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The effect of drivers' eye contact on pedestrians' perceived safety

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ABSTRACT

Many fatal accidents that involve pedestrians occur at road crossings, and are attributed to a breakdown of communication between pedestrians and drivers. Thus, it is important to investigate how forms of communication in traffic, such as eye contact, influence crossing decisions. Thus far, there is little information about the effect of drivers' eye contact on pedestrians' perceived safety to cross the road. Existing studies treat eye contact as immutable, i.e., it is either present or absent in the whole interaction, an approach that overlooks the effect of the timing of eye contact. We present an online crowdsourced study that addresses this research gap. 1835 participants viewed 13 videos of an approaching car twice, in random order, and held a key whenever they felt safe to cross. The videos differed in terms of whether the car yielded or not, whether the car driver made eye contact or not, and the times when the driver made eye contact. Participants also answered questions about their perceived intuitiveness of the driver's eye contact behavior. The results showed that eye contact made people feel considerably safer to cross compared to no eye contact (an increase in keypress percentage from 31% to 50% was observed). In addition, the initiation and termination of eye contact affected perceived safety to cross more strongly than continuous eye contact and a lack of it, respectively. The car's motion, however, was a more dominant factor. Additionally, the driver's eye contact when the car braked was considered intuitive, and when it drove off, counterintuitive. In summary, this study demonstrates for the first time how drivers' eye contact affects pedestrians' perceived safety as a function of time in a dynamic scenario and questions the notion in recent literature that eye contact in road interactions is dispensable. These findings may be of interest in the development of automated vehicles (AVs), where the driver of the AV might not always be paying attention to the environment.

1. Introduction

Worldwide, more than 50% of traffic-related deaths are that of vulnerable road users such as pedestrians (World Health Organization, 2020). Most pedestrian deaths occur in urban areas at non-intersection locations (National Highway Traffic Safety Administration, 2020; SWOV, 2020).

A possible cause of these casualties is a breakdown in communication with other road users such as car drivers (European Road Safety Observatory, 2018). Färber (2016) noted that road users communicate via informal means, such as eye contact, in addition to relying on formal traffic rules. Understanding the role of eye contact in traffic is a relevant topic in recent times, with the development of AVs in which the driver may be intermittently attentive. To illustrate, according to Google Scholar, from the 45 papers citing a recent

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paper on the effect of pedestrian's eye contact on the speed of approaching vehicles (Ren, Jiang, & Wang, 2016), 30 (67%) are directly related to AV interaction with vulnerable road users, based on the titles of the citing works.

Thus far, a few studies have investigated the effect of drivers' eye contact on pedestrians, as listed below:

- In a Wizard of Oz experiment, Malmsten Lundgren et al. (2017; $N = 13$) found that pedestrians reported greater willingness to cross the road when the driver of a supposed AV made eye contact with them, compared to when the driver was inattentive by reading a newspaper or talking on the phone.
- Yang (2017; $N = 40$) presented participants with pictures of a driver making eye contact, talking on the phone, sleeping, or being hidden from view by blinded windows. This study found that the driver's eye contact made participants feel more certain they were safe to cross compared to when the driver was inattentive or hidden from view.
- In a crowdsourcing study using images of an intersection from a cyclist's perspective, Bazilinskyy, Dodou, Eisma, Vlakveld, and De Winter (2021) found that a driver's eye contact increased the willingness of cyclists to cross compared to no driver's eye contact. This effect was only found in their second experiment ($N = 1086$), in which observers were asked to rate features of an AV in the image; it was not found in their first experiment ($N = 1260$), in which participants made a quick go/stop decision.
- In a Wizard of Oz study by Rodríguez Palmeiro et al. (2018; $N = 24$), no significant differences were observed between pedestrians' moments of making a crossing decision between attentive-driver and distracted-driver conditions, including a distracted driver reading a newspaper.
- In another Wizard of Oz study by Faas, Stange, and Baumann (2021; $N = 65$), pedestrians felt safer to cross in front of a car with a driver making eye contact compared to a driver reading a newspaper or a car with blinded windows. No significant differences were observed, however, in terms of crossing onset times.
- In a study using a head-mounted display, Nuñez Velasco et al. (2021; $N = 20$) let pedestrians cross a virtual road in front of an AV with an external Human Machine Interface (eHMI), which featured an attentive driver, a distracted driver, or no driver. The study concluded 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. This raises the question about the needs, purpose, and added value of eHMIs*" (p. 57).
- In a virtual reality study, Chang, Toda, Sakamoto, and Igarashi (2017; $N = 15$) evaluated an eHMI in the form of artificial eyes and found that pedestrians reached a correct crossing decision faster and reported feeling safer when the eyes made eye contact with them, compared to when they did not. Similar eHMI concepts were proposed by Alvarez, De Miguel, García, and Olaverri-Monreal (2019), Alvarez, Moreno, Sipele, Smirnov, and Olaverri-Monreal (2020), Rover (2018), Löcken, Golling, and Riener (2019), Mahadevan, Somanath, and Sharlin (2018), Pennycooke (2012), Verma, Pythoud, Eden, Lalanne, and Evéquoz (2019), and Wang et al. (2021). In Löcken et al. (2019), the virtual eyes concept came out as the most untrustworthy from a total of five eHMI concepts. Additionally, Furuya, Kim, Bruder, and Wisniewski (2021) tested a virtual human embodiment in AV-pedestrian interaction and found that a 'driver that looks at you' was preferred over 'no driver' and a 'static driver' by 25 out of 26 participants.

