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Will pedestrians cross the road before an automated vehicle? The effect of drivers' attentiveness and presence on pedestrians' road crossing behavior

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A R T I C L E I N F O

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A B S T R A C T

The impact of automated vehicles (AV) on pedestrians' crossing behavior has been the topic of some recent studies, but findings are still scarce and inconclusive. The aim of this study is to determine whether the drivers' presence and apparent attentiveness in a vehicle influences pedestrians' crossing behavior, perceived behavioral control, and perceived risk, in a controlled environment, using a Head-mounted Display in an immersive Virtual Reality study.

Twenty participants took part in a road-crossing experiment. The VR environment consisted of a single lane one-way road with car traffic approaching from the right-hand side of the participant which travelled at 30 kmph. Participants were asked to cross the road if they felt safe to do so. The effect of three driver conditions on pedestrians' crossing behavior were studied: Attentive driver, distracted driver, and no driver present. Two vehicles were employed with a fixed time gap (3.5 s and 5.5 s) between them to study the effects of time gaps on pedestrians' crossing behavior. The manipulated vehicle yielded to the pedestrians in half of the trials, stopping completely before reaching the pedestrian's position. The crossing decision, time to initiate the crossing, crossing duration, and safety margin were measured.

The main findings show that the vehicle's motion cues (i.e. the gap between the vehicles, and the yielding behavior of the vehicle) were the most important factors affecting pedestrians' crossing behavior. Therefore, future research should focus more on investigating how AVs should behave while interacting with pedestrians. Distracted driver condition leads to shorter crossing initiation time but the effect was small. No driver condition leads to smaller safety margin. Findings also showed that perceived behavioral control was higher and perceived risk was significantly lower when the driver appeared attentive. Given that drivers will be allowed to do other tasks while AVs are operating in the future, whether explicit communication will be needed in this situation should be further investigated.

Introduction

Pedestrians are one of the most vulnerable road users in traffic because of their relatively low mass and their lack of a protective shell that can absorb the kinetic energy that is created in a crash with another road user. Collisions between pedestrians and motorized vehicles are the main causes of pedestrians' deaths, globally, with 310,500 killed in 2018 (World Health Organisation, 2018). Automated vehicles (AVs) are expected to reduce traffic accidents and thus reduce pedestrian fatalities, but that remains to be proven (ITF/OECD, 2018). In particular, highly automated vehicles (i.e. level 4/5; SAE International, 2016) are expected be able to operate without a driver, a human on board, or the driver will be allowed to do other tasks and therefore might appear distracted to other road users. The effect it will have on pedestrians is relevant to their safety. AVs should be able to interact with all kinds of road users. Therefore, the interaction between AVs and pedestrians has received growing attention.

Studies on pedestrians' road crossing behavior have shown that the speed of the vehicle, its distance to the pedestrian, road infrastructure, and pedestrians' characteristics are determinant factors of pedestrians'

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road crossing behavior (Rasouli et al., 2018). The gap between a pedestrian and a vehicle has been a main focus point in a number of studies. The mean accepted time gap for the pedestrians to cross the road, while interacting with conventional vehicles, has been found to be between 3 and 7 s. If the time gap is lower than 3 s, it is unlikely for a pedestrian to cross, while the likelihood of crossing increases if the gap is higher than 7 s (Rasouli et al., 2018). Pedestrians can make a rough estimate of when a vehicle will arrive at their position, but base their crossing decision mainly on the perceived distance (Oxley et al., 2005). The assessment of the distance and speed of the vehicle deteriorates with increasing vehicle speeds (Sun et al., 2015). There is much evidence suggesting that motion cues and implicit information are the most commonly used in the decision to cross, and that explicit communication rarely occurs during interactions between pedestrian and vehicle (Lee et al., 2020; Dey & Terken, 2017) and sometimes the presence of drivers is not even perceived (Risto, Emmenegger, Vickhuyzen, Cefkin & Hollan, 2017, Sucha, Dostal & Risser, 2017; Straub & Schaefer, 2018). However, the situation might change while interacting with Automated Vehicles.

Studies that have used the “Wizard of Oz” technique (which, for example, involves control by a human hidden behind an especially designed seat) to mimic a driverless AV found no difference in pedestrians’ crossing behavior, compared to when the vehicle was driven by a visible human driver (Rodríguez Palmeiro et al., 2018; Rothenbücher et al., 2016). However, when asked how the individuals felt while interacting with a driverless vehicle, most reported themselves to have acted differently than normal (Rodríguez Palmeiro et al., 2018), or were simply less willing to cross (Lundgren et al., 2017).

The aim of the current study is to investigate the effect of a driver’s presence and a driver’s perceived attentiveness on pedestrians’ crossing behavior. We employed an immersive virtual reality environment that allowed experimental control over the presence and attentiveness of drivers which is difficult to recreate in real life conditions. The VR also allowed the time gaps, speed and deceleration to be fully controlled, and the participants’/pedestrians’ actual crossing behavior to be measured. Crossing behavior is recorded as well as psychological factors that can provide insights into the mechanisms of why the behavior is performed. We expected the motion cues to have the largest effect on crossing behavior (in line with Oxley et al., 2005; Sun et al., 2015). We also expected psychological factors such as trust and perceived behavioral control may affect pedestrians’ crossing behavior. If the findings show that the driver conditions affect the crossing decisions, one could conclude that there may be an added value of external Human Machine Interfaces (eHMIs) in future AVs. However, if that is not the case there may be a need to rethink the purpose and capabilities of such interfaces. Thus, our findings can help to design AVs in a safe way.

Method

Participants

Twenty individuals participated in the experiment and they all completed the 108 crossing trials. Eleven out of twenty participants were female, and all were British. They had never suffered from extreme motion sickness and did not have a history of epilepsy. Their age varied from 18 to 33 years old, ($M = 22.8$; $SD = 3.8$). Eighteen of the participants reported in a survey that they knew to some extent what an automated vehicle is, and everyone noticed the differences between the driver conditions and could tell which conditions were presented. Two participants were not able to complete the experiment due to equipment failure and only completed 72 out of 108 trials. Their data was still included in the analysis. No participants had to be excluded due to motion sickness. The mean Misery Scale (MISC) score was below “1” for all the blocks. The highest MISC score was “2” which indicates that the participants experienced light dizziness, warmth, headache, stomach awareness, and/or sweating. The experiment was approved by University of Leeds Research Ethics Committee - Ref: LTTRAN-097. All participants received £10 as compensation for their time in completing the study.

