle intent was communicated even before the vehicle began to decelerate. The increased willingness indicates that behavioural cues of the vehicle, when understood correctly, can help the pedestrian make a decision before braking begins. It might be valid to investigate if earlier onset of vehicle behavioural cue helps pedestrian initiate crossings quicker.

Merat et al. (2018), in their questionnaire-based study on pedestrians' impressions of automated vehicles in a shared space, found that pedestrians would like information on the vehicle's intended path (like going straight or turning) in addition to whether it successfully detected them. May et al. (2015) also found a significant effect of turn indicators in increasing human comfort when conveying the navigational intent of a mobile robot. There is also a hypothesis that pedestrians might be confused whether the vehicle is slowing down to yield for them or slowing down just to make the turn (Habibovic et al., 2018). 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. If yielding behaviour is similar for both vehicle paths, it is expected that there would be some difference in pedestrians' crossing behaviour arising from the ambiguity of deciding if the vehicle is indeed slowing down for them or slowing down to just make the turn.

1.4 Behavioural research on movement and distance as communication cues

The effects of proximity, interpersonal distance and interpretation of abstract movements have been extensively studied in behavioural research. Spatial distance from an object is considered to be an effective nonverbal cue and is perceived even in infants (Leslie, 1982), indicating that it is a clearly perceivable stimulus. The effect that interpersonal distance (and changes in it due to movement) has on people's expectations of behaviour has also been previously explored by Hall (1966). He proposes that there are four levels of distance zones (intimate, personal, social, public) and that the expectations of interactions are based on where other people are located with respect to these zones. For example, the social zone (between four to twelve feet away) is the range of distance within which there is expectation of a social interaction if another person is present. In addition to interpersonal interactions, similar effects of distance are also seen in the human-robot interaction studies by Mumm and Mutlu (2011) and Hoffman and Ju (2012). The tendency of humans to assign intentions to abstract movements has also been studied for both animate and inanimate objects (Baldwin and Baird, 2001; Meltzoff et al., 2001). In fact, this tendency has been shown to hold true for pedestrian-vehicle interactions as well. In their study of nonverbal communication between pedestrians and vehicles by Schmidt et al. (2019), participants assigned different intentions to the vehicle based on its behaviour, regardless of the presence of an actual driver. It is hence possible that the behavioural effects of spatial distance and object movement could be valid for pedestrians as well and warrant further investigation.

1.5 Research questions

The lateral deviation of the vehicle appears to be a promising intent communication cue that might be independent of the pedestrians' perceptual limitations for longitudinal motion. So far, the motion parameters of HAVs for which effect on pedestrian crossing behaviour has been investigated include deceleration (Beggiato et al. 2017, Schmidt et al. 2019, Dietrich et al. 2019), stopping distance from crosswalk (Moore et al., 2019) and vehicle pitch (Dietrich et al. 2019). Lateral deviation of the vehicle has been investigated by Fuest et al. (2018), but crossing decision was not part of the participants' tasks. Hence in this study, the effect of lateral deviation of the vehicle within its lane and its effect on pedestrians' willingness to cross is investigated. The primary research question was to study which deviation direction (towards/away from pedestrian) of the vehicle feels more intuitive and easy to learn when trying to communicate yielding and non-yielding intent.

The second research question for the study is to validate if there is an ambiguity in understanding vehicle intent to yield, when the vehicle is taking a turn versus when going straight. It is also investigated if the proposed lateral deviation cue can help reduce the ambiguity.

Since there are two possible direction-behaviour mappings (i.e., deviation towards pedestrian to yield, deviating away from pedestrian to not yield and vice versa), a between-subjects design was used in order to study the effectiveness and learning curve of each combination while preventing carryover effects from one mapping to the other. Additionally, the effects of magnitude of deviation, earlier and later onset of deviation, are also analysed. The second hypothesis is tested by flashing the right turn indicator to imply the vehicle's intention to turn, and no indicator to imply it is going straight ahead.

2. Method

2.1 Study Design

The experiment consisted of a series of video clips shown to the participant, in which an automated vehicle approached them along a straight road. The independent variables in this experiment are listed in Table 1. Deviation levels for the vehicles were chosen based on the value used in the study by Fuest et al. (deviation of 0.5 m) and the maximum limit to which it could deviate while still managing to stay within the lane. The values were then equally spaced, finally resulting in deviation steps of 0.4 m, 0.8 m and 1.2 m. The vehicle began its deviation at a distance of 50 m or 30 m away from the pedestrian. The vehicle controller asset used in Unity has an inherent trade-off between the accuracy of vehicle path followed and the speed of the vehicle. As a result, a preset deviation in vehicle path cannot be achieved instantly; it requires time to stabilize its trajectory. As a result, there is a discrepancy between the designed path and what is actually realised by the vehicle in the virtual environment. Both the vehicle paths can be compared in Figure 1. A depiction of what these paths look like from the pedestrian's perspective is shown in Figure 2. For all trials, the initial velocity of the vehicle was 40 km/h. In trials with yielding vehicles, the videos end right after the vehicle comes to a stop, and in trials with non-yielding vehicles, the videos end after the vehicle passes by the pedestrian. For trials where vehicle intent was to turn, the vehicle decelerated a little even if it was not going to yield, as the aim was to mimic realistic turning behaviour. Table 2 contains details of yielding and non-yielding behaviour for each intended vehicle path. Figure 3 shows the variations in vehicle speed along the length of the vehicle path. The experiment used a modified version of the environment previously used in De Clercq et al., 2018 and Kooijman et al., 2019.

All the videos were 1280px wide, 720px high and had a framerate of 60 fps. Each video was 9 s long, and a black frame 1 s long was added to the beginning and end of each video to make transitions between the trials less abrupt, bringing the total duration to 11 s. Each video showed one experimental condition, and there was no sound in any of the videos. Vehicle braking began 6.05 s into the video, and the vehicle stopped at 10.07 s for the yielding trials, while the earliest onset of deviations (the 50 m onset trials) occurred 4.21 s into the video. Since braking begins when the vehicle is 30 m away from the pedestrian, onset of deviation at 30 m also happens at 6.05s.

There were two levels of the between-subjects design – one level for the direction-behaviour mapping specified and the other for the type of instructions provided at the start of the experiment. Hence, one group of participants viewed trials where deviation away from them meant the vehicle was yielding and towards them meant the vehicle was not yielding. The opposite cues were implemented for the other group. Additionally, one group of participants would either be informed that the vehicle would deviate in its lane to communicate if it is going to stop, while the other group was not informed. Thus, four total groups of participants were created, as shown in Table 3. Further information on instructions can be found in Section 2.2. Each group viewed 24 trials with deviation (3 levels of deviation x 2 onset points of deviation x 2 intended vehicle paths x 2 vehicle behaviours) plus 4 baseline trials (2 vehicle behaviours x 2 intended vehicle paths). For final data analysis, Group 1 had 139 participants, Group 2 had 160 participants, Group 3 had 179 participants, and Group 4 had 152 participants, while 8 participants remained unclassified.

Table 1. List of independent variables in the experiment

Variable	**Values**
Vehicle Deviation	• 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
Deviation Direction	• Deviating away from pedestrian • Deviating towards pedestrian
Vehicle behaviour	• Yielding • Not Yielding
Onset of deviation	• Deviation starts 50 m away from pedestrian • Deviation starts 30 m away from pedestrian
Intended vehicle path	• Going straight ahead • Taking a turn

Table 2. Vehicle behaviour for each intended vehicle path

Intended vehicle path	**Yielding behaviour**	**Non-Yielding behaviour**
Going straight ahead	Vehicle starts braking 30 m away and stops 7.5 m away from pedestrian	Constant velocity of 40 km/h
Taking a turn (Turn indicator starts flashing 30.5 m away from pedestrian)	Vehicle starts braking 30 m away and stops 7.5 m away from pedestrian	Vehicle decelerates to a speed of 20 km/h as it passes the pedestrian

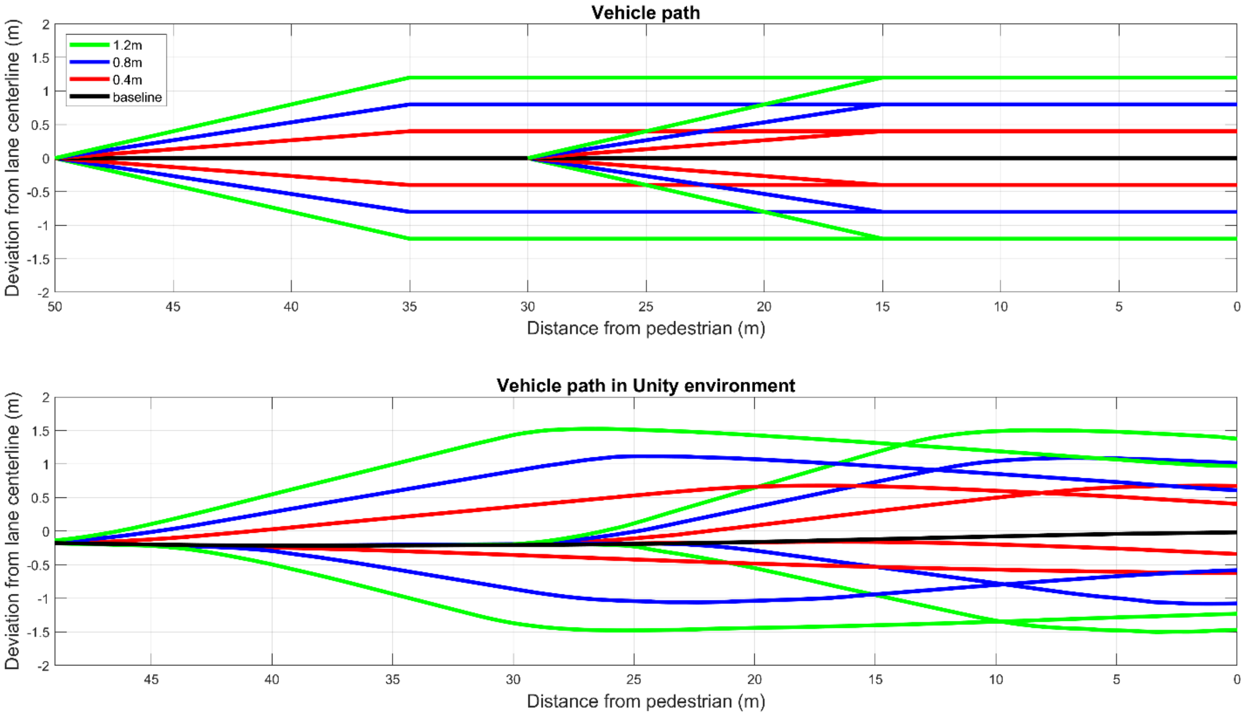

Figure 1. The plot on top represents how the paths have been design in theory. The plot on the bottom represents the behaviour of the vehicle based on output co-ordinates from the Unity environment.

Figure 2. The following images are taken at t = 6s of the videos. They are part of the groups where deviation towards pedestrian denotes yielding, and deviation away denotes non-yielding (i.e., Groups 1 and 2). The pair of images in each row represent yielding and non-yielding behaviour for the condition where the intended vehicle path is to go straight ahead, so vehicles in the first column are decelerating while those in the second column are

moving with constant speed. The first row indicates the baseline, and each subsequent row has vehicles from the trials with 0.4 m, 0.8 m and 1.2 m deviation levels, respectively.

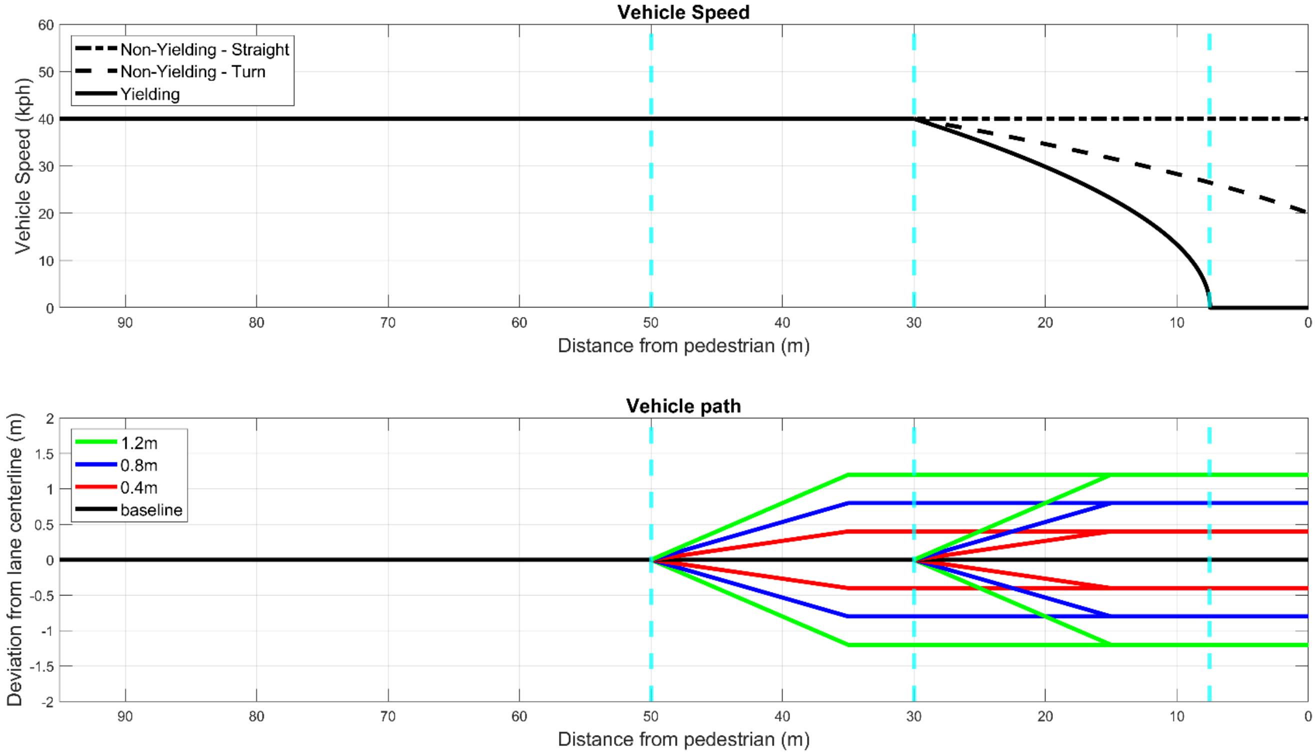

Figure 3. The plot on top represents the changing speeds of the vehicle for 'non-yielding straight', 'non-yielding turn' and 'yielding' conditions. The cyan line at 50 m represents the vehicle's deviation onset at 50 m (after t = 4.21 s into the video), the line at 30 m represents the vehicle's braking initiation/onset of deviation at 30 m (after t = 6.05 s into the video) and the line at 7.5 m represents vehicle stopping (after t = 10.07 s into the video), at which point the video ends.