From the above, it appears that drivers' eye contact can, in some cases, make pedestrians feel safer to cross as compared to no eye contact. These findings are in line with research in social and evolutionary psychology, suggesting that eye contact has various functional rules, including signaling, recognizing, facilitating joint attention, and encouraging compliance (Argyle & Dean, 1965; Hamlet, Axelrod, & Kuerschner, 1984; Tomasello, Hare, Lehmann, & Call, 2007).

However, most of the studies listed earlier concerned situations where the driver was completely disengaged from the driving task, for example by reading a newspaper. These are unlikely scenarios to encounter on real roads since AVs are not yet at a level of automation that (legally) allows drivers to be this lax at the wheel. Thus, the positive impact of drivers' eye contact on pedestrians' crossing behavior noted by the above studies may be because these studies used a completely disengaged driver as the baseline, instead of simply an attentive driver who does not make eye contact.

More problematically, the above studies used only two simplified conditions: eye contact is either present or absent in the crossing conflict. They also used only a single go/stop decision moment without examining the evolution of such decision-making as the car is approaching. Since eye contact is a phenomenon that spans a finite length of time, and because traffic interactions themselves are typically brief affairs, there is incentive to investigate eye contact in relation to crossing behavior as a function of time. The results of such an approach would provide a more truthful account of the importance of eye contact on the road.

At the same time, it has been argued that implicit communication cues viz. car speed and distance are probably more dominant cues for pedestrians to understand the intention of an approaching car (Clamann, Aubert, & Cummings, 2017; Dey & Terken, 2017; Lee et al., 2021; Nuñez Velasco et al., 2021). In an online survey study, AlAdawy, Glazer, Terwilliger, Schmidt, Domeyer, Mehler, Reimer, and Fridman (2019) reported that pedestrians are usually unable to see the driver through the windshield because of sunshine, shadows, glare, or darkness. In the same vein, it has been noted that drivers are less compelled than pedestrians to make eye contact (Sucha, Dostal, & Risser, 2017) and that pedestrians may not even notice the absence of a driver (Rothenbücher, Li, Sirkin, Mok, & Ju, 2016). Moore, Currano, Strack, and Sirkin (2019) devoted an entire paper to arguing that eHMIs are superfluous, as pedestrians can judge whether it is safe to cross based solely on the kinematics of the approaching car.

In summary, research so far suggests that drivers' eye contact may encourage vulnerable road users to cross the road, but that implicit communication is more dominant. However, there appears to be neither systematic investigation that isolates drivers' eye contact from other confounding driver behaviors (e.g., being distracted) nor research about the effects of eye contact timing on pedestrians' perception of safety and crossing decisions. In the present online crowdsourced study, we examined participants' perceived safety to cross the road in front of an approaching car, measured by means of a keypress response, for various timings of a driver's eye contact.

Fig. 1. Top: Screenshot from a video showing the driver making eye contact while the car was standing still. Bottom: Screenshot from a video showing the driver not making eye contact while the car was standing still.