Design

The design of this experiment is adapted from Lee et al. (2019) as is the virtual environment. Participants were asked to cross the road between the two approaching vehicles if they felt safe to do so. In half of the scenarios, both vehicles continued driving with a constant speed of 30 kmph and without yielding to the pedestrian. In the other half, only the second vehicle decelerated and came to a full stop 2.5 m before reaching the pedestrian’s crossing path, i.e. yielding to the pedestrian. The deceleration model is as follows. The vehicle started to decelerate at 32.5 m (3.9 s) distance to the pedestrian with a constant deceleration rate of 8.3 m per second finally reaching a full stop at 2.5 m away from the participant. A 3 × 2 × 2 repeated measures design was used to investigate the crossing behavior in an immersive virtual reality (VR) environment. The three independent variables were: (1) Driver’s status: no-driver, attentive driver or distracted driver. (2) The time gap between the first and second vehicles: 3.5 s or 5.5 s, and (3) the second vehicle’s yielding behavior: yielding or not yielding. We chose these crossing gaps because we wanted to gain insights in how the variables affected pedestrians’ crossing behavior in a critical and in a less critical scenario. Literature shows that a gap of around 2 s is the minimal critical gap (Das et al., 2005) and gaps of 5.3 s or more were the most accepted gaps (Brewer et al., 2006). The combination of these factors resulted in 12 conditions, as shown in Table 1. During the scenarios multiple measurements of behavior were made as can be seen in Table 2. These 12 conditions were repeated 3 times per block, and the study consisted of a total of 3 blocks. Thus, each participant faced 108 crossing trials (12 scenarios × 3 repetition per block × 3 blocks). These multiple trials per scenario helps reduce measurement error. The scenarios were randomized in each block to reduce order effects.

Apparatus

Virtual reality simulation

The immersive virtual environment was built using Unity and was presented to the participants with an HTC Vive head-mounted display (Fig. 1). The HTC Vive was tracked by two lighthouse sensors that translated the wearer’s position in the real world. The virtual environment resembled a one-way street with a sidewalk on both sides of the road in an urban neighborhood as shown in Fig. 1. The street featured houses on both sides of the road, and trees and streetlights on opposite sides of the road. The participants started on the tree side and were only able to start a new trial from the same side to eliminate the roadside as a variable. That meant that they had to cross back if they decided to cross. Two bollards were placed on both sides of the road to indicate the starting position and its opposite if the road was crossed in a perpendicular line.

Table 1
Independent variables included in the scenarios.

Variable name	Levels	Annotation	Explanation
Driver	3	AD	Attentive Driver
		DD	Distracted Driver
		ND	No Driver
Yield	2	Y	The vehicle yielded for the pedestrian
		NY	The vehicle did not yield for the pedestrian
Gap size	2	SG	Gap between vehicle and pedestrian was 3.5 s
		LG	Gap between vehicle and pedestrian was 5.5 s

Table 2
Dependent variables that formed the crossing behavior.

Variable name	Definition
Crossing decision	The decision to cross the road.
Initiation time	The time it took the participant to start crossing (by tracking the head movement). The reference point was the moment the first vehicle cleared the way completely for the pedestrian.
Crossing duration	The time it took the participant to reach the other side of the road from the start of crossing.
Safety margin	The time between the participant reaching the opposite side of the road and the second vehicle passing behind the participant. The reference point used was the moment the pedestrian reached the opposite side of the road and cleared the way completely for the vehicle.

Two sedan vehicles were presented, where the first vehicle was always white, and the second vehicle was always blue. The windows of the vehicles were removed to stop reflections from preventing the driver to be seen. The drivers in both vehicles were male. The driver of the white vehicle was different from the other two in terms of hair and clothing (see Figs. 1 & 2). The posture of the driver of the approaching vehicle was adapted to create an “attentive”, forward looking driver, and a “distracted” driver, a rightwards looking, driver (see Fig. 2). The driver was sitting on the right seat of the vehicle behind the wheel as is custom in the UK. The “no driver” condition consisted of a vehicle without anyone inside the vehicle. The vehicle’s speed was 30 kmph.

The recorded measurements inside the virtual reality simulation can be found in Table 2. The reference point for the initiation time was set to be the point in time were the first vehicle passed the pedestrian and thus the road was clear for the pedestrian to cross before the arrival of the second vehicle. To measure the initiation time, we used the head movement of the participants to determine the exact moment they initiated their crossing. A down- and forward tilt of the head indicates that the participant is going to start crossing the road (Lee et al., 2019). The initiation time is tightly linked with the gap between the pedestrian and the vehicle. The gap becomes smaller when the initiation time is higher. The crossing duration gives an indication of the walking speed of the pedestrian. The walking speed can be used as a proxy for the safety the pedestrian perceives, a slower speed could suggest lower perceived risk.

Surveys

We used an adapted version of the Trust in Automation survey developed by Payre et al. (2016) to capture the trust the participants had in automated vehicles. The participants scored their agreement with 6 statements on a 7-points Likert scale. Example statements included: *Globally, I trust the automated vehicle*, and *I trust the automated vehicle to avoid obstacles*.

Furthermore, we measured the perceived behavioral control the participants felt (i.e. the perception of being able to perform a behavior successfully (Ajzen, 1991)) per driver condition after completing the three blocks of the VR sessions. Two items adopted from Zhou et al.

Fig. 1. The environment of the crossing experiment.

Fig. 2. The three driver conditions (from left to right): Distracted driver (driver looking to the right at his phone), attentive driver (driver looking straight ahead), and no-driver.

(2009) were used for this: '*For me, crossing the road in this way would be…*', and '*I believe that I have the ability to cross the road in this way…*'. Pictures were shown of the driver conditions and the two items were scored per condition. No further information about the driver condition was given. The items were scored on a 7-point bipolar Likert scale explaining how easy and how much the participants agree with the statements, respectively. The mean of the two items was used as the PBC score. Also, the perceived risk per driver condition was measured on a 7-point scale but this one was inverted. The item was the following: '*Crossing the road in this situation would be…*'.