Table 3. The four groups used for the between-groups design of the experiment

Group	**Direction of deviation for yielding**	**Direction of deviation for not yielding**	**Instructed about the deviation at the before the experiment**	**Total Participants (after filtering)**
1	Towards pedestrian	Away from pedestrian	No	139
2	Towards pedestrian	Away from pedestrian	Yes	160
3	Away from pedestrian	Towards pedestrian	No	179
4	Away from pedestrian	Towards pedestrian	Yes	152

2.2 Crowdsourcing Experiment

The crowdsourcing service Figure Eight (www.figure-eight.com) was used to conduct the experiment. It was acquired by Appen (https://appen.com/) shortly after experiment completion, but will be referred to as Figure-Eight for the purposes of this report. 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.

There was a questionnaire at the beginning of each experiment (the complete form can be seen in Appendix A). The title of the study was mentioned as "Measuring pedestrian's willingness to cross in front of an automated vehicle". The contact details of study organisers was provided, and the participants were informed that the study would take approximately 15 minutes. It was also mentioned that they had to be at least 18 years old to participate and that their details would remain anonymous. The initial part of the questionnaire was aimed at collecting participant demographics (age, gender, etc.) and driving behaviour information. They were then given further details about the experiment, regarding the fact 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. They had to click a link to leave Figure-Eight and go to the page with the videos. Just before the videos were shown they were given exact instructions for the task to be performed. As explained in section 2.1, there were two kinds of instructions presented, one with information about vehicle deviation and one without.

The instructions with deviation information were as follows:

"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.

You will view 28 animations. Press 'F' when you feel safe to cross the road in front of the car. You can release the button and then press it again multiple times during the video. After each 5 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."

The version without deviation information was as follows:

"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.

You will view 28 animations. Press 'F' when you feel safe to cross the road in front of the car. You can release the button and then press it again multiple times during the video. After each 5 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."

The participants were given an option to take a break after every 5 video with the following text being displayed – "*You have now completed 5 [10,15,20,25,28] videos out of 28. When ready press 'C' to proceed to the next batch*."

The jsPsych framework (De Leeuw, 2015) was modified and used to create this experiment. The same approach was previously used to study reaction times for multimodal stimuli (Bazilinskyy and De Winter, 2018) and effects of different eHMI configurations on pedestrians' perceived safety (Bazilinskyy et al., 2020).

Each participant received a unique code at the end of the experiment, which had to be entered in the questionnaire as proof of completion, in order to receive the remuneration. After entering the code, the next field in the survey had the following question – *"In the experiment, the car sometimes steered to the left or right. Why did the car do that? Please elaborate. (required)"*. The aim was to collect subjective impressions of the participants regarding the vehicle behaviour presented in the experiment.

2.3 Analyses

The effects of each variable (deviation magnitude, onset location, vehicle behaviour, intended vehicle path) was assessed for each of the four participant groups. Since between-group designs require a substantially higher number of participants to achieve the same statistical power as within-subject designs, most of the analyses were done individually for each of the four groups or by comparing two groups for a given instruction condition to ensure reasonable statistical power is obtained.

When checking results for towards vs away deviations, a comparison was done using an independent samples t-test for when instructions were and were not given. (so Groups 1 and 3 were compared, as well as Groups 2 and 4). Subsequently, a sign test was performed to compare the baseline against each of the two groups for a given instruction condition. Yielding and non-yielding trials were compared separately. In general, both the signed-rank test and a sign test check whether the median of differences in the data is zero, but the signed-rank test also assumes equal distribution of data. Since the comparison within groups was done between the 4 baseline trials (combined) versus the 12 deviation conditions (combined), equal data distribution in both observations was not expected, which is why the sign test was chosen for the analyse. Subsequent variables are also statistically tested using the sign test.

For the conditions of deviation levels and deviation onset, statistical significance was calculated within each group using sign tests between the levels of the independent variables. For the intended vehicle path, the comparison was made using sign tests within a group, separately for the deviation trials and the baseline trials to check if significant difference indeed existed based on the hypothesis in Section 1.5.

The aforementioned statistical tests were performed on the percentage of time the participants press the key (in 1 s increments of the video). Following the recommendation of Benjamin et al. (2018), a significance value of 0.005 was used.

Perceived-safety percentages were calculated for each block of videos and averaged over participants per block. This percentage represented the percentage of time the participant pressed the response key between 4 s and 10 s into the video (earliest vehicle deviation for the early onset trials starts at 4.21 s into the video, and each video is 11 s long).

This data analysis approach is based on the methods used by Bazilinskyy et al. (2020), where the authors used a similar approach in a crowdsourced study to measure the effectiveness of different eHMI configurations.

3. Results

There were 945 total participants. They completed the study between 1 April 2020 and 4 April 2020. The total cost of the survey was 396.90 USD. The survey received an overall rating of 4.5 out of 5.0 from the participants. People who participated more than once, did not read the instructions, or faced technical issues with the playback were removed. In all, 638 participants were included in the final analysis, and 307 were removed. The survey took 21.58 minutes to complete on average (SD = 14.87), for the filtered participants.

The filtered participants were from 57 different countries, with the highest number of participants coming from Venezuela (N = 144), followed by the USA (N = 46) and Egypt (N = 45). There were 436 male and 202 female respondents, with the overall mean age of the participants being 36.9 years (SD = 10.9). The participants viewed 26.65 videos on average. This is a small deviation from the expected number of 28 videos, which could have been due to interruptions in the browser during the experiment (page reload, opening new tabs, etc.).

The following figures contain keypress information exhibiting the following trend: the keypresses increase as the vehicle is still far away from the pedestrian (1 to 6 s) of the video. As the vehicle approaches, the keypresses begin to decrease. Braking starts 6.05 s into the video and the vehicle comes to a stop 10 s into the video for yielding trials, so an increase in keypresses is usually seen towards the end. For non-yielding trials, since the video ends right after the vehicle passes by the pedestrian, the keypresses continuously decrease after 6 s into the video. The early onset of deviation starts at 4.21 s into the video, and the turning indicator starts flashing around 6.05 s into the video with the hypotheses (in section 1.5) being that these events would have an influence on the keypresses.

The following results were observed:

1) **Yielding behaviour:**

   For both direction-behaviour mappings, vehicle deviation had a significant effect over baseline in all groups, but only for yielding behaviour. The significance for deviation towards pedestrian (Figures 4 and 5) existed between the duration of 7 and 9 s of the video, while the significance for deviation away from the pedestrian (Figures 6 and 7) was found only for the 7 to 8 s window. For the 7 to 8 s window, significant difference ($p < 0.005$) was observed for all four independent groups.

2) **Non-yielding behaviour:**

   Comparison of trials deviation with deviation against baseline did not give statistically significant results for all four groups. The results are summarised in Figure 8.

3) **Magnitude of lateral deviation:**

   The results were significant only in the yielding trials for 0.4 m deviation compared to 1.2 m deviation, during 8 to 9 s of the video. The statistical significance occurred for both direction-behaviour mappings when instructions were given to participants (Groups 2 and 4 were significant) as seen in Figures 9 and 10. When deviation towards the pedestrian was used to convey yielding, 1.2 m deviation resulted in higher keypress percentage (Figure 9). When the deviation away from the pedestrian was used to convey yielding, 0.4 m deviation resulted in higher keypress percentage (Figure 10).

4) **Deviation onset:**

Across all four groups, no significant results were found when comparing trials where deviation onset occurred 30 m away from pedestrian to trials where it occurred 50 m away from the pedestrian. The results of groups where yielding was indicated by deviation towards pedestrian (Groups 1 and 2) are summarised in Figure 11. Figure 12 shows results for groups where yielding was indicated by deviation away from the pedestrian (Groups 3 and 4).

5) **Intended vehicle path:**

For a given deviation direction (baseline, towards pedestrian, away from pedestrian), comparison was made between yielding trials which indicated that vehicle intended to take a turn (i.e., the right turn indicator was flashing) versus yielding trials which indicated that vehicle intended to go straight ahead. Significant results only occured when vehicle deviated towards pedestrian to yield, with instructions being given (Group 2) as seen in Figure 13. Higher keypress percentage was seen for vehicles that indicated an intent to turn versus vehicles that did not show a turn indicator when deviation was present. There was no significant difference between the baseline yielding trials in Group 2.

6) Learning behaviour:

Learning curves were formulated for yielding and non-yielding trials across all groups, for both deviation-behaviour mappings (Figures 14 and 15). Learning curves for yielding behaviour in straight and turning trials for each mapping are presented in Appendix G.

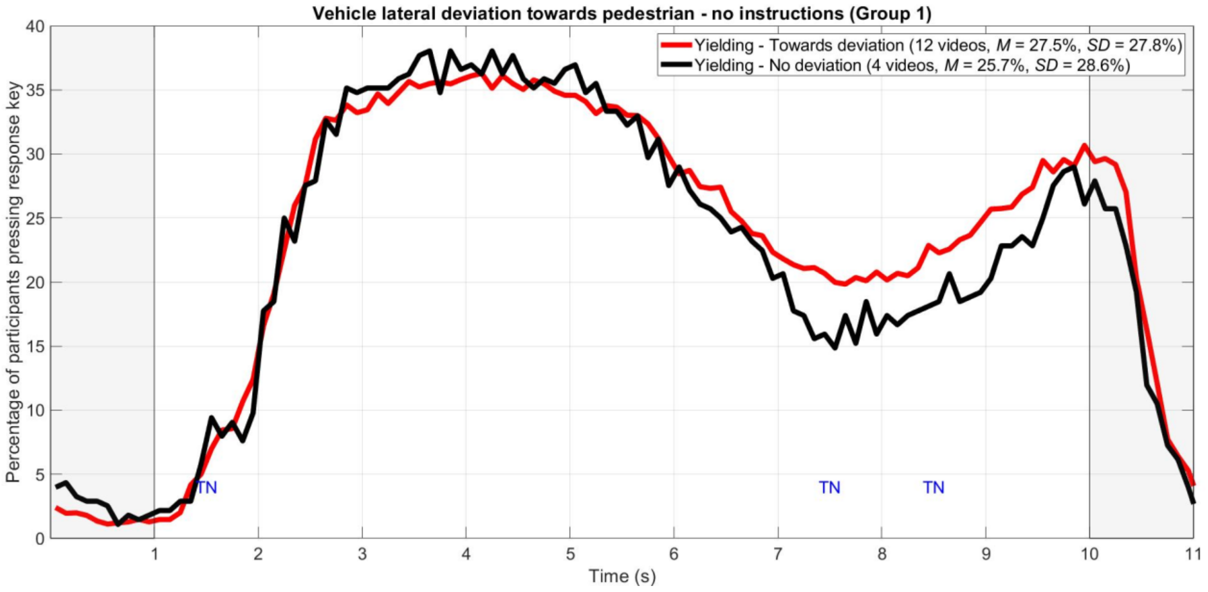

Figure 4. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing the deviation towards pedestrian to represent yielding against the baseline, while instructions were not given (Group 1). The legend shows means and standard deviations across participants between 4 and 10 s of the video. TN indicates that a significant difference exists between 'towards pedestrian deviation' versus baseline for that second of the video.

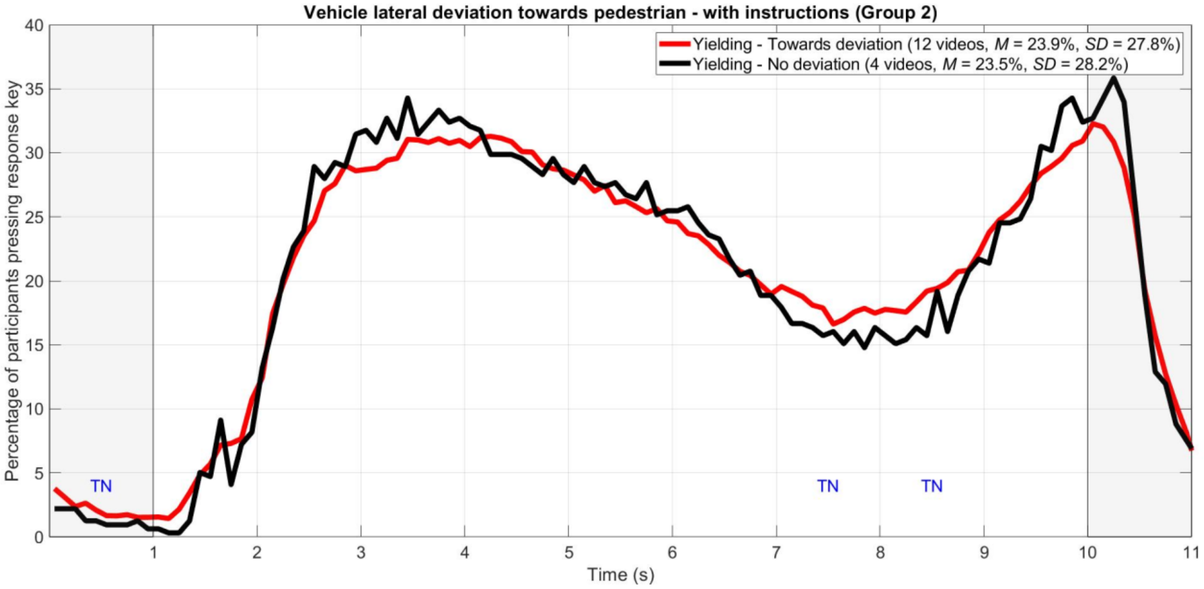

Figure 5. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing the deviation towards pedestrian to represent yielding against the baseline, while instructions were given (Group 2). The legend shows means and standard deviations across participants between 4 and 10 s of the video. TN indicates that a significant difference exists between 'towards pedestrian deviation' versus baseline for that second of the video.