It was hypothesized that pedestrians feel safer to cross the road when the driver makes eye contact with them compared to when the driver does not make eye contact. The initiation of eye contact is a salient event due to the head turn involved. Thus, it is possible that not only eye contact itself, but also the *change* in the state of a driver's eye contact influences the pedestrian's crossing decisions. Furthermore, it is plausible that the highest perceived safety to cross is achieved when the change in a car's state of yielding (i.e., the initiation of braking) accompanies and complements a change in the state of a driver's eye contact (i.e., the initiation of eye contact).

2. Method

2.1. Videos

Participants watched a set of 13 videos twice. Each video presented the viewpoint of a pedestrian standing on a sidewalk while a car (Smart Fortwo) with a driver was approaching from the left on a two-lane, 10 m-wide road. In 11 videos, the car yielded, and in 2 videos, it did not. Furthermore, in 11 videos, the driver made eye contact, and in 2 videos, he did not. The videos differed based on the initiation and termination of the driver's eye contact.

The videos were generated using an open-source simulator built in Unity3D (Bazilinskyy, Kooijman, Dodou, & De Winter, 2020). They had a frame rate of 25 fps and a resolution of 1280 $\times$ 720 pixels. The videos included the engine sound of an approaching car (stereo, sample rate: 48 kHz). Videos were shown to participants via the cloud platform Heroku (https://www.heroku.com). The virtual camera in the animation was positioned 1.67 m above the pavement, which itself was 0.25 m above the road. The camera was

Table 1
Characteristics of the videos.

Video	Yielding	Eye contact interval	Timing of eye contact
1	Yes	None	No eye contact
2	Yes	1.0–17.6	First visible–Full stop
3	Yes	1.0–22.9	First visible–Take-off
4	Yes	17.6–22.9	Full stop–Take-off
5	Yes	22.9–26.5	Take off–Out of sight
6	Yes	1.0–26.5	First visible–Out of sight
7	Yes	17.6–26.5	Full stop–Out of sight
8	Yes	1.0–13.6	First visible–Braking start
9	Yes	13.6–17.6	Braking start–Full stop
10	Yes	13.6–22.9	Braking start–Take-off
11	Yes	13.6–26.5	Braking start–Out of sight
12	No	None	No eye contact
13	No	1.0–16.7	First visible-Out of sight

also angled to obtain a full view of the road and was 0.7 m from the edge of the pavement. These values were regarded as comparable to the eye position of a typical pedestrian standing on the curb and turning to look at an approaching car. The field of view of the camera was set to relatively low values of 21 deg horizontally and 12 deg vertically, creating a ‘zoomed in’ effect. A narrow field of view was chosen to mimic the psychological experience of focused attention on approaching cars in real traffic. Wider fields of view were tried in the design of the experiment but were deemed less suitable, as in those cases, the car occupied a smaller part of the computer screen, which itself subtends only a limited field of view for the participant. Narrower fields of view, on the other hand, caused parts of the road and sidewalks to go out of sight, which was undesirable.

The 11 videos in which the car yielded were 31.0 s long, and the 2 videos in which the car did not yield were 21.0 s long. All videos started with a black screen lasting 1 s to prevent abrupt transitions between videos. The driver’s eye contact in the videos was implemented by rotating the driver’s head from its default straight-ahead orientation to the orientation of the line connecting the driver’s and pedestrian’s heads. Initiation and termination of eye contact was achieved by turning the driver’s head between these two orientations in 0.2–0.3 s. While making eye contact, the driver’s head smoothly tracked the pedestrian’s as the car approached.

The car’s initial speed and longitudinal distance relative to the pedestrian (i.e., the camera’s point of view in the videos) were 13.2 km/h and 66 m, respectively. It was expected that at lower speed, the effect of explicit communication, such as the driver’s eye contact, becomes more important relative to the effect of implicit communication, such as the car’s speed (Dey et al., 2021; Färber, 2016; Merat, Louw, Madigan, Wilbrink, & Schieben, 2018; Schneemann & Gohl, 2016).