To capture the performance of the VR environment, the Presence Questionnaire and the Misery Scale (MISC) were employed. The Presence Questionnaire contains 16 items over 4 factors (i.e. involvement, sensory fidelity, adaptation/immersion, & interface quality). Questions about haptic or sound fidelity were excluded because they were irrelevant. The MISC was used to assess the simulation sickness symptoms of the participants. The participants were able to score how many symptoms they experienced and how heavily on a score from 0 to 10. The MISC was filled in 4 times per participant as detailed in the next section.

Finally, questions about AVs and their perceptions were included in the survey. Participants had to state how much they knew about AVs, and whether they perceived the vehicles in the experiment as AVs. Also, a control question was included which asked the participants to state which driver conditions they had seen. The three conditions were included as answers and a false answer (i.e. "driver and passenger" condition) was added.

Procedure

The procedure consisted of four parts. During the first part, participants were provided with information about the study and what they were expected to do, and written informed consent was obtained. The MISC was filled in before the start of the VR experiment and served as a baseline.

The second part consisted of the VR experiment. They put the equipment on and while they were in the virtual simulation the experiment leader informed them again about where they had to stand, cross, and which button to press to start a trial. The participants started at the edge of the road inside of the virtual environment. They had to press a button on their controller to start the next trial and could only do that if they were on the left side of the road as seen from the approaching vehicle. This meant that after crossing the road they had to walk back to their initial position before the next trial could start. Participants completed a small number of practice trials, until they said they were ready to start the experiment. Once the experiment started, they experienced 12 different scenarios (3 effects of driver, 2 time gaps, and 2 deceleration profiles) which were repeated three times in random order. This was called a block and each block lasted approximately 15 min. After each block, the participant had a break to counter fatigue effects, depending on the participant's need, and filled in the MISC. In total, there were three blocks.

After the third block was completed, the third part of the study commenced. To assess when and if the driver was visible for the participants and at what distance, a task was completed. Six scenarios were presented, three driver conditions multiplied by two time gaps. The participants pressed a button if and when they saw that there was a driver inside the vehicle. The moment the button was pressed and the distance from the pedestrian to the vehicle were recorded. The amount of errors (e.g. pressing when there is no driver or vice versa) were logged.

The fourth and final part consisted of an online survey that included the questionnaires in Section 2.2.2. Once finished, they received their compensation. In total, the experiment lasted for one hour.

Analysis

The crossing behavior data was analyzed using mixed effect models (MEMs). These models allowed the use of both continuous and categorical variables as dependent variables. Furthermore, MEMs were able to cope with missing data of some participants without completely removing the participants from the dataset. The MEMs used were binomial logistic regression for the data on crossing decision and linear regression for the other three dependent variables (i.e. initiation time, crossing duration, and safety margin). A random intercept was included in all the models to allow individual differences to be captured. Finally, due to a lack of assumption with respect to the error structure an unstructured covariance matrix was assumed (Singer, 1998).

Results

First, the descriptive statistics are presented followed by the results of the Perceived behavioral control (PBC) and the results of the Perceived risk (PR). Then, the four models on pedestrians' crossing behavior will be presented. Those results will be divided per dependent variable. In addition, the results of the findings on the visibility of the driver are shown. Finally, the results on the Misery Scale (MISC) and the presence questionnaire are presented. In this study, the level of significance used was $\alpha = 0.05$.

Automated vehicles

Twelve out of twenty participants, seven males and five females, felt that they were interacting with AVs and the other eight did not. The mean trust in AVs score was 4.1 (SD = 1.0) on a 7-point Likert scale, the more trust the higher the score. There was no difference in trust scores between males ($M = 4.3$, $SD = 1.1$) and females ($M = 3.9$, $SD = 1.0$), $t(18) = 0.90$, $p = .38$, Cohen's $d = 0.40$. Furthermore, participants who thought the vehicles were AVs had a mean trust score of 4.0 ($SD = 1.1$) while those who did not think the vehicles were AVs had a mean score on trust of 4.3 ($SD = 1.0$). The scores were not significantly different, $t(18) = -0.63$, $p = .54$, Cohen's $d = 0.29$. All the participants noticed all the driver conditions.

Pedestrians' crossing behavior

To investigate the effects of the considered factors on the four dependent variables we estimated a MEM per dependent variable which accounted for the driver condition, time gap, yielding behavior, gender, whether the participant thought the vehicles were automated or not, trust in AVs, the perceived behavioral control per driver, and the perceived risk per driver. Interactions were only included where they aided the understanding of the effects.

Crossing decision

A binary logistic regression MEM with logit link function was used to

Table 3
Estimation results of the crossing decision model.

Fixed Coefficients	Odds Ratio	95% CI	*t*	*p*
Intercept (mean)	1.73	(2.37, 442.93)	−2.61	0.68
Driver (ND, AD1)	1.24	(0.83, 1.84)	−1.06	0.29
Driver (DD, AD1)	1.54	(0.96, 2.42)	−1.77	0.07
Time gap (3.5 s, 5.5 s1)	0.08	(0.06, 0.12)	14.30	<0.001
Gender (M, F1)	2.10	(1.42, 2.83)	−3.94	<0.001
AVs? (Yes, No1)	0.58	(0.42, 0.84)	2.95	<0.01
Trust in AVs	1.10	(0.94, 1.27)	−1.19	0.23
Perceived Behavioral Control	1.19	(1.00, 1.37)	−2.00	0.04
Perceived Risk	1.06	(0.91, 1.23)	−0.74	0.46

1Reference category. 2Variable was redundant. Participants: 20. Total number of cases: 1043.

study the effects of the considered factors on crossing decision, as presented in Table 3. Only the scenarios where the vehicle did not yield were considered for this model because all the participants crossed the road when the vehicle yielded (see Fig. 3). They were instructed to cross the road as they would in everyday life. When the vehicle was yielding participants crossed all the time, some did before the vehicle came to a standstill and some when the vehicle was at a full stop. However, this model is only considering the binomial decision whether to cross or not. Therefore, variability in the crossing decision was only found in the scenarios where the vehicle did not yield. The results suggest the significant variables that affect the crossing decision are time gap, gender, whether a participant thought that the vehicle was an AV or not (i.e. AVs?), and perceived behavioral control. The driver condition did not have a significant effect on the decision to cross. Time gap had a negative effect on the decision to cross. Participants crossed less when the time gap was small. Gender had a positive effect, men crossed more compared to women. If the participant thought the vehicle was an automated vehicle, then she/he crossed more compared to participants who did not think that the vehicle was an automated vehicle. Finally, perceived behavioral control had a positive effect on the crossing decisions. The more successful the participants perceived to be able to cross the road, the more they crossed.