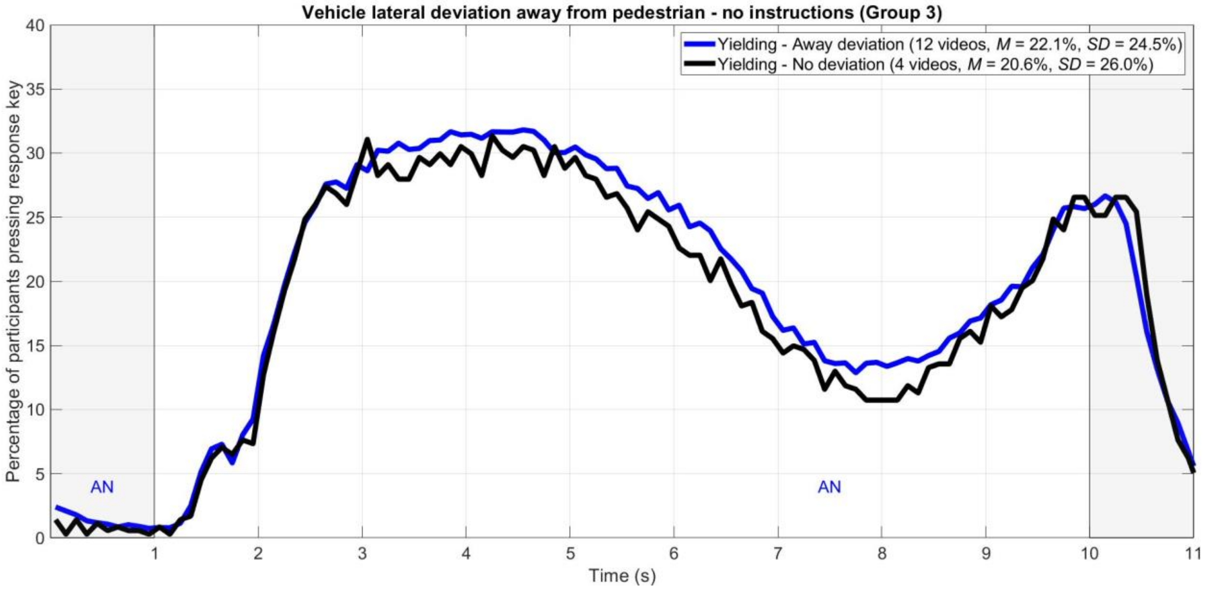

Figure 6. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing the deviation away from pedestrian to represent yielding against the baseline, while instructions were not given (Group 3). The legend shows means and standard deviations across participants between 4 and 10 s of the video. AN indicates that a significant difference exists between 'away pedestrian deviation' versus baseline for that second of the video.

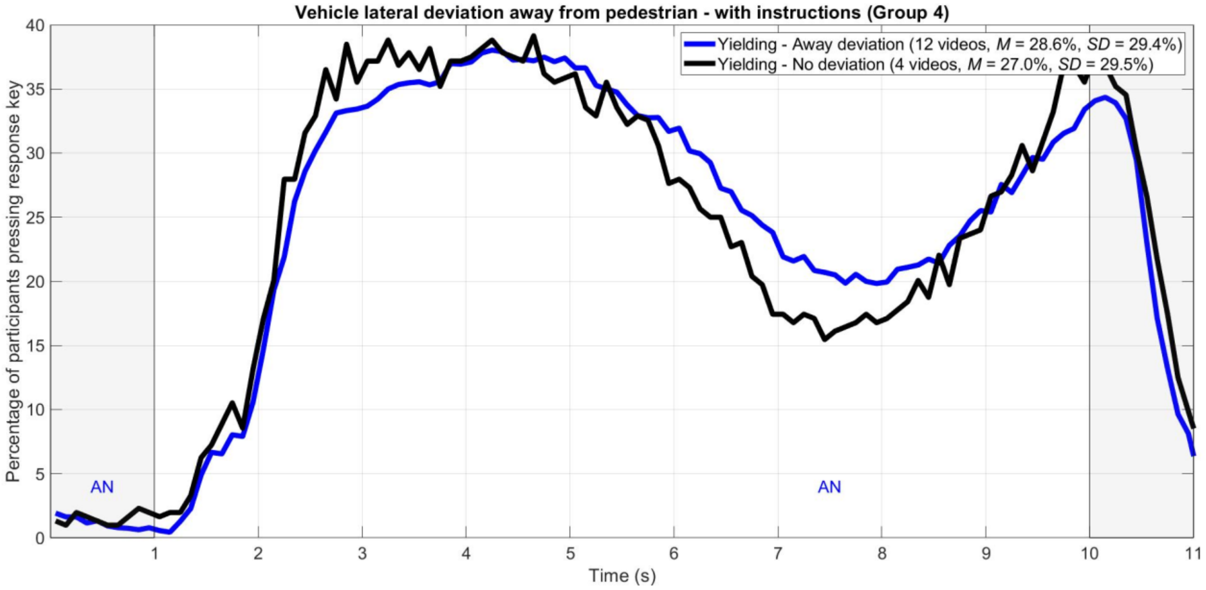

Figure 7. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing the deviation away from pedestrian to represent yielding against the baseline, while instructions were given (Group 4). The legend shows means and standard deviations across participants between

4 and 10 s of the video. AN indicates that a significant difference exists between ‘away pedestrian deviation’ versus baseline for that second of the video.

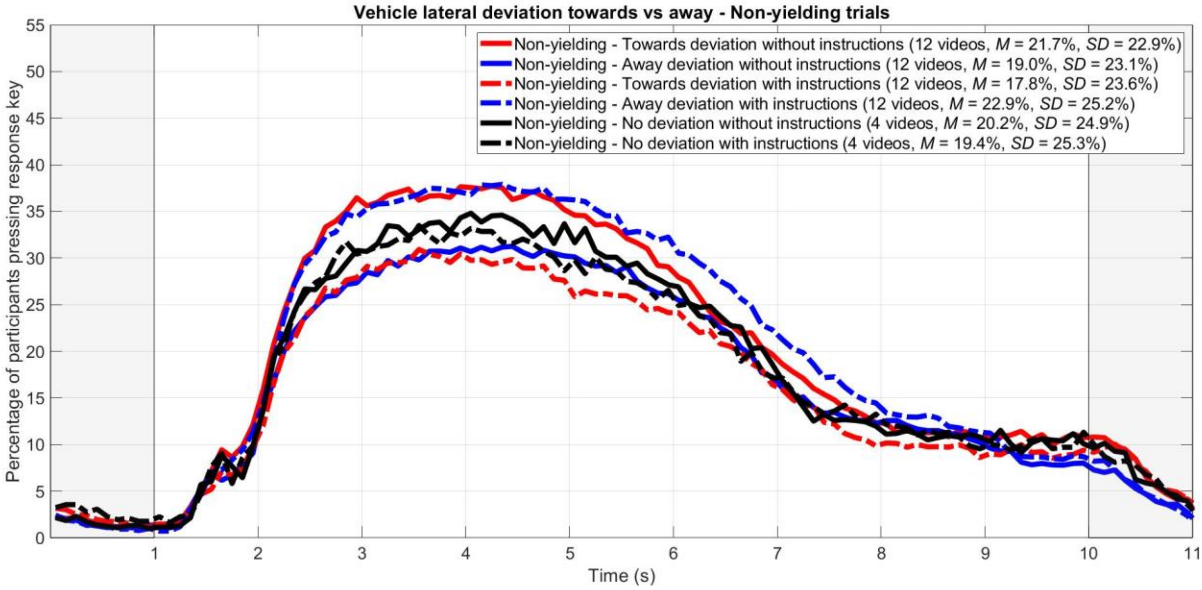

Figure 8. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing all deviation trials that represent non-yielding against the baseline, for all groups. The legend shows means and standard deviations across participants between 4 and 10 s of the video.

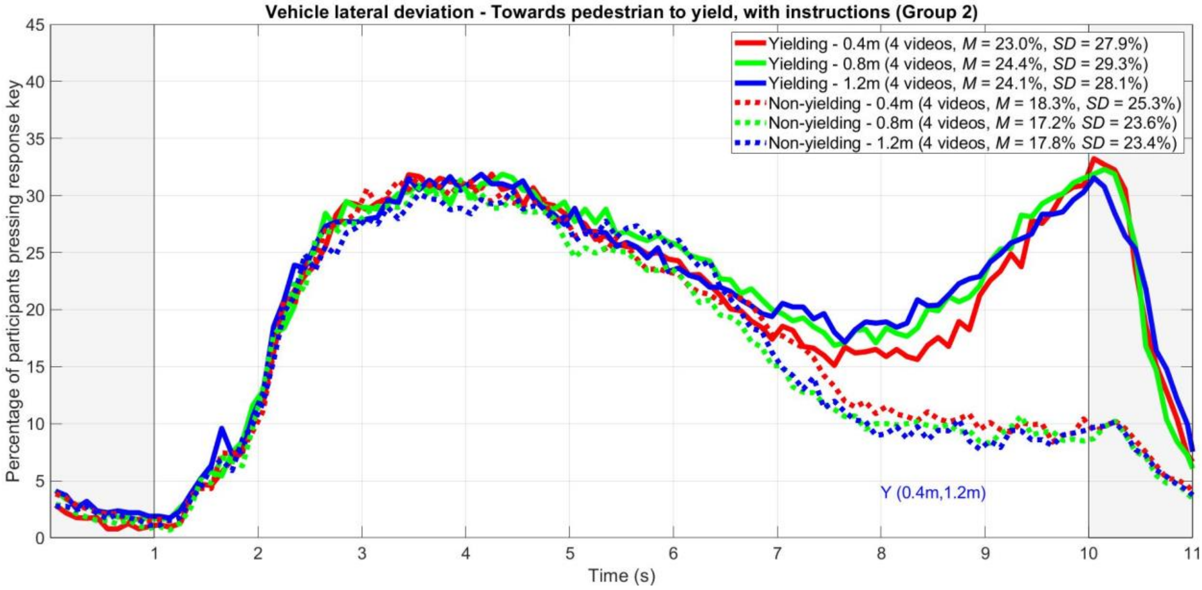

Figure 9. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing the different deviation levels for the group in which deviation towards pedestrian

indicates yielding, and instructions are given (Group 2). The legend shows means and standard deviations across participants between 4 and 10 seconds of the video. Y(0.4m, 1.2m) shows that significant difference exists between lateral deviations of 0.4 m and 1.2 m for yielding behaviour of the vehicle, in that second of the video.

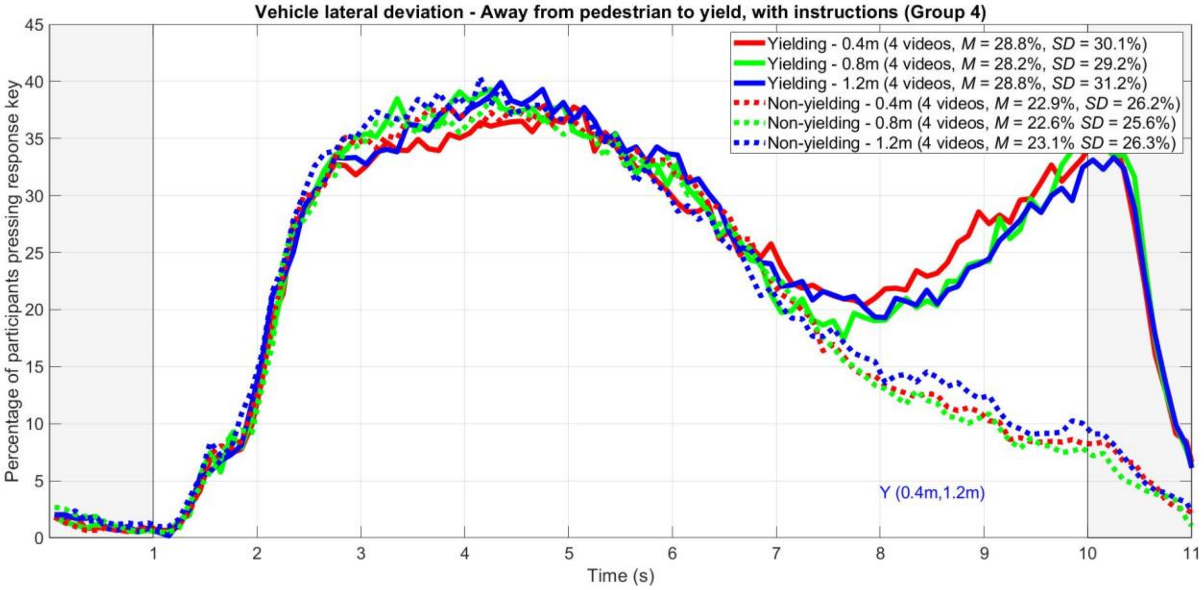

Figure 10. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing the different deviation levels for the group in which deviation away from pedestrian indicates yielding, and instructions are given (Group 4). The legend shows means and standard deviations across participants between 4 and 10 seconds of the video. Y(0.4m, 1.2m) shows that significant difference exists between lateral deviations of 0.4 m and 1.2 m for yielding behaviour of the vehicle, in that second of the video.