In case the car yielded, it did so at a deceleration of 1 m/s^2, starting at a distance of 19.8 m (13.6 s) from the pedestrian and coming to a stop at a distance of 13.7 m (17.6 s). Distances were considered longitudinally between the location of the pedestrian’s head (i.e., the camera’s position) and the car’s center. Given the Smart Fortwo’s length of 2.695 m, the distance from the car’s front end to the pedestrian at full stop was 12.35 m. Although the distance at stop was high compared to what one might see in real-life scenarios, it did not appear as high due to the low field of view (see Fig. 1). Shorter distances were tried, but they caused the car to be partially or entirely out of view when stopped. The car stood still for 5.3 s, and then drove off with an acceleration of 1 m/s^2. Acceleration and deceleration values were set according to what was deemed a gentle change of speed for a Smart Fortwo, that is, about one-third of its maximum acceleration of 3.47 m/s^2, calculated based on a 0–60 km/h time of 4.8 s (Smart, 2021). The driver went out of sight 26.5 s into the videos involving a yielding car. For videos involving a non-yielding car, the driver went out of sight after 16.7 s from the start of the video.

Table 1 summarizes the characteristics of the videos in terms of yielding behavior of the car and eye contact interval. The reasoning behind the various eye contact intervals was that they represented all possible combinations between five distinct moments in a typical driver-pedestrian interaction:

1. The moment the approaching car is first visible (‘First visible’)
2. The moment the car starts to slow down (‘Braking start’)
3. The moment the car reaches a standstill in front of the pedestrian (‘Full stop’)
4. The moment the car starts to move again (‘Take-off’)
5. The moment the car leaves the pedestrian’s view (‘Out of sight’)

In the case of a non-yielding car, only the first and last entries from the above are applicable. This rationale led to a total of 13 videos, each involving a unique interval of eye contact. Fig. 1 showcases screenshots from videos with and without the driver’s eye contact.

2.2. Participants

Two thousand participants were recruited from across the world via the online job portal Appen (https://www.appen.com). The job was titled “*Eye contact in traffic*”. In Appen, participants first encountered a brief description of the study, followed by a question asking for informed consent. This research was approved by the Human Research Ethics Committee of the Delft University of Technology (reference number 1444).

2.3. Procedure

After providing informed consent, participants completed a questionnaire on their basic data and road behavior. Next, a link took them to the experiment on the Heroku platform, where the videos were preloaded to minimize delays, and the participants were presented with the following task instructions:

You will watch videos of approaching cars from the point of view of a pedestrian standing on the side of the road. Some cars will stop and other cars will not stop. In some videos, the driver will make eye contact with you. Imagine that you are the pedestrian and that you want to cross the road. Before the start of each video, you will briefly see a black screen. Please PRESS AND HOLD the 'F' key on your keyboard during this time. Once the video starts, continue holding the key as long as you feel safe to cross. RELEASE the key if you do not feel safe to cross anymore. You can press, hold and release the key as many times as you want per video.

Before proceeding, participants calibrated their device's volume against a piece of royalty-free music to ensure that they could hear the video sound clearly. They were then shown the 13 videos twice, all in random order, with a break after every 10 videos (the last batch contained only 6 videos). Under each video, the following text was present: "*PRESS AND HOLD the 'F' key when you feel safe to cross. RELEASE the key when you don't feel safe.*"

After each video, participants were presented with a question and a statement:

1. "*Did the driver make eye contact with you*?" (*No*, *Yes*)
2. "*The driver's eye contact behaviour was intuitive for me to decide whether I could or could not cross*" (five-point Likert scale ranging from '*Completely disagree*' to '*Completely agree*')

In addition, a total of 10 true–false test questions (e.g., "*Bananas are yellow*") were randomly inserted in each batch for each participant. These questions were used to screen out inattentive participants.

After all 26 videos were viewed, the penultimate page presented three additional statements:

1. "*Eye contact between drivers and pedestrians is important for road safety*"
2. "*I prefer eye contact to no eye contact*"
3. "*I could concentrate well during the study*"

Participants responded to these statements on five-point Likert scales of '*Completely disagree*' to '*Completely agree*'.

On the final page, participants received a unique worker code that they were required to enter in Appen as proof of completing the experiment and to receive payment. Each participant received a reimbursement of $0.45.

2.4. Analyses

First, participants who did not yield data or who may not have taken the task seriously were screened out. Next, trials that took longer than 33 s (for videos with a yielding car) or 23 s (for videos with a non-yielding car), i.e., more than 2 s longer than the nominal video duration were excluded. This exclusion was done to remove trials where participants may have suffered from technical problems such as lag while rendering in the browser or buffering of videos.