Initiation time

A linear regression MEM was used to assess the effects of the factors considered and the interactions between them on the initiation time. The initiation time reference point was the first moment the participant could cross the road after the first vehicle had passed. If participants crossed before that, the initiation time was negative. The initiation time was only recorded if the participant crossed in between vehicles. Time gap was a very strong factor that influenced the initiation time, as shown in Table 4. Yielding behavior of the vehicle did not have a significant main effect on the initiation time, however there was an interaction between yielding behavior and time gap. In Fig. 4 we can see that if the vehicle was yielding, the mean initiation time was the highest when the time gap was short. This meant that most of the participants decided to cross after the vehicle had stopped completely. In contrast, when the vehicle was not yielding the initiation time was the highest when the time gap was longer.

Table 4
Estimation results of the initiation time model.

Fixed Coefficients		*All*		*Without Yielding*	
		Estimates (S.E.)	*p*	Estimates (S.E.)	*p*
β_0	Intercept (mean)	−0.24 (1.26)	0.85	−0.28 (0.18)	0.12
β_{Driver}	Driver (ND, AD1)	−0.04 (0.03)	0.15	−0.03 (0.02)	0.18
β_{Driver}	Driver (DD, AD1)	0.07 (0.04)	0.05	−0.03 (0.02)	0.19
$\beta_{gapsize}$	Time gap (3.5 s, 5.5 s1)	3.08 (0.13)	<0.001	−0.09 (0.01)	<0.001
β_{yield}	Yielding behavior (NY, Y1)	−0.03 (0.02)	0.24	–	–
β_{Gender}	Gender (M, F1)	−0.12 (0.02)	<0.001	−0.10 (0.02)	<0.001
β_{AVs}	AVs? (Yes, No1)	0.24 (0.01)	<0.001	0.24 (0.02)	<0.001
β_{Trust}	Trust in AVs	−0.01 (0.01)	0.07	−0.01 (0.01)	0.27
β_{PBC}	Perceived Behavioral Control	0.04 (0.05)	<0.001	0.03 (0.01)	<0.001
β_{PR}	Perceived Risk	−0.02 (0.01)	0.02	−0.02 (0.01)	0.04
$\beta_{Int:Y\&Driver}$	Yielding behavior*Driver (NY*DD)	−0.10 (0.04)	0.01	–	–
$\beta_{Int:Y\&TimeGap}$	Yielding behavior*Time gap (NY*3.5 s)	−3.17 (0.13)	<0.001	–	–

1Reference category. 2Variable was redundant. Participants: 20. Total number of cases: 1776.

In addition, an interaction effect of yielding behavior and driver condition was included to assess whether an interaction happened. Of the different driver conditions, only the distracted driver showed a significantly longer initiation time than the attentive driver condition, as shown in Table 4. However, when the vehicle did not yield and there was a distracted driver, the initiation time was significantly shorter as compared to the other scenarios.

Furthermore, the gender of the participants had a significant effect

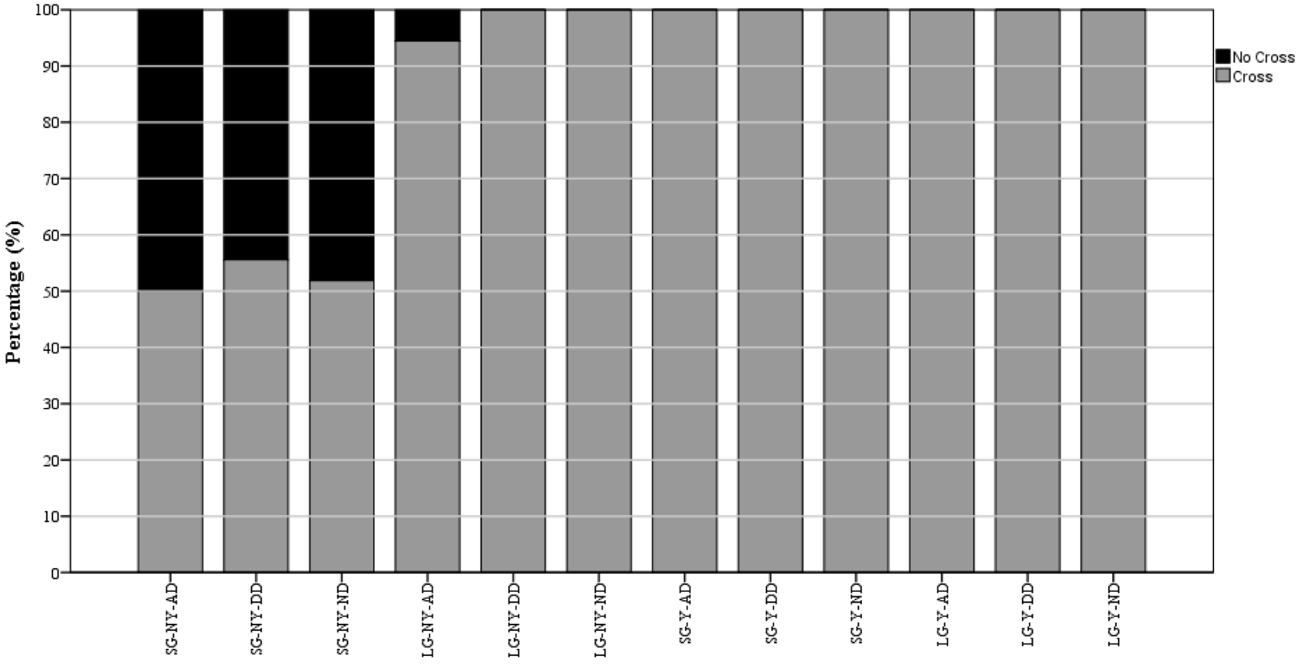

Fig. 3. The percentage of crossings per scenario (labels are in Table 1).