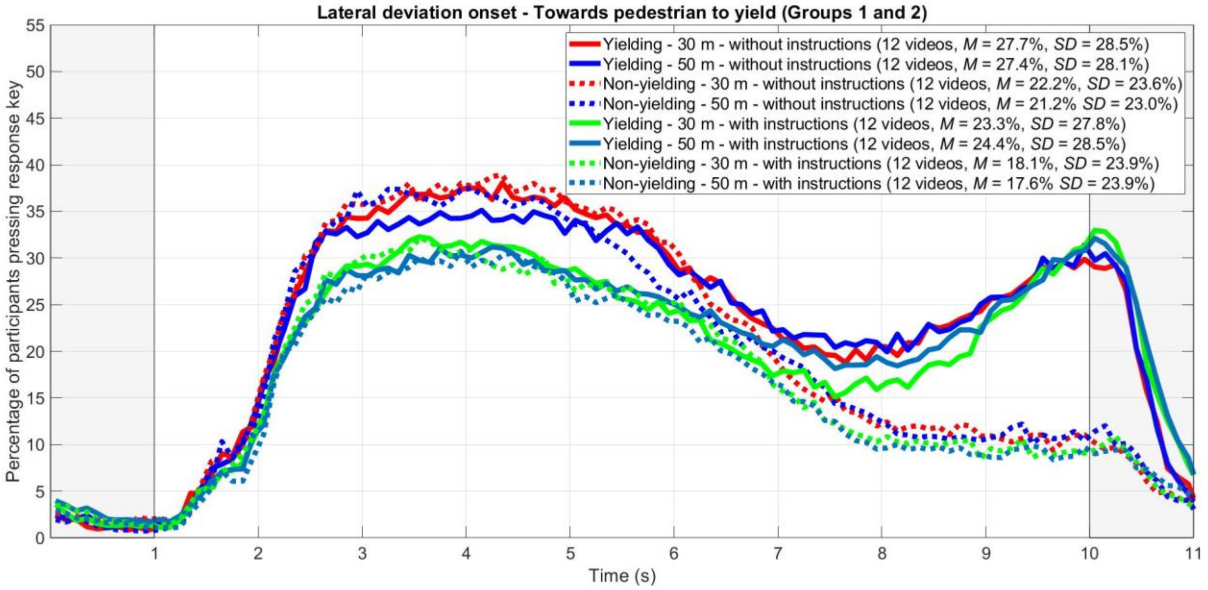

Figure 11. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, for trials where the onset of deviation occurs 50 m and 30 m away from the pedestrian. The figure includes groups with and without instructions for the trials where indication to yield is given by deviation towards pedestrian. The legend shows means and standard deviations across participants between 4 and 10 seconds of the video.

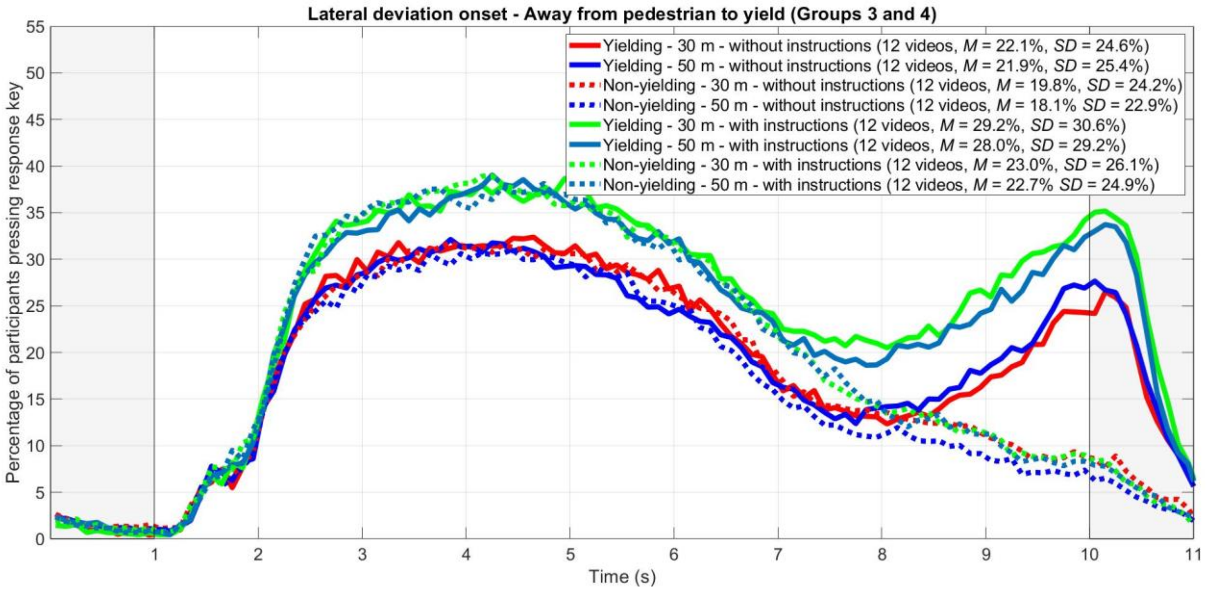

Figure 12. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, for trials where the onset of deviation occurs 50 m and 30 m away from the pedestrian. The figure includes groups with and without instructions for the trials where indication to yield is given by deviation away

from the pedestrian. The legend shows means and standard deviations across participants between 4 and 10 seconds of the video.

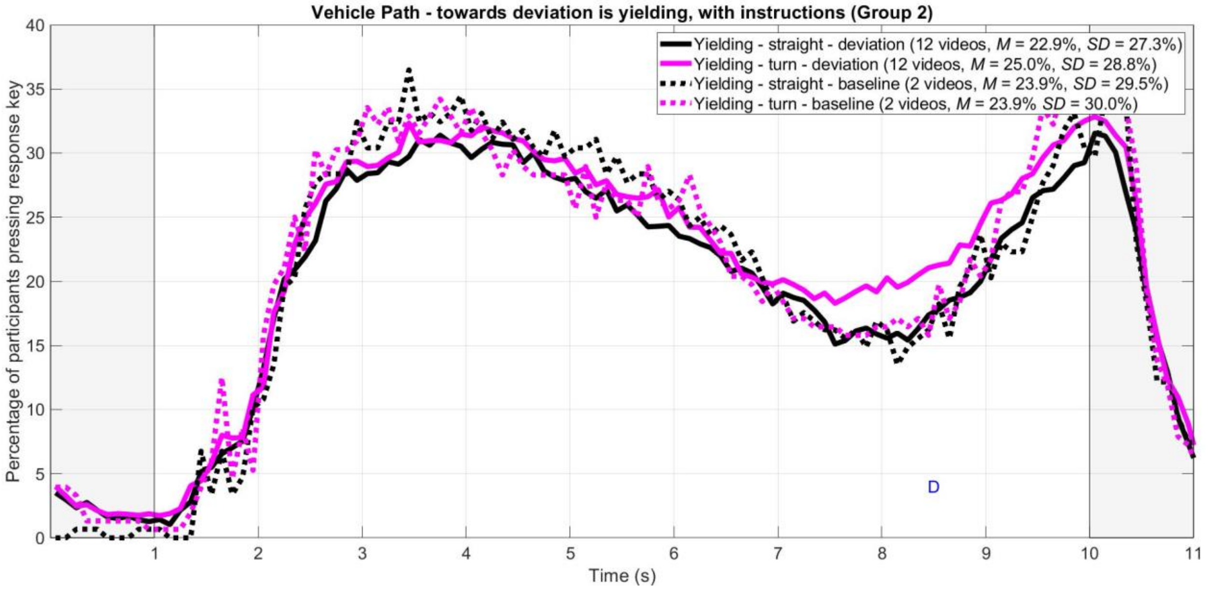

Figure 13. The percentage of participants who felt safe to cross (pressed the response key) as a function of elapsed video time, when comparing the yielding trials within Group 2 for different intended vehicle paths, when deviation exists versus no deviation. The legend shows means and standard deviations across participants between 4 and 10 seconds of the video. D - shows that a significant difference exists between the straight and turning trials when a deviation is present, for that second of the video

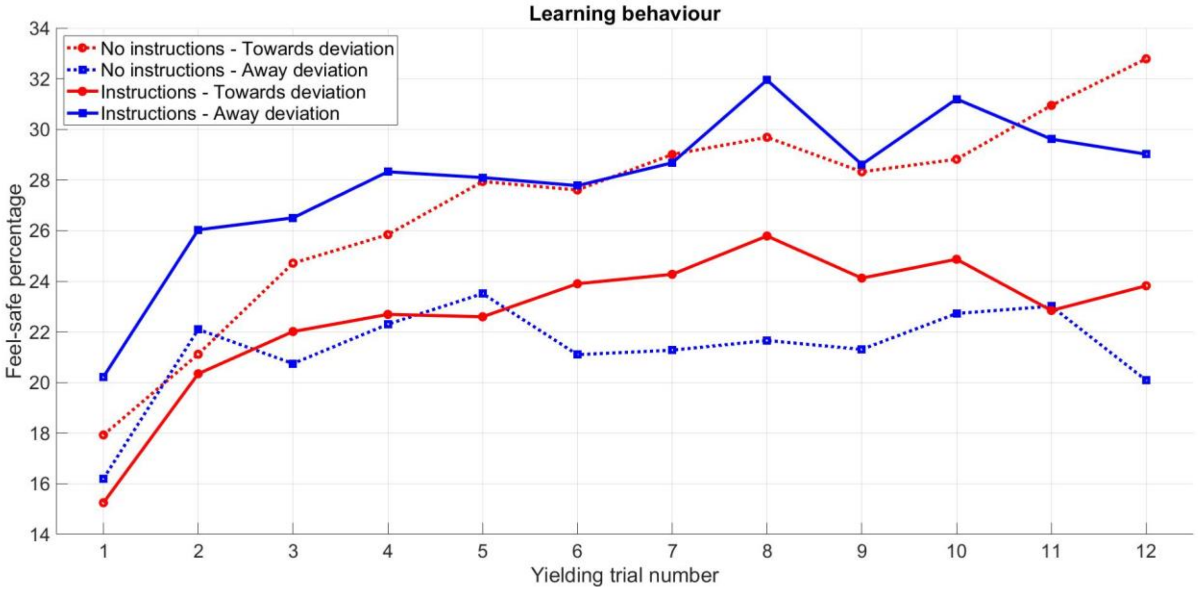

Figure 14. The percentage of participants who felt safe to cross (pressed the response key) as a function of trial number, for yielding trials. There were 12 trials per participant for each of the four groups.

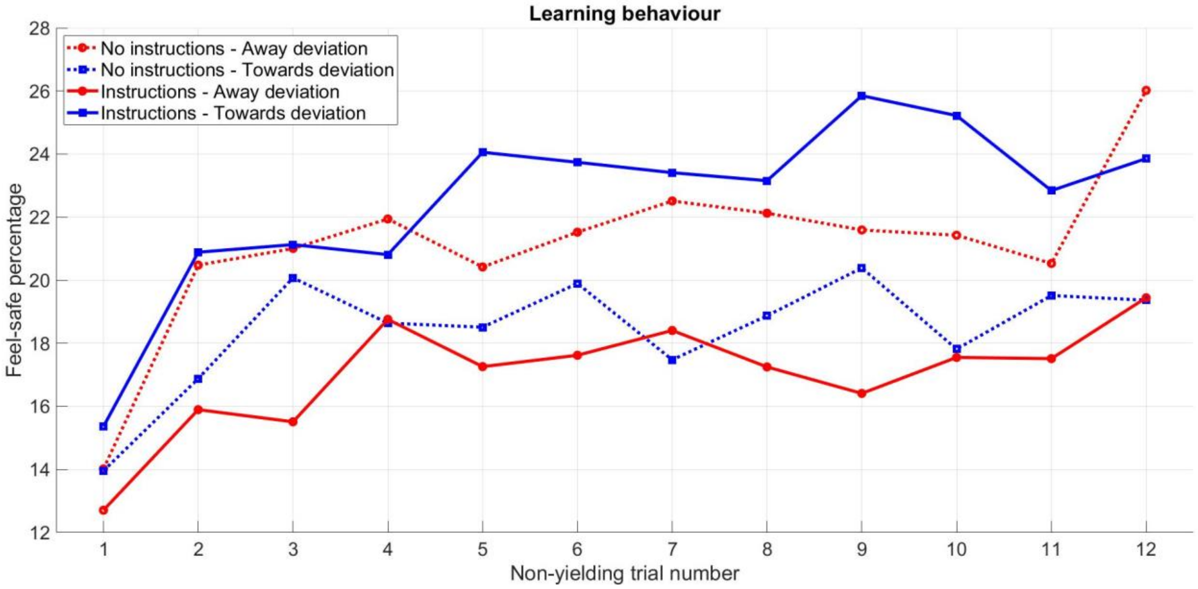

Figure 15. The percentage of participants who felt safe to cross (pressed the response key) as a function of trial number, for non-yielding trials. There were 12 trials per participant for each of the four groups.

4. Discussion

The current study focused on the effect of lateral vehicle deviation on pedestrians' willingness to cross, and an initial assessment was made regarding its effectiveness as an intent communication signal.

4.1 Effects of direction and magnitude of deviation

Across all four groups, deviation accompanied by yielding has a statistically significant effect on pedestrian willingness to cross in front of the car. Lateral deviation occurs 4 s into the video for the early onset (50 m away from pedestrian) trials, and 6 s into the video for the later onset (30 m away from pedestrian) trials. Vehicle braking starts around the 6 s mark at 40 km/h, and the vehicle slows down further in the 7 to 9 s window. So the largest effects are expected to be seen in the 6 to 9 s interval. For the 9 to 10 s interval, the vehicle moves very slowly (ultimately stopping at the 10 s mark) so it is evident that the vehicle is going to yield for the pedestrian, and there is no contribution expected from the lateral motion cue in intent communication. Consistent with these expectations, vehicle deviation has a statistically significant effect between 7 to 8 s for all conditions (figures 4 to

7), which corresponds to the vehicle slowing down to 30 km/h in the videos. The absence of significant effect of deviation onset (figures 11 and 12) might explain why there were no significant results in the 4 to 6 s interval.

In the groups that received no prior information about the cue, deviation towards pedestrian shows a clear trend of higher crossing willingness, so this might have contributed to a statistical difference against the baseline for the 8 to 9 s window as well. In the groups that did receive the information about deviation before the experiment, significant results can again be seen in the 8 to 9 s window when vehicle deviates towards the pedestrian to yield. In this case however, there is no clear trend to compare the two directions. When examining the results only for the two groups where deviation towards pedestrian indicated yielding, it seems counter-intuitive that participants without instructions exhibited a shorter learning curve (as seen in the 'No instructions – towards deviation' line in Figure 14). There is some evidence to suggest that an unexpected change in motion attracts attention (Howard and Holcombe, 2010; Schmidt et al., 2019), so it is possible that participants observed the vehicle behaviour more keenly. However, there were no significant differences between the four independent groups for learning behaviour (elaborated further in section 4.3), so it is difficult to draw an overall conclusion about the effect of instructions given prior to the experiment.

Logically, the detection of yielding intent through vehicle motion alone would first require detection of deceleration. Current studies in external intent communication interfaces (De Clercq et al. 2019, Eisma et al. 2020) have already demonstrated that yielding intent can be conveyed before vehicle deceleration begins. This was done by displaying a message in the vehicle's external display that communicated yielding intent before the vehicle started braking. Similar methods of enhancing yielding intent detection could perhaps be achieved through vehicle motion cues as well. In Ackermann et al. (2019), reported that when a vehicle is moving at 40 km/h begins to decelerate at 3.4 m/s^2 with a time to arrival (TTA) of 3.5 to 4.5 s from the target, the mean time taken by participants to detect the deceleration is about 2.5 s. For the yielding trials in the current study, the vehicle speed is also 40 km/h and since it comes to a stop at the 10 s mark, the deceleration rate is 2.74 m/s^2 and TTA is 4 s. The vehicle kinematics in the current study as well as Ackermann et al. are similar, so similar detection times for deceleration are expected. The earliest significant difference in crossing willingness in the current study occurs in the 7 to 8 s interval, which is almost 1 s earlier (40% less) than the mean deceleration detection times in the Ackermann et al. study. The quick increase in crossing willingness does not necessarily mean earlier detection of deceleration, as that was not part of the participants' task in this study. However, it indicates the possibility for usage of vehicle behavioural cues to convey yielding intent, independent of vehicle deceleration.

Non-yielding behaviour did not show significant results in any of the groups. A possible explanation for this is presented in Section 4.3. In the study of Fuest et al. (2018), only non-yielding behaviour was investigated and the deviation to indicate non-yielding in that study was away from the pedestrian. Their results showed that when asked to evaluate vehicle driving behaviour on a five-point Likert scale, pedestrians rated the non-yielding trials with deviation higher than the non-yielding trials without deviation. However, the actual effect on crossing decisions was not examined. In combination with the current results, there is an indication that the direction-behaviour mapping of moving towards pedestrian to yield and away to not yield seems more promising than the opposite combination. Further research is required for a clear choice to be made between the two mappings.

The lateral deviation results (Figures 9 and 10) show that a significant effect on perceived safety exists for 0.4 m deviation compared to 1.2 m deviation and only for yielding trials when instructions are given (Groups 2 and 4). Since these are the two extreme values of the deviation levels, such results might indicate that a larger deviation would be necessary to elicit a strong enough change in perceived safety. Specifically looking at Group 2 (Figure 9), it can be seen that there is a clear improvement in keypress percentage for 0.4 m compared to 1.2 m (for yielding). The direction-behaviour mapping for this group comprised of deviation towards pedestrian for yielding and away from pedestrian for not yielding, which is the same mapping that yielded better results in the data of Figures 4 and 5. The contrast here, however, is that significance was found only for the groups with instructions. The statistical significance is seen only in the 8 to 9 s window, which is well past the deviation onset time of even the 30 m condition (6.05 s). It is possible that the recognition of yielding behaviour in this window had a confounding effect. Another important aspect that might have an effect on the results is that the vehicle path in the virtual environment was not achieved precisely. This means that by design, the vehicle should travel 15 m before achieving the peak lateral deviation, but it instead travels over 20 m. The subsequently results in maximum deviation being achieved between the 8 to 9 s interval of the video, instead of 7 to 8 s (further details in Appendix I). Hence the most optimal range for lateral deviation requires further investigation.

4.2 Effect of intended vehicle path (straight vs turning)

The comparison of keypresses between yielding trials in which vehicle intended to go straight versus yielding trials in which vehicle intended to turn showed significant results only in Group 2, when lateral deviation is present (as seen in Figure 13). For this group, yielding was indicated by the vehicle deviating towards the pedestrian and the instructions at the start of the experiment informed the participant about the deviation.

The hypothesis was that there is an ambiguity in making a crossing decision, when the vehicle signals that it is taking a turn but yielding versus a vehicle that is going straight ahead and yielding. The existence of this ambiguity for the current study is defined as the presence of significant differences in keypress behaviour between the two vehicle paths (straight vs turn), when same vehicle kinematics and behavioural cues exist. For the baseline yielding condition, there was no significant difference in results for straight ahead vs turning trials, so it seems that this hypothesis can be rejected. For the yielding trials with deviation present, statistical significance between the results of straight and turning trials occurred in the 8 to 9 s window. It can also be seen that when comparing baseline trials with deviation trials, the difference in results for turning trials is larger than the difference in results for straight trials. By this point in the video, the vehicle would have considerably slowed down, and as stated earlier, yielding behaviour is usually well-recognised by pedestrians, so it is expected that both straight and turning trials should have similar results in terms of keypress percentages. An increase in crossing willingness for the turning trials in the 7 to 9 s interval, when the deviation is present, indicates that the ambiguity hypothesis might have some validity. It is also interesting to note that the significance occurs only in the group where deviation towards pedestrian indicates yielding which was seen for the lateral deviation as well.

4.3 Trends in learning behaviour

Looking at the learning behaviour for yielding trials in Figure 14, it is evident that there is some form of a learning effect over the course of the experiment. Statistically, there were no significant effects of learning found for any of the four groups, so it is difficult to determine if the participants correctly understood the purpose of the lateral deviation by the end of the experiment. Looking at Figure 15, we see that the feel-safe percentages have increased even for the non-yielding trials, with an increase in trial number. Thus, the effect is the opposite of what was intended. A possible explanation for the constant increase in feel-safe percentage even in non-yielding trials is that the learning curve for these trials might be confounded by the learning curve of the overall task. The participant's task in this study was to press and hold a specific button as a reaction to an approaching vehicle, and it can be seen from the data reported in the appendices C – F that participants felt more comfortable in pressing and holding the button as the experiment progressed, which could have led to the confounding effect mentioned above.

4.4 Subjective results from participant replies

At the end of the experiment, to see if the presented behavioural cue was clearly understood, participants were asked to elaborate on why the vehicle could have deviated in either direction. After a subjective analysis of the replies, roughly 10% of the total participants correctly understood that lateral deviation was a signal of yielding intent. The group for which deviation away from the pedestrian indicated yielding and no instructions were given before the experiment, had the least percentage of correct answers (4.5%). The other three groups had about 10 to 13% participants who correctly understood the presented cue. Among the two groups that received instructions, it was interesting to note that indication of yielding through deviation in either direction showed similar rates of correct answers. A possible explanation for the similarity is that vehicle deceleration itself is a confounding factor in trying to identify the vehicle behaviour. Since yielding vehicles slow down to a complete stop, the connection between lateral deviation and yielding intent can be guessed correctly after a few trials, regardless of deviation direction. Another interesting trend was that in most of the incorrect answers, participants assumed the vehicle was reacting to their presence, instead of proactively communicating with them. As a result, they assumed the deviation of the vehicle for non-yielding trials meant the vehicle was trying to avoid a collision with them as they were crossing the road. This could explain a consistent lack of significant results for the non-yielding trials in all groups, since participants kept pressing the ‘safe to cross’ button expecting that the vehicle will execute evasive manoeuvres.

4.5 Conclusions

Overall, both deviation-behaviour mappings were found to have statistically significant effects on crossing willingness in front of a yielding vehicle. All four groups reported a higher crossing willingness when deviation was present, compared to no deviation. For different magnitudes of lateral deviation, statistically significant results were obtained for the two groups that were informed of the deviation before the experiment. A deviation of 1.2 m versus 0.4 m increased crossing willingness when deviation towards pedestrian indicated yielding and for deviation away from pedestrian, the opposite effect was observed. For intended vehicle path in yielding trials, when lateral deviation was present, a statistically significant increase in crossing willingness was observed when vehicle intended to go straight versus when vehicle intended to take a turn. However, this occurred only for one group, in which deviation towards pedestrian indicated yielding and participants received instructions at the start of the experiment which informed them of the deviation.

Additionally, one of the recurring results from the eHMI studies (e.g., Lagström and Lundgren 2015; Ackermans 2019), was that informing the pedestrians of the vehicle’s driving mode using an eHMI seemed to alleviate their anxiety when encountering the vehicle. For the current study, the participants were explicitly informed that they would encounter an autonomous vehicle, and the vehicle in the videos shown to the participant always had an empty driver seat. A statistically significant increase in crossing willingness despite the absence of a driver might also indicate the potential of vehicle motion as a cue to convey intent.

4.6 Limitations

There are still several limitations in this study that need to be addressed. One concern is the between-subjects design. As this modality of communication was scarcely explored, the idea was to investigate as wide a range of conditions as possible without causing confusion in participants due to the inverted behaviours in each mapping. However, this design led to a loss in statistical power, forcing a minimal analysis to be performed on the data, even with a fairly large sample size available (Group 1, N = 139; Group 2, N = 160; Group 3, N = 179; Group 4, N = 152). Choosing a within-subjects design which can provide higher power in the statistical analysis is recommended for the future, especially for the topics similar to the current research and which may be expected to have small effects. The other aspect is that for a communication method that is novel and not currently exhibited even by human drivers, it is thus recommended to conduct more than 24 trials per participant to evaluate long-term learning.

The vehicle controller in Unity can also be improved in order to investigate a finer difference between the perception of different deviations. A later onset of deviation in the virtual environment compared to the designed path meant that lateral deviation magnitudes were not achieved at the desired time interval of the videos. The current results show no significant difference in learning behaviour between the four independent groups. For non-yielding trials, the vehicle was programmed to exhibit different behaviour when going straight versus when taking a turn in order to be more realistic. As a result, they could not be directly compared and included in the current analysis. It is recommended to specifically examine a wider range of turning behaviours alone so that non-yielding can be compared as well.

There is also the fact that there was little control over the conditions in which the participant performed the experiment, how much attention they paid to the cues and so on, which can be quite significant when studying a communication modality that is still at a nascent stage in research. Finally, of course, a question of real-life validation of this behaviour, which could perhaps be performed using a Wizard of Oz method (Moore et al., 2019; Rothenbücher et al., 2016).

4.7 Recommendations

The mapping of deviating towards pedestrian to indicate yielding is the opposite of the non-yielding behaviour that gave significant results in Fuest et al.'s experiment, so there is agreement between the studies, albeit indirectly and it is recommended to use this mapping for future studies. Appendices D and F respectively contain the results of the yielding trials for the groups that received information about the deviation and the groups that did not receive this information. It can be seen that the mapping where deviation towards pedestrian indicates yielding results in higher feel-safe percentages. Also, from a traffic-flow and safety standpoint, this behaviour seems feasible, as the opposite mapping has the vehicle slowing down and moving towards the road centre, and moving towards the curb without a change in speed, both of which seem less safe at first glance.

For a preliminary investigation, the levels of vehicle lateral deviation studied here were in steps of 0.4 m. For future research, a finer implementation of the vehicle movement in Unity coupled with smaller deviations can perhaps find the exact range in which deviations are best perceived by the pedestrian.

Additionally, when testing the effectiveness of communication cues to convey vehicle intent, it would be worthwhile also to include turning trials in addition to straight-line behaviour. This is perhaps more applicable for studies in which behavioural cues are investigated (like the current study), where the expectation is the recognition of a pattern in vehicle motion. For cues that rely on external interfaces (eHMIs) to communicate, the turning condition would probably have less of an effect.

For overall experimental methods, different keys to denote willingness and unwillingness to cross can be used, instead of pressing/releasing a single key to denote the same. This could decouple the learning curve of the task from the learning curve of the actual cue presented in the experiment. Ackermann et al. (2018) propose a similar solution to their study where detection time for vehicle acceleration or deceleration was measured using the same button. While the results obtained in their study using this method did reflect the detection times, it was not possible to verify if the participant correctly detected the type of motion presented. Using different buttons was proposed as a method to simultaneously measure reaction time as well as the type of motion detected. A similar solution can perhaps be adopted for future research to distinguish between a yes or no decision to cross the road.

Based on the subjective results, it seems that consistent detection of yielding behaviour of the vehicle leads to similar learning behaviour for either deviation direction. To evaluate the intuitiveness of each direction-behaviour mapping, it is recommended to collect a separate score and not estimate it indirectly through crossing willingness.

5. Future outlook

Domeyer et al. (2020), in their analysis of interaction mechanisms between HAVs and other road users, postulate that a framework for improving communication between the two entities would require both kinematic cues as well as external interfaces to be used in order to be effective. Also, the ability to program and precisely execute desired driving behaviour is one of the key advantages offered by HAVs over human drivers. Since pedestrians have demonstrated that they do perceive changes in vehicle motion within certain thresholds, it might be worthwhile to investigate kinematic cues like lateral vehicle deviation which can help augment the messages displayed through explicit modalities and ultimately improve pedestrian-AV communication.

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Appendix

Appendix A Survey page displayed on Figure-Eight

Measuring Pedestrian's Willingness To Cross In Front Of An Automated Vehicle

Instructions

You are invited to participate in a research study entitled "Measuring pedestrian's willingness to cross in front of an automated vehicle ". The study is being conducted by Anirudh Sripada, Dr. Pavlo Bazilinskyy and Dr. Joost de Winter, Department of Cognitive Robotics, Delft University of Technology, The Netherlands, p.bazilinskyy@tudelft.nl (mailto:p.bazilinskyy@tudelft.nl).