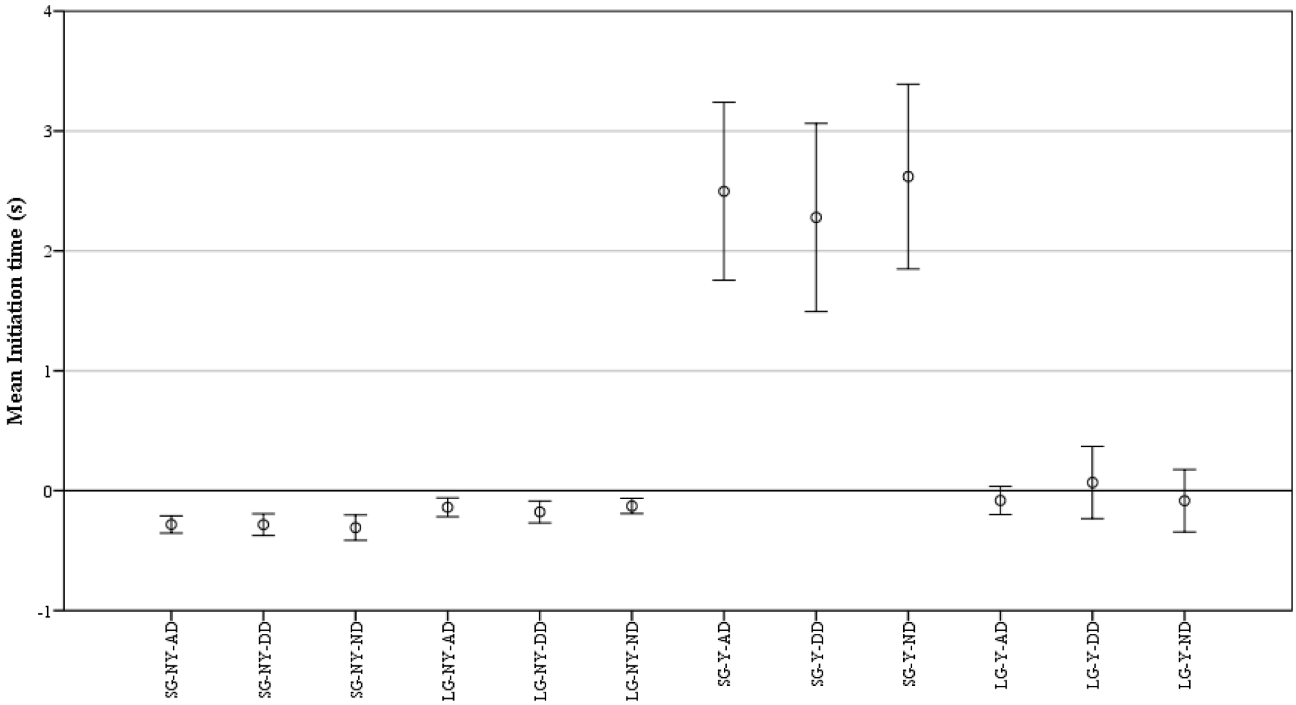

Fig. 4. The mean initiation time per scenario (labels are in Table 1).

on the initiation time. Male pedestrians have shorter initiation time compared to female pedestrians. The effect of expecting to be interacting with automated vehicles (i.e. AVs?) had a significant positive effect on the initiation time which means that participants who thought they were interacting with AVs started crossing the road later and thus accepted a smaller gap. In contrast, trust in automated vehicles did not affect the initiation time significantly. The perceived behavioral control per driver condition had a small significant positive effect on the initiation time. Perceived risk had a small significant negative effect.

When only the non-yielding scenarios were considered in the model, we found that the initiation time decreased when the time gap was shorter. This means that participants crossed earlier when they were confronted with a short time gap. Furthermore, we see that the effect of the distracted driver becomes non-significant.

Table 5
Estimation results of the crossing duration model.

Fixed Coefficients		*All*		*Without Yielding*	
		Estimates (S.E.)	*p*	Estimates (S.E.)	*p*
β_0	Intercept (mean)	3.85 (0.53)	<0.001	3.62 (0.51)	<0.001
β_{Driver}	Driver (ND, AD[1])	0.00 ()	0.99	0.01 (0.04)	0.78
β_{Driver}	Driver (DD, AD[1])	0.03 ()	0.48	0.01 (0.05)	0.89
$\beta_{gapsize}$	Time gap (3.5 s, 5.5 s[1])	−0.37 ()	<0.001	−0.66 (0.04)	<0.001
β_{yield}	Yielding behavior (NY, Y[1])	−0.34 ()	<0.001	–	–
β_{Gender}	Gender (M, F[1])	−0.25 ()	<0.001	−0.27 (0.04)	<0.001
β_{AVs}	AVs? (Yes, No[1])	0.53 ()	<0.001	0.40 (0.04)	<0.001
β_{Trust}	Trust in AVs	−0.02 ()	0.09	0.02 (0.02)	0.16
β_{PBC}	Perceived Behavioral Control	0.07 ()	<0.001	0.04 (0.02)	0.07
β_{PR}	Perceived Risk	−0.01 ()	0.97	0.02 (0.02)	0.33

[1] Reference category. [2] Variable was redundant. Participants: 20. Total number of cases: 1773.

Crossing duration

The results of the linear regression MEM of crossing duration are presented in Table 5 and Fig. 5. Driver condition did not have a significant effect on crossing duration. Neither did time gap and vehicles' yielding behavior. Gender did have a significant effect on crossing duration. Males needed less time to reach the other side of the road as compared to females. Perceiving the vehicles as automated also significantly impacted the crossing duration. Those who did not think the vehicles were automated crossed faster than those who did. Finally, perceived behavioral control had a positive effect on the crossing duration. The higher one's perceived ability to successfully cross the road the more time one took to cross the road. Other factors were not found to be significant in this model.

The model reflecting the results of only the non-yielding scenarios shows that the crossing duration became shorter when the time gap was smaller. Perceived Behavioral Control was not found to be significant in this model.