You are free to contact the investigator at the above email address to ask questions about the study. You must be at least 18 years old to participate. The survey will take approximately 15 minutes of your time. In case you participated in a previous survey of one of the present investigators, your responses may be combined with the previous survey.

The information collected in the survey is anonymous. Participants will not be personally identifiable in any research papers arising from this study. If you agree to participate and understand that your participation is voluntary, then continue. If you would not like to participate, then please close this page. Before the study starts, the videos will be preloaded. This may take a few minutes depending on your Internet connection.

Please do use Internet Explorer for this study.

General questions

Have you read and understood the above instructions? (required)

- Yes
- No

What is your gender? (required)

- Male
- Female
- I prefer not to respond

What is your age? (required)

In which type of place are you located now? (required)

- Indoor, dark
- Indoor, dim light
- Indoor, bright light
- Outdoor, dark
- Outdoor, dim light
- Outdoor, bright light
- Other
- I prefer not to respond

If you answered 'Other' in the previous question, please decribe the place where you located now below.

Which input device are you using now? (required)

- Laptop keyboard
- Desktop keyboard
- Tablet on-screen keyboard
- Mobile phone on-screen keyboard
- Other
- I prefer not to respond

If you answered 'Other' in the previous question, please decribe your input device below.

At which age did you obtain your first license for driving a car or motorcycle?

What is your primary mode of transportation (required)

- Private vehicle
- Public transportation
- Motorcycle
- Walking/Cycling
- Other
- I prefer not to respond

On average, how often did you drive a vehicle in the last 12 months? (required)

- Every day
- 4 to 6 days a week
- 1 to 3 days a week
- Once a month to once a week
- Less than once a month
- Never
- I prefer not to respond

About how many kilometers (miles) did you drive in the last 12 months? (required)

- 0 km / mi
- 1 - 1,000 km (1 - 621 mi)
- 1,001 - 5,000 km (622 - 3,107 mi)
- 5,001 - 15,000 km (3,108 - 9,321 mi)
- 15,001 - 20,000 km (9,322 - 12,427 mi)
- 20,001 - 25,000 km (12,428 - 15,534 mi)
- 25,001 - 35,000 km (15,535 - 21,748 mi)
- 35,001 - 50,000 km (21,749 - 31,069 mi)
- 50,001 - 100,000 km (31,070 - 62,137 mi)
- More than 100,000 km (more than 62,137 mi)
- I prefer not to respond

How many accidents were you involved in when driving a car in the last 3 years? (please include all accidents, regardless of how they were caused, how slight they were, or where they happened) (required)

- ○ 0
- ○ 1
- ○ 2
- ○ 3
- ○ 4
- ○ 5
- ○ More than 5
- ○ I prefer not to respond

How often do you do the following?: Becoming angered by a particular type of driver, and indicate your hostility by whatever means you can. (required)

- ○ 0 times per month
- ○ 1 to 3 times per month
- ○ 4 to 6 times per month
- ○ 7 to 9 times per month
- ○ 10 or more times per month
- ○ I prefer not to respond

How often do you do the following?: Disregarding the speed limit on a motorway. (required)

- ○ 0 times per month
- ○ 1 to 3 times per month
- ○ 4 to 6 times per month
- ○ 7 to 9 times per month
- ○ 10 or more times per month
- ○ I prefer not to respond

How often do you do the following?: Disregarding the speed limit on a residential road. (required)

- ○ 0 times per month
- ○ 1 to 3 times per month
- ○ 4 to 6 times per month
- ○ 7 to 9 times per month

- 10 or more times per month
- I prefer not to respond

How often do you do the following?: Driving so close to the car in front that it would be difficult to stop in an emergency. (required)

- 0 times per month
- 1 to 3 times per month
- 4 to 6 times per month
- 7 to 9 times per month
- 10 or more times per month
- I prefer not to respond

How often do you do the following?: Racing away from traffic lights with the intention of beating the driver next to you. (required)

- 0 times per month
- 1 to 3 times per month
- 4 to 6 times per month
- 7 to 9 times per month
- 10 or more times per month
- I prefer not to respond

How often do you do the following?: Sounding your horn to indicate your annoyance with another road user. (required)

- 0 times per month
- 1 to 3 times per month
- 4 to 6 times per month
- 7 to 9 times per month
- 10 or more times per month
- I prefer not to respond

How often do you do the following?: Using a mobile phone without a hands free kit. (required)

- 0 times per month
- 1 to 3 times per month
- 4 to 6 times per month
- 7 to 9 times per month
- 10 or more times per month
- I prefer not to respond

Experiment to measure willingness to cross in front of an automated vehicle In this experiment you will see multiple videos of a vehicle approaching you and your task is to press and hold a specific key when you feel safe to cross the road. You will be asked to leave figure-eight to participate in the experiment. You will need to open the link below. Do not close this tab. In the end of the experiment you will be given a code to input in the next question on this tab. Please take a note of the code. Without the code, you will not be able to receive money for your participation. All videos will be downloaded before the start of the experiment. It may take a few minutes. Please do not close your browser during that time.

Open this link (https://videos-animations-crowdsourced.herokuapp.com/?work=ANIM1) to start experiment.

Type the code that you received at the end of the experiment. (required)

In the experiment, the car sometimes steered to the left or right. Why did the car do that? Please elaborate. (required)

Miscellaneous questions

In which year do you think that most cars will be able to drive fully automatically in your country of residence? (required)

Please provide any suggestions that could help engineers to build safe and enjoyable automated cars.

Appendix B Experiment materials

Supplementary material that includes the videos, virtual environment (Unity), anonymised data, MATLAB code used for analysis may be found at https://www.dropbox.com/sh/fwh528o660xd2yq/AAC_ko_BT5Wu1tE9FKnSXl1-a?dl=0

Links to videos: (Each link includes baseline trials)

Trials where deviation towards pedestrian indicates yielding:

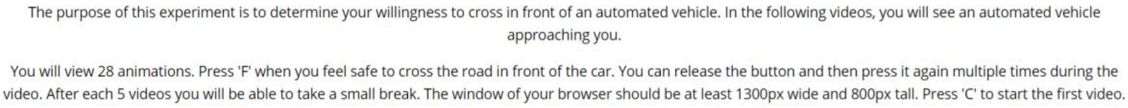
https://www.youtube.com/playlist?list=PLAm7VqbG0eIZoH1fYjzTMKF9YIwQhjynh

Trials where deviation away from pedestrian to indicate yielding:

https://www.youtube.com/playlist?list=PLAm7VqbG0eIaGfmbjLZ8EHIlm0iRx5NMQ

Screenshots of the experiment:

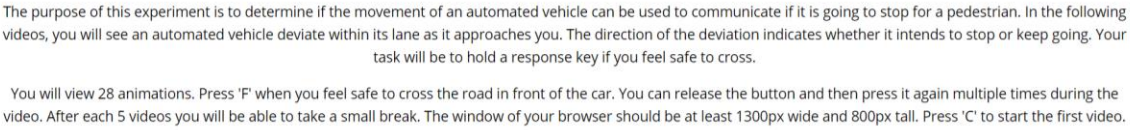
1) Instructions given prior to the experiment (without deviation information)



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.

You will view 28 animations. Press 'F' when you feel safe to cross the road in front of the car. You can release the button and then press it again multiple times during the video. After each 5 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.

2) Instructions given prior to the experiment (with deviation information)



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.

You will view 28 animations. Press 'F' when you feel safe to cross the road in front of the car. You can release the button and then press it again multiple times during the video. After each 5 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.

3) Screenshot of video as seen by the participants

Press and HOLD 'F' when you feel safe to cross.

Appendix C Tables for feel-safe percentages sorted in ascending order for non-yielding vehicles for groups in which instructions were given

video_id	Vehicle Deviation	Deviation Direction	Braking Behaviour	Onset of Deviation	Vehicle Path	Feel-safe percentage
video_15	0.8m	towards centre	non-yielding	50 m	turning	21.79
video_8	0.4m	towards centre	non-yielding	50 m	straight	22.62
video_29	none	none	non-yielding	none	straight	22.91
video_16	1.2m	towards centre	non-yielding	50 m	turning	23.05
video_6	0.8m	towards centre	non-yielding	30 m	straight	23.13
video_10	1.2m	towards centre	non-yielding	50 m	straight	23.22
video_1	none	none	non-yielding	none	straight	23.28
video_12	0.8m	towards centre	non-yielding	30 m	turning	23.35
video_54	0.4m	towards curb	non-yielding	50 m	turning	23.46
video_46	0.8m	towards curb	non-yielding	30 m	straight	23.66
video_50	1.2m	towards curb	non-yielding	50 m	straight	23.68
video_53	1.2m	towards curb	non-yielding	30 m	turning	23.73
video_3	none	none	non-yielding	none	turning	23.87
video_55	0.8m	towards curb	non-yielding	50 m	turning	24.09
video_5	0.4m	towards centre	non-yielding	30 m	straight	24.22
video_56	1.2m	towards curb	non-yielding	50 m	turning	24.32
video_13	1.2m	towards centre	non-yielding	30 m	turning	24.34
video_49	0.8m	towards curb	non-yielding	50 m	straight	24.41
video_48	0.4m	towards curb	non-yielding	50 m	straight	24.60
video_9	0.8m	towards centre	non-yielding	50 m	straight	24.67
video_52	0.8m	towards curb	non-yielding	30 m	turning	25.04
video_31	none	none	non-yielding	none	turning	25.28
video_11	0.4m	towards centre	non-yielding	30 m	turning	25.30
video_45	0.4m	towards curb	non-yielding	30 m	straight	25.44
video_14	0.4m	towards centre	non-yielding	50 m	turning	25.48
video_47	1.2m	towards curb	non-yielding	30 m	straight	25.55
video_7	1.2m	towards centre	non-yielding	30 m	straight	25.81
video_51	0.4m	towards curb	non-yielding	30 m	turning	26.28

Appendix D Tables for feel-safe percentages sorted in ascending order for yielding vehicles for groups in which instructions were given

video_id	Vehicle Deviation	Deviation Direction	Braking Behaviour	Onset of Deviation	Vehicle Path	Feel-safe percentage
video_30	none	none	yielding	none	straight	23.40
video_37	0.8m	towards centre	yielding	50 m	straight	24.42
video_32	none	none	yielding	none	turning	24.83
video_33	0.4m	towards centre	yielding	30 m	straight	24.90
video_21	0.8m	towards curb	yielding	50 m	straight	25.08
video_44	1.2m	towards centre	yielding	50 m	turning	25.17
video_43	0.8m	towards centre	yielding	50 m	turning	25.57
video_42	0.4m	towards centre	yielding	50 m	turning	25.58
video_34	0.8m	towards centre	yielding	30 m	straight	25.73
video_36	0.4m	towards centre	yielding	50 m	straight	25.81
video_25	1.2m	towards curb	yielding	30 m	turning	25.84
video_35	1.2m	towards centre	yielding	30 m	straight	25.86
video_19	1.2m	towards curb	yielding	30 m	straight	26.15
video_40	0.8m	towards centre	yielding	30 m	turning	26.19
video_4	none	none	yielding	none	turning	26.22
video_38	1.2m	towards centre	yielding	50 m	straight	26.23
video_26	0.4m	towards curb	yielding	50 m	turning	26.42
video_20	0.4m	towards curb	yielding	50 m	straight	26.43
video_39	0.4m	towards centre	yielding	30 m	turning	26.55
video_41	1.2m	towards centre	yielding	30 m	turning	26.67
video_17	0.4m	towards curb	yielding	30 m	straight	26.93
video_2	none	none	yielding	none	straight	27.11
video_24	0.8m	towards curb	yielding	30 m	turning	27.21
video_22	1.2m	towards curb	yielding	50 m	straight	27.54
video_18	0.8m	towards curb	yielding	30 m	straight	27.59
video_27	0.8m	towards curb	yielding	50 m	turning	27.93
video_28	1.2m	towards curb	yielding	50 m	turning	28.21
video_23	0.4m	towards curb	yielding	30 m	turning	28.29

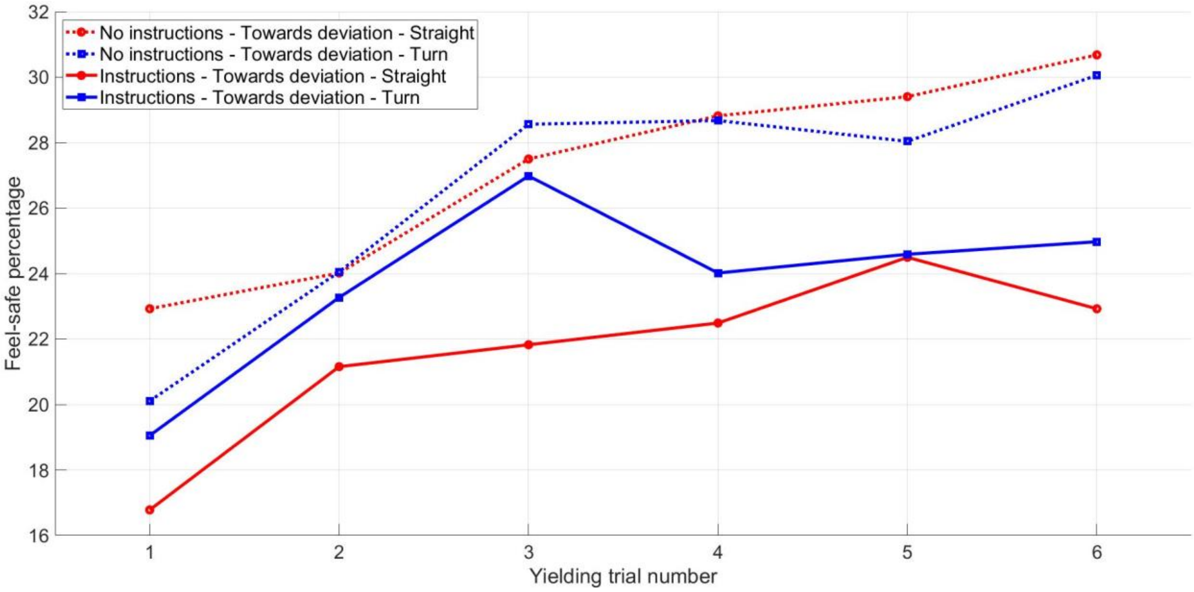
Appendix E Tables for feel-safe percentages sorted in ascending order for non-yielding vehicles for groups in which instructions were not given

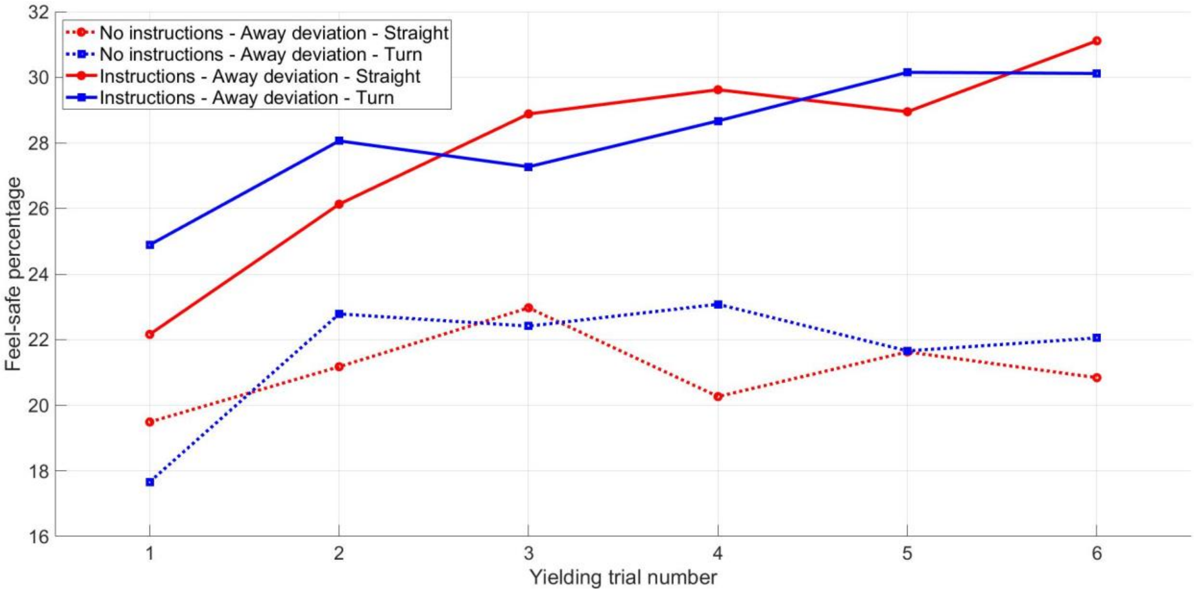
video_id	Vehicle Deviation	Deviation Direction	Braking Behaviour	Onset of Deviation	Vehicle Path	Feel-safe percentage
video_29	none	none	non-yielding	none	straight	19.80
video_50	1.2m	towards curb	non-yielding	50 m	straight	20.19
video_56	1.2m	towards curb	non-yielding	50 m	turning	20.72
video_49	0.8m	towards curb	non-yielding	50 m	straight	20.77
video_53	1.2m	towards curb	non-yielding	30 m	turning	21.25
video_46	0.8m	towards curb	non-yielding	30 m	straight	21.97
video_54	0.4m	towards curb	non-yielding	50 m	turning	21.97
video_55	0.8m	towards curb	non-yielding	50 m	turning	22.29
video_45	0.4m	towards curb	non-yielding	30 m	straight	22.43
video_31	none	none	non-yielding	none	turning	22.74
video_48	0.4m	towards curb	non-yielding	50 m	straight	22.81
video_51	0.4m	towards curb	non-yielding	30 m	turning	23.02
video_52	0.8m	towards curb	non-yielding	30 m	turning	23.05
video_15	0.8m	towards centre	non-yielding	50 m	turning	24.14
video_8	0.4m	towards centre	non-yielding	50 m	straight	24.61
video_47	1.2m	towards curb	non-yielding	30 m	straight	24.61
video_10	1.2m	towards centre	non-yielding	50 m	straight	24.89
video_6	0.8m	towards centre	non-yielding	30 m	straight	25.52
video_12	0.8m	towards centre	non-yielding	30 m	turning	26.52
video_13	1.2m	towards centre	non-yielding	30 m	turning	26.97
video_11	0.4m	towards centre	non-yielding	30 m	turning	27.28
video_3	none	none	non-yielding	none	turning	27.33
video_16	1.2m	towards centre	non-yielding	50 m	turning	27.40
video_1	none	none	non-yielding	none	straight	27.65
video_14	0.4m	towards centre	non-yielding	50 m	turning	28.52
video_9	0.8m	towards centre	non-yielding	50 m	straight	28.56
video_5	0.4m	towards centre	non-yielding	30 m	straight	29.09
video_7	1.2m	towards centre	non-yielding	30 m	straight	30.67

Appendix F Tables for feel-safe percentages sorted in ascending order for yielding vehicles for groups in which instructions were not given

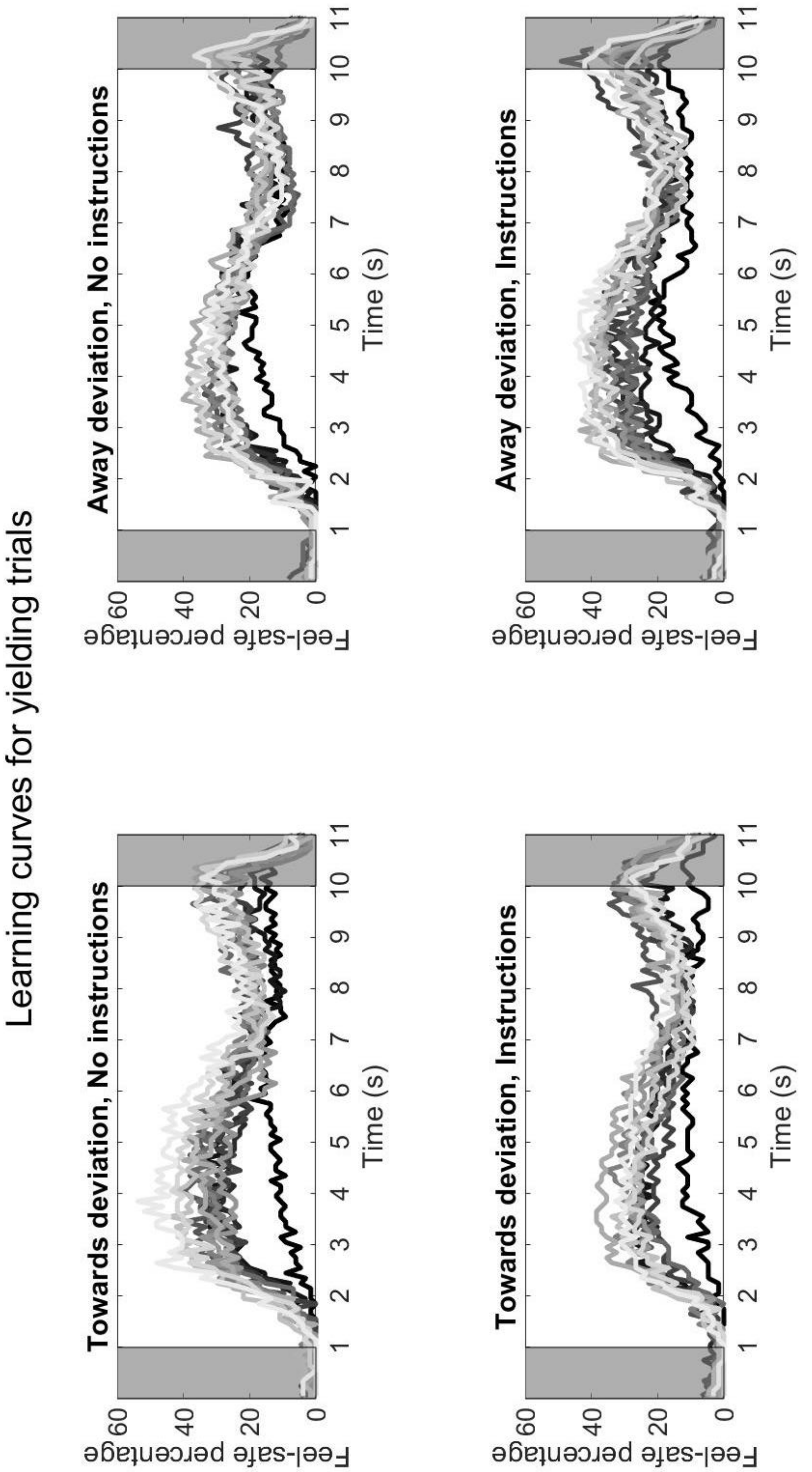
video_id	Vehicle Deviation	Deviation Direction	Braking Behaviour	Onset of Deviation	Vehicle Path	Feel-safe percentage
video_37	0.8m	towards centre	yielding	50 m	straight	20.39
video_30	none	none	yielding	none	straight	20.80
video_42	0.4m	towards centre	yielding	50 m	turning	21.50
video_33	0.4m	towards centre	yielding	30 m	straight	21.66
video_35	1.2m	towards centre	yielding	30 m	straight	21.91
video_32	none	none	yielding	none	turning	21.93
video_44	1.2m	towards centre	yielding	50 m	turning	22.21
video_40	0.8m	towards centre	yielding	30 m	turning	22.24
video_34	0.8m	towards centre	yielding	30 m	straight	22.30
video_38	1.2m	towards centre	yielding	50 m	straight	23.24
video_41	1.2m	towards centre	yielding	30 m	turning	23.49
video_43	0.8m	towards centre	yielding	50 m	turning	23.72
video_36	0.4m	towards centre	yielding	50 m	straight	24.31
video_39	0.4m	towards centre	yielding	30 m	turning	24.58
video_21	0.8m	towards curb	yielding	50 m	straight	26.77
video_25	1.2m	towards curb	yielding	30 m	turning	27.46
video_4	none	none	yielding	none	turning	28.31
video_26	0.4m	towards curb	yielding	50 m	turning	28.69
video_28	1.2m	towards curb	yielding	50 m	turning	29.00
video_2	none	none	yielding	none	straight	29.37
video_20	0.4m	towards curb	yielding	50 m	straight	29.39
video_27	0.8m	towards curb	yielding	50 m	turning	29.73
video_19	1.2m	towards curb	yielding	30 m	straight	29.77
video_24	0.8m	towards curb	yielding	30 m	turning	30.62
video_18	0.8m	towards curb	yielding	30 m	straight	30.99
video_22	1.2m	towards curb	yielding	50 m	straight	31.02
video_23	0.4m	towards curb	yielding	30 m	turning	31.52
video_17	0.4m	towards curb	yielding	30 m	straight	32.79

Appendix G Learning curve comparisons – Feel-safe percentage variation with trial number, for yielding trials where vehicle indicated that it is going straight versus when it indicates that it is taking a turn

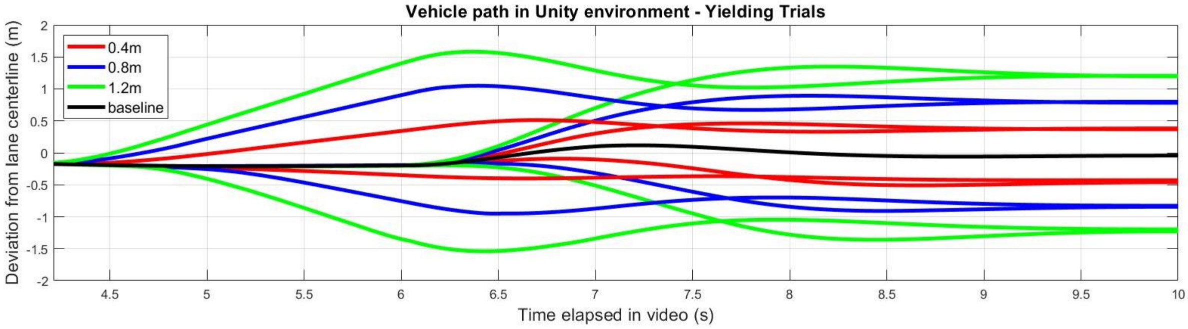


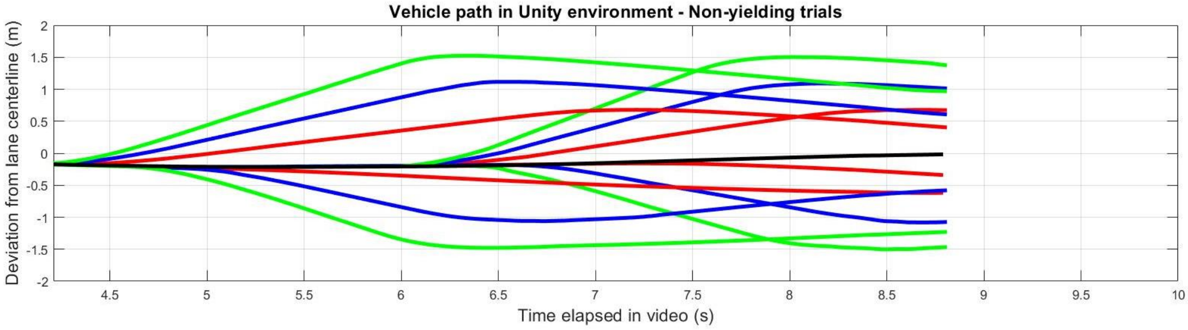


Appendix H Learning curve comparisons – variation of Feel-safe percentages with trial number, for yielding trials within all 4 groups. Darkest line indicates the first trial, with subsequent trials becoming lighter in colour.