Safety margin

Finally, the results on safety margin can be found in Table 6 and Fig. 6. Driver condition did have a significant effect on safety margin, whereby no driver condition led to smaller safety margin as compared to attentive driver. In the non-yielding condition, neither the 'no driver' or the 'distracted driver' condition affected safety margin significantly as compared to an attentive driver condition. Also, the vehicles' motion cues, time gap and yielding behavior, did have a significant effect on safety margin. The safety margin was smaller when the time gap was 3.5 s as compared to when a 5.5 s time gap was used. When the vehicle did not yield the safety margin was significantly smaller as compared to when the vehicle did yield. Furthermore, gender had a significant effect on the safety margin. Males had a significantly larger safety margin as compared to females. Participants who thought that the vehicles were automated had a significantly smaller safety margin as compared to their peers who did not think that. The remaining variables were not found to affect the safety margin significantly.

The model with only non-yielding scenarios shows that the driver condition was not a significant predictor of the safety margin anymore.

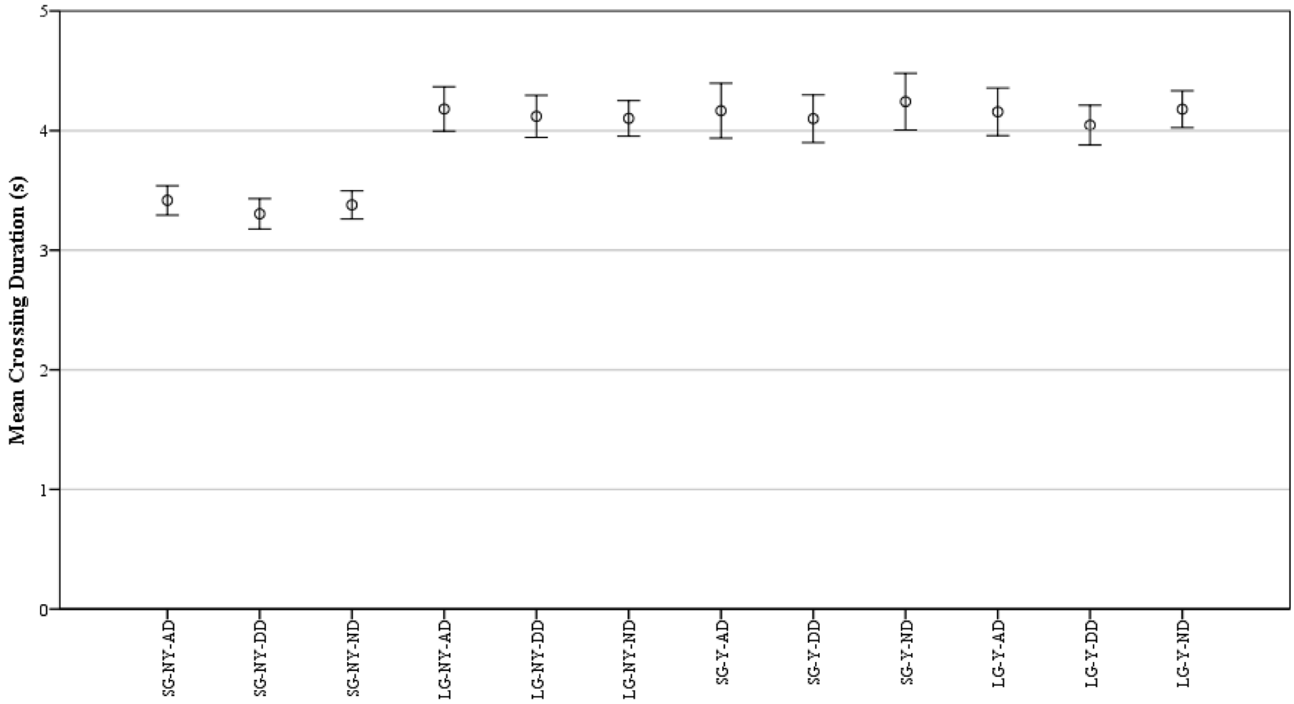

Fig. 5. The mean crossing duration per scenario (labels are in Table 1).

Table 6
Estimation results of the safety margin model.

Fixed Coefficients		*All* Estimates (S.E.)	*All* *p*	*Without Yielding* Estimates (S.E.)	*Without Yielding* *p*
β_0	Intercept (mean)	2.33 (0.48)	<0.001	1.66 (0.55)	<0.01
β_{Driver}	Driver (ND, AD1)	−0.08 (0.04)	0.03	−0.01 (0.08)	0.88
β_{Driver}	Driver (DD, AD1)	−0.06 (0.04)	0.11	−0.10 (0.09)	0.27
$\beta_{gapsize}$	Time gap (3.5 s, 5.5 s1)	−0.66 (0.02)	<0.001	−1.40 (0.06)	<0.001
β_{yield}	Yielding behavior (NY, Y1)	−0.92 (0.03)	<0.001	–	–
β_{Gender}	Gender (M, F1)	0.13 (0.03)	<0.001	0.24 (0.07)	<0.001
β_{AVs}	AVs? (Yes, No1)	−0.30 (0.03)	<0.001	−0.58 (0.07)	<0.001
β_{Trust}	Trust in AVs	−0.01 (0.01)	0.57	0.05 (0.03)	0.11
β_{PBC}	Perceived Behavioral Control	−0.04 (0.01)	0.02	−0.06 (0.03)	0.05
β_{PR}	Perceived Risk	−0.02 (0.01)	0.28	−0.01 (0.03)	0.89

1Reference category. 2Variable was redundant. Participants: 20. Total number of cases: 1776.

Furthermore, the effect of the time gap increased as did the effect of suspecting the vehicles being AVs.

Perceived Behavioral Control (PBC) & perceived risk

After the VR study, participants were asked to complete the perceived behavioral control (PBC) and the perceived risk questionnaires, for each of the three driver conditions. Significant differences were found between the various driver manipulations and the behavioral control the participants perceived, $F(2,519) = 9.89$, $p < .001$. The participants' perceived behavioral control was significantly higher with the attentive driver ($M = 5.61$, $SD = 1.29$) as compared to the inattentive ($M = 4.55$, $SD = 1.40$) and no-driver conditions ($M = 5.03$, $SD = 1.44$), as a result of a paired comparison test with Bonferroni correction, $p < .001$. The perceived risk is significantly different between driver manipulations, $F(2,519) = 144.92$, $p < .001$. A paired comparison test with Bonferroni correction showed again that perceived risk inverted score was significantly higher with the attentive driver ($M = 5.69$, $SD = 1.24$) as compared to the inattentive ($M = 3.02$, $SD = 1.60$) and no-driver conditions ($M = 3.98$, $SD = 1.57$), $p < .001$ meaning that they felt safer during the attentive driver condition as compared to the other two conditions. No significant differences were found for both PBC and PR between the conditions no-driver and inattentive driver.

Visibility of driver

To assess how well the participants were able to see the driver conditions we asked them to report the moment they were able to see the driver. The distance of the vehicle to the participant and the accuracy of the participants were recorded and examined. Fifteen participants did not make any error. Four participants had 1 error out of six trials, and one had 2 errors. The mean distance a participant was able to distinguish a driver sitting inside the vehicle was 34.2 m ($SD = 14.5$). The time it took the vehicle to close the mean distance (i.e. reach the participants assuming the vehicle was not yielding) was 4.1 s. The distance participants indicated they saw the driver ranged between 10.3 and 75.3 m. Three errors were false positives (i.e. participants pressed the button when there was no driver) and three were false negatives (i.e. participants failed to press the button when there was a driver). All of the false negatives occurred when there was a distracted driver aboard the vehicle. No significant difference was found in the distance needed to identify a vehicle with a distracted driver ($M = 34.4$, $SD = 13.3$) as compared to an attentive driver ($M = 34.0$, $SD = 15.7$), $t(75) = 0.12$, $p = .91$.

Presence questionnaire

The Presence questionnaire was used with 16 items on a 7-point scale (1 = low presence, 7 = high presence). The descriptive statistics can be found in Table 7 for 3 factors: involvement, adaptation/immersion, and interface quality. The factor sensory fidelity was removed from the scale

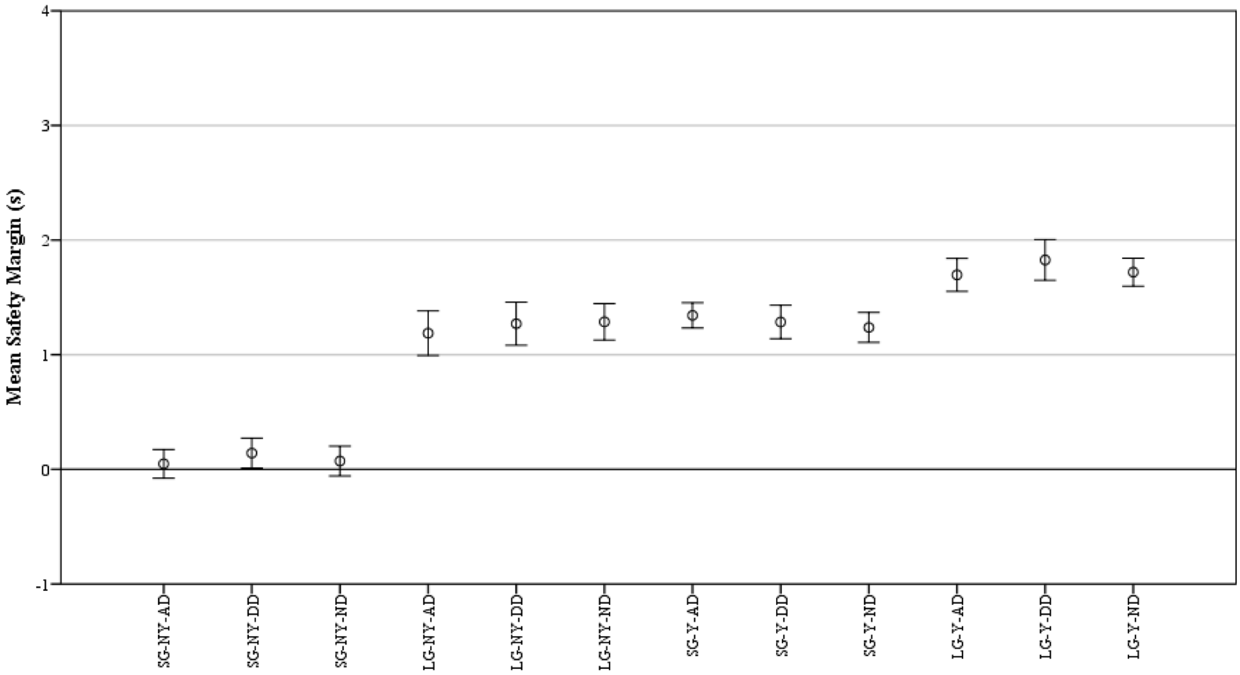

Fig. 6. The mean safety margin per scenario (labels are in Table 1).

Table 7
Descriptive Statistics of the Presence Scales (Range: 1 (low) to 7 (high).

	Involvement	Adaptation/ Immersion	Interface quality	Total mean
Mean	5.28	5.87	2.58	4.96
Std. Deviation	0.69	0.51	1.06	0.44

because it was irrelevant for this study. The factors “Involvement” and “Adaptation/Immersion” scored high relative to the “Interface quality” factor.

Discussion

The aim of this study was to investigate the effect of driver presence and attentiveness on the crossing behavior of pedestrians. In addition, users’ perceived behavioral control and perceived risk were measured per driver condition. Finally, the realism of the virtual reality environment was tested.