Appendix I Plot of vehicle path versus time for yielding and non-yielding trials, from virtual environment



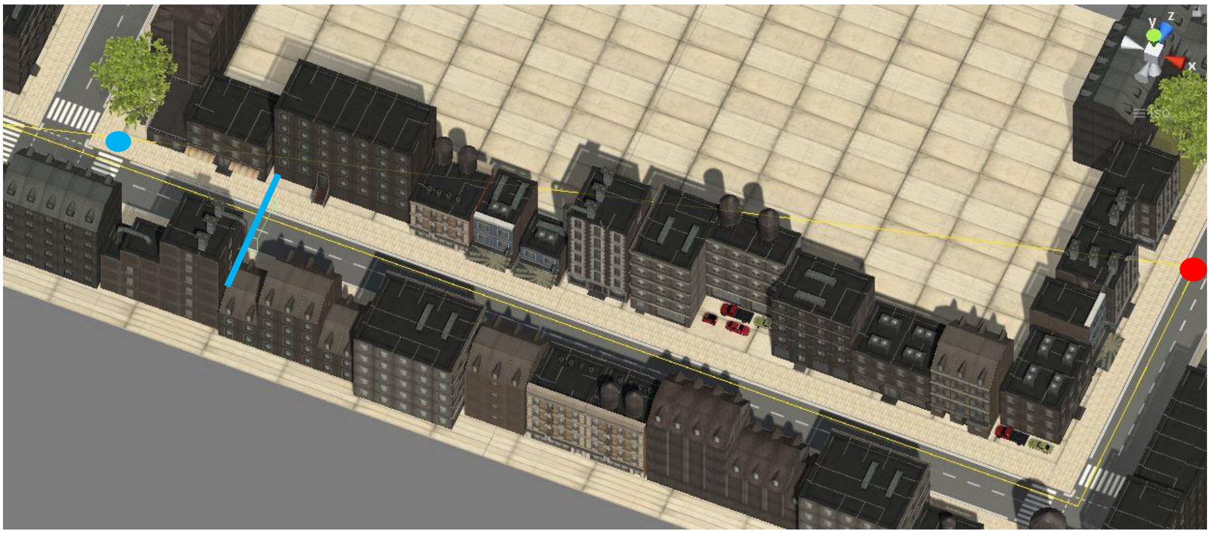


Appendix J Pilot experiment to collect driving behaviour

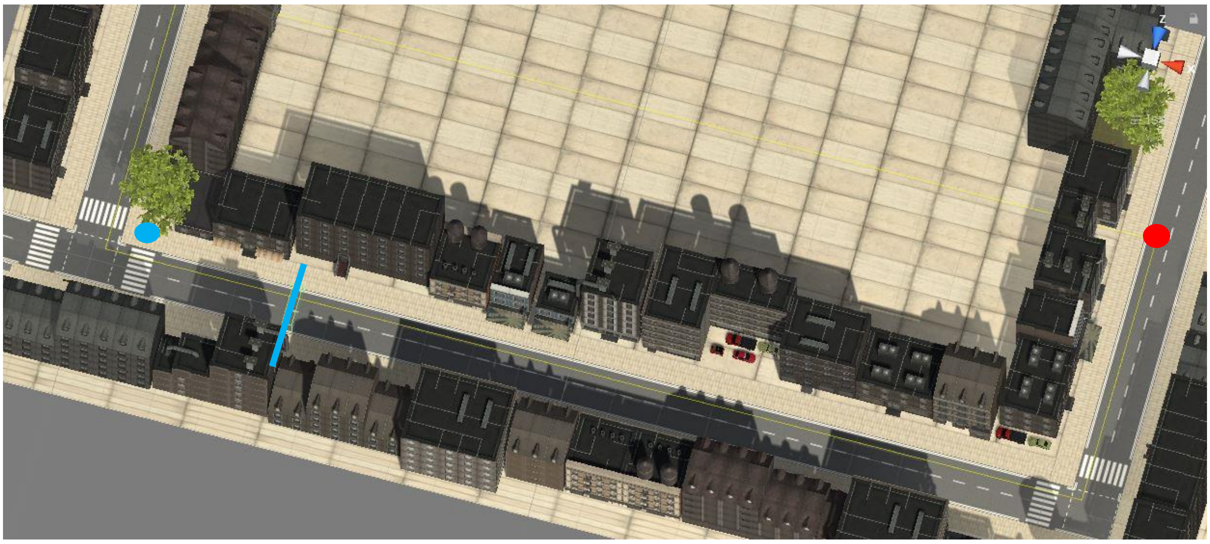
Experiment Design:

A pilot driving experiment was conducted prior to the main research presented in this paper. The objective was to collect data on driver speeds and lateral deviations by asking participants to drive in a virtual environment shown below, along two different routes.

One route had the driver going straight ahead after encountering the pedestrian at the intersection, as shown below in form of a yellow line with the start point represented by the red dot on the right edge, the blue circle representing the pedestrian position on the sidewalk and the blue line representing the point at which the trigger to wait for the pedestrian is displayed to the driver.



The other route had the driver taking a turn after encountering the pedestrian at the intersection, as shown below in form of a yellow line with the start point represented by the red dot on the right edge, the blue circle representing the pedestrian position on the sidewalk and the blue line representing the point at which the trigger to wait for the pedestrian is displayed to the driver.



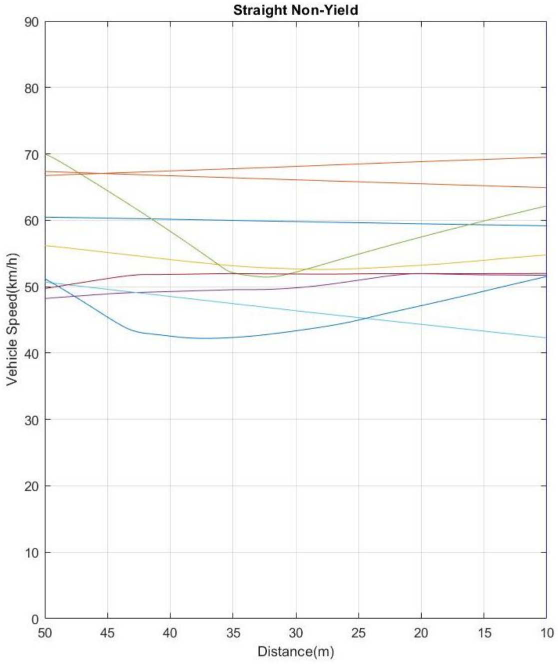
The drivers would either yield or not yield for the pedestrian based on whether they received a message to wait when crossing the trigger (blue line shown above). This trigger is located at a distance of 32.5m from the pedestrian.

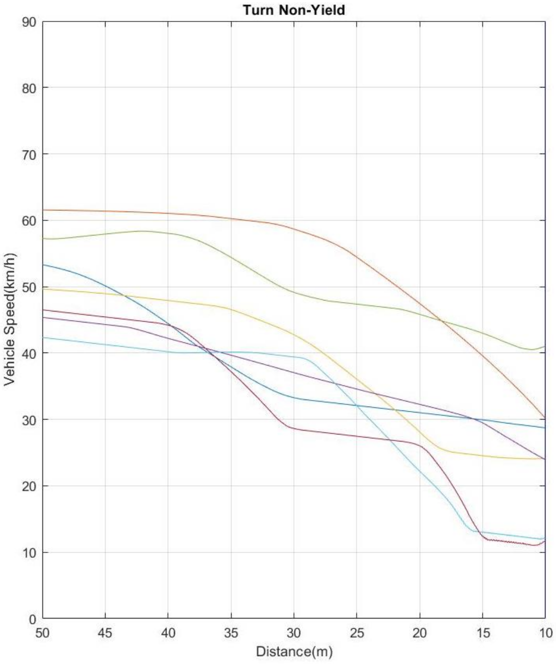
Data was collected by a script attached to the moving vehicle that collected vehicle data at 50 Hz, and the equipment used to drive in the virtual environment was a Logitech G25 steering wheel and pedals. A VR headset was not used, the participants could directly look at the screen when driving. There were a total of 8 participants.

Results:

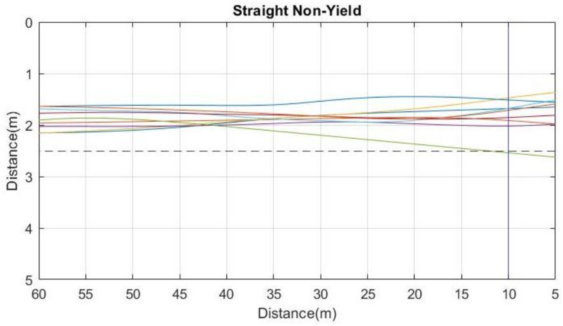
While the data was directly not used in the final experiment, the following points were taken for reference:

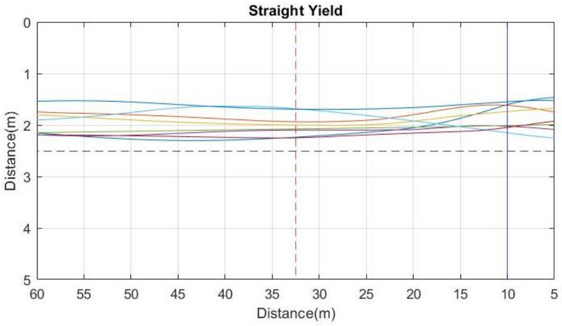
- Non-yielding, turning behaviour is accompanied by higher decelerations compared to straight ahead behaviour, even though the driver is informed of the yielding behaviour only 40 m away from the intersection. (Velocity vs distance plot below)

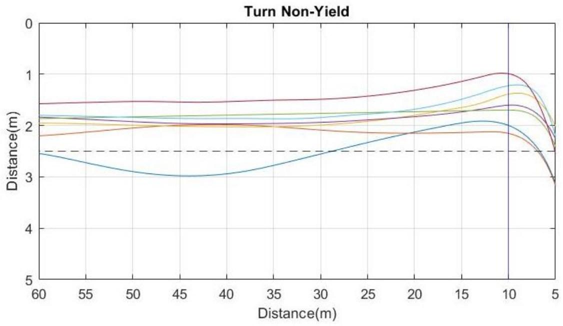


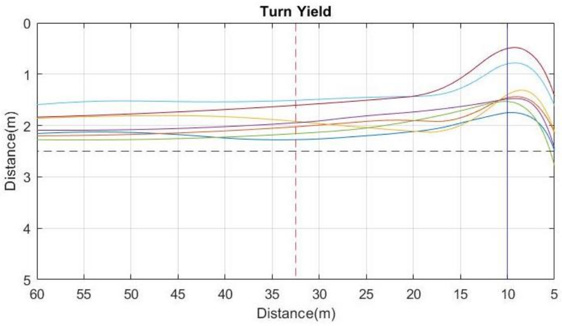


- Maximum lateral deviation of 1.2m occurs but only when intending to take a turn after yielding, deviation greater than 1m was not recorded in most trials. In the plots below, the vertical blue line at x = 10 m represents the position of the pedestrian (10 m away from the intersection), the vertical red dotted line (at x = 30 m) represents the point at which driver is asked to wait for the pedestrian (only in yielding trials).









Appendix K Informed Consent form for the driving experiment mentioned in Appendix J

Department of Cognitive Robotics
Faculty of Mechanical, Maritime and Materials Engineering

Informed consent form

Analysing the influence of vehicle trajectories on pedestrian crossing behaviour

Researcher:	Anirudh Sripada
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Please take the time to read the following information carefully

You are about to participate in a virtual reality study which involves collecting driving data for different scenarios.

WHAT IS THE PURPOSE OF THIS STUDY?
This is a pilot study that aims to collect driving data which will be used to generate different vehicle trajectories. Participants acting as pedestrians in a different study will be shown these trajectories and their behaviour will be recorded.

WHAT WOULD I HAVE TO DO?
After signing this form, you will be asked to complete a demographics questionnaire. As a participant, you will experience a virtual reality representation of a city, in which you will be asked to drive along a specific route.

Route Details
There are 3 different routes, 2 of which are in a city environment and 1 route is a long (2 km) straight road. The 2 city routes are basically two different paths you can take after an intersection. If you see road blocks (see Figure 1), that path is closed and you have to take the other route. Each city route will have two scenarios, one with a pedestrian at an intersection and one without. The pedestrian scenarios are simulated in the form of a stationary figure standing on the footpath to your right.

Figure 1: Road blocks indicating which path is shut down

Driving instructions

Instructions related to driving will be indicated on the windshield of the vehicle. There will be a '<u>Start</u>' message displayed at the beginning of each trial. If there is a pedestrian at an intersection, you will see a '<u>Wait</u>' message as you approach that intersection, which means you have to wait at the crossing for the pedestrian. A few seconds later, you will see a message that says '<u>Continue</u>', after which you can resume driving. A '<u>Stop</u>' message is also displayed at the end of the trial after which you need to bring the vehicle to a complete stop. When all the experimental trials are done, you will see the message '<u>End of experiment!</u>'

You will have 2 practice trials for each scenario, followed by the 10 experiment trials that are divided into 2 blocks of 5 trials each. Please try to drive as you normally would on a public road, in terms of lanekeeping, vehicle speeds, etc.

WHAT ARE THE RISKS?

If at any point you begin to experience any symptoms of motion sickness like discomfort, disorientation or nausea, please notify the experimenter and the experiment will be paused or stopped entirely. If you report a 4 or higher when answering the motion sickness questions that will be asked after each block, the experiment will be stopped as well. Please do not engage in potentially hazardous activities (e.g., driving, cycling) in case you continue to feel nauseous after the experiment. There is also a possibility that any unsafe driving situation may be experienced as genuinely stressful or frightening, due to the high level of visual immersion.

DO I HAVE TO PARTICIPATE?

The experiment will take around 20-25 minutes, and you may stop at any time. If you want to stop the experiment, please notify the researcher immediately. Participation in this experiment is voluntary.

WILL MY RECORDS BE KEPT PRIVATE?

All data obtained through this experiment will be anonymised. The gathered data may be used for statistical analysis, an MSc thesis, a resulting publication and stored in a public repository in the anonymous form.

SIGNATURES

By signing this form, you state that you have read the informed consent form and agree with the conditions on this form of consent. You are free to stop the experiment at any time, and if you have any questions concerning this experiment please ask or contact the researcher Anirudh Sripada. You will receive a copy of this form.

Participant’s Name	Signature and Date
Investigator/Delegate’s Name	Signature and Date