Driver condition

Driver condition (attentive, distracted or no driver) was found to influence the time it took participants to start their crossing (i.e. initiation time) and safety margin. The willingness to cross the road was not affected by the driver condition. The effect on initiation time was only significant in the distracted driver condition and was small and positive. The longer crossing initiation time when confronted with a distracted driver implies a smaller gap is accepted, as compared to the attentive driver or absent driver conditions. This result was unexpected, since we assumed that a distracted or absent driver would be perceived as riskier than the attentive driver condition comparable to what was found in the previous literature (Habibovic et al., 2016). If that were the case, we would have found lower initiation times in the riskier scenarios meaning that the participants accepted only a larger gap in comparison to the attentive driver condition. A bigger gap implies also being safer to cross. It could have been that it took the participants more time to decide whether to cross or not if the driver was distracted. Initiation time is likely to reflect the decision-making process – the longer it takes to decide to cross, the slower the initiation time. No driver condition leads to smaller safety margin meaning that the pedestrians left a smaller margin between reaching the other side of the road and the vehicle passing behind them. Findings also showed that perceived behavioral control was higher and perceived risk was significantly lower when the driver appeared attentive. Given that drivers will be allowed to do other tasks while AVs are operating in the future, whether explicit communication will be needed in this situation should be further investigated.

Motion cues

The time gap had a large effect on the initiation time and there was also an interaction between the time gap and yielding behavior. The interaction shows that when the time gap is 3.5 s and the vehicle did not yield, the initiation time of the participants to cross was significantly shorter as compared to the other scenarios. This result is as expected. Pedestrians will decide sooner whether to cross or not if the time during which they must decide is limited. If the vehicle was far away, it did not matter whether it was yielding because participants were already willing to cross. The opposite was also true. If the vehicle was close, participants preferred to wait until it was almost standing still before they crossed. So, motion cues of the vehicle had the biggest impact on the time it took the pedestrians to initiate a crossing, in line with previous studies (Mahadevan et al., 2018; Rothenbücher et al., 2016). Safety margin was also affected by time gap and yielding behavior of the vehicle. The safety margin was lower when the time gap was smaller. In that case, there was less time to cross the road which led to the vehicle being closer to the participants when they reached the opposite site. Furthermore, when the vehicle did not yield the time was limited. Overall, the time gap and the interaction of the time gap and yielding behavior of the vehicle were significant predictors of initiation gap and safety margin.

Participants’ crossing decision was significantly affected by the vehicles’ motion cues. However, the design of the experiment forced the participants to cross when the vehicle yielded. So, the yielding behavior was a less important factor when examining the crossing decisions even though it had one of the largest effects. Time gap had a large effect on crossing decision. The participants crossed less when the time gap was smaller. This was as expected. Crossing duration was also found to be significantly affected by vehicles' motion cues. This could mean that if the crossing could not be made within a certain time frame the participant decided not to cross the road.

Perceived behavioral control & perceived risk

As expected, the score on perceived behavioral control when interacting with a present and attentive driver was higher than when compared with the other two conditions. The participants felt they were most likely to cross successfully when the driver was attentive. In addition, the inverted scores on perceived risk when the driver was present and attentive were higher than in the other conditions. In other words, the participants perceived more risk when interacting with a distracted driver or no driver as compared to an attentive one.

Visibility

On average, 34.2 m was enough to tell whether there was a driver present. This meant that the participants saw the driver on average 4.1 s before the vehicle arrived next to the participant because the vehicle was travelling at 30 kmph. So, the driver was most probably visible to the participant before they could cross when the time gap was 3.5 s. On the other hand, the driver was visible on average 1.5 s after the participant was able to cross when the time gap was 5.5 s. In other words, the vehicle was further away than 34.2 m when participants started to cross. This means that the driver condition would have a major effect on the shorter time gap because it was better distinguishable, but this was not supported by the data. No interaction effect between driver condition and time gap was found. Thus, the effect of being able to spot the driver did not influence the initiation time. This suggests being able to see a driver is irrelevant when deciding to cross when there is a reasonably safe time gap between vehicles. It must be considered that the virtual windows of the vehicle were removed, and that the low speed of the vehicle was in place to make sure the driver would be visible. Even with the adaptations we made, the vehicle needed to be relatively close to the pedestrian. It raises questions about the utility of eye contact. Although, some papers seem to hint that eye contact is used by pedestrians to decide whether to cross (e.g. Rasouli & Tsotsos, 2019), it seems that eye contact cannot be used in all situations. Interactions occur without the possibility of seeing the other road users' eyes leaving unclear the importance of eye contact. Our findings show that there is a limited range in which the driver can be distinguished, and it is to be expected that the vehicle needs to be even closer for a pedestrian to be able to see the drivers' eyes. Therefore, future research should study how the visibility of the driver interacts with the distance from a vehicle to the pedestrian in a real-life setting. In addition, the vehicles' behavior was a better predictor of the crossing behavior meaning that the importance of the driver may be overestimated.

Virtual reality performance

In terms of realism, the scores on the presence scale are good overall, except on the interface quality. The scores on the misery scale were good and showed that the participants experienced vague symptoms of simulation sickness at most. Mostly, no symptoms were experienced. This is to be expected according to previous studies (Nuñez Velasco et al., 2019; Schwebel et al., 2017). The use of this type of virtual reality proved to be useful for studying pedestrian-vehicle interactions.

Limitations

This study was performed in a virtual reality environment which means that the results are not directly generalizable to the real world. However, studies suggest that the trends in virtual reality correlate with real world effects (Schneider & Bengler, 2020). More research is needed to prove the generalizability of findings from virtual reality studies. The visibility within the virtual environment may not be the same as in the real world. Furthermore, the windows were removed from the vehicles to increase visibility. Field experiments may find that the glare of windows or other factors introduced by glass windows may affect driver visibility.

The sample size was small and homogenous, and therefore further research should focus on the differences in crossing behavior when interacting with AVs between cultures, gender and age.

The task designed to test how well the driver was visible was performed at the end of the virtual reality session leaving unclear at what moment the participants started to notice the various driver conditions. This was done on purpose to not influence the crossing decision tactics of the participants.

Conclusions

This VR study illustrated that the most important factor affecting pedestrians' road crossing behavior was the motion cues derived from the vehicle, rather than the presence or state of the driver. Immersive virtual reality is a useful tool to study the mechanisms of pedestrians' crossing behavior.

CRediT authorship contribution statement

Juan Pablo Nuñez Velasco: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Yee Mun Lee:** Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Supervision. **Jim Uttley:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Albert Solernou:** Methodology, Software, Investigation, Resources. **Haneen Farah:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Supervision. **Bart van Arem:** Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition. **Marjan Hagenzieker:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Natasha Merat:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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