The first dependent variable, pedestrians' perceived safety, was analyzed by visualizing and statistically comparing the percentage of trials in which participants pressed the response key, for different videos. Statistical comparisons between videos were made at the level of participants using paired samples t-tests for each 0.1 s of video time. A conservative significance level (alpha = 0.001) was used to minimize the probability of false positives. Our approach is similar to Manhattan plots in molecular genetics, which use a stringent alpha value to visualize which of many genetic variants are predictive of a particular phenotype (Cook, Ryckman, & Murray, 2013).

The second dependent variable was the mean intuitiveness rating of eye contact in helping make a crossing decision. Mean scores of the different videos were compared, and pairs of conditions were compared using paired samples t-tests, with an alpha value of 0.005 (Benjamin et al., 2018).

In addition, a performance score was calculated for the 11 videos depicting a yielding car. The performance score was calculated as: ((mean keypress percentage over the interval 13.6–22.9 s) + (100% − mean keypress percentage over the interval 22.9–26.5 s))/2. Accordingly, the performance score represents the extent to which participants felt safe to cross when it was indeed safe to cross (i.e., the braking and standing still phases) combined with the degree to which participants did not feel safe to cross when it was indeed unsafe to cross (i.e., the take-off phase).

3. Results

Participants who indicated that they did not read the instructions ($n = 29$), who indicated that they were younger than 18 ($n = 3$), who completed the study within 1000 s, suggesting cheating or carelessness ($n = 89$), who could not be linked to the data due to a data storage issue or cheating ($n = 14$), who made more than 2 mistakes out of the 10 test questions ($n = 16$), or who suffered video playback delays, defined as more than 2 videos taking more than 5 s too long to complete ($n = 49$) were excluded, leaving 1835 participants from 64 countries. Multiple participations from the same IP address were permitted, as there was no reliable way to

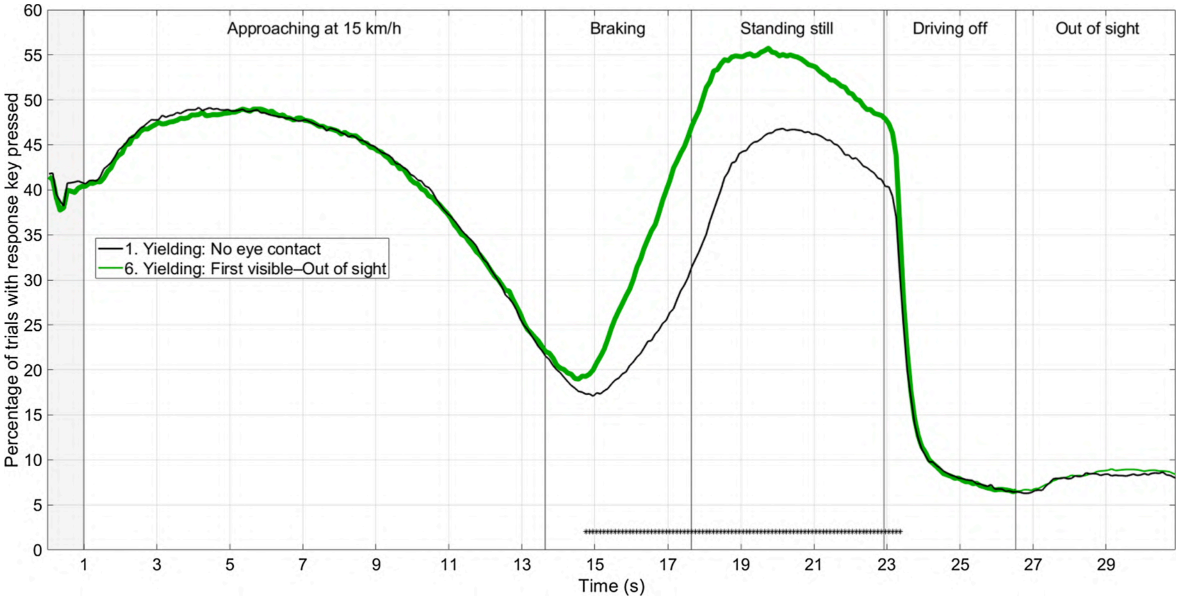

Fig. 2. Percentage of trials in which the response key was pressed for no driver's eye contact (Video 1) and driver's eye contact throughout (Video 6), for the videos in which the car yielded. The bold sections of the lines indicate that there was eye contact at those moments. The asterisks at the bottom indicate significant differences, $p < 0.001$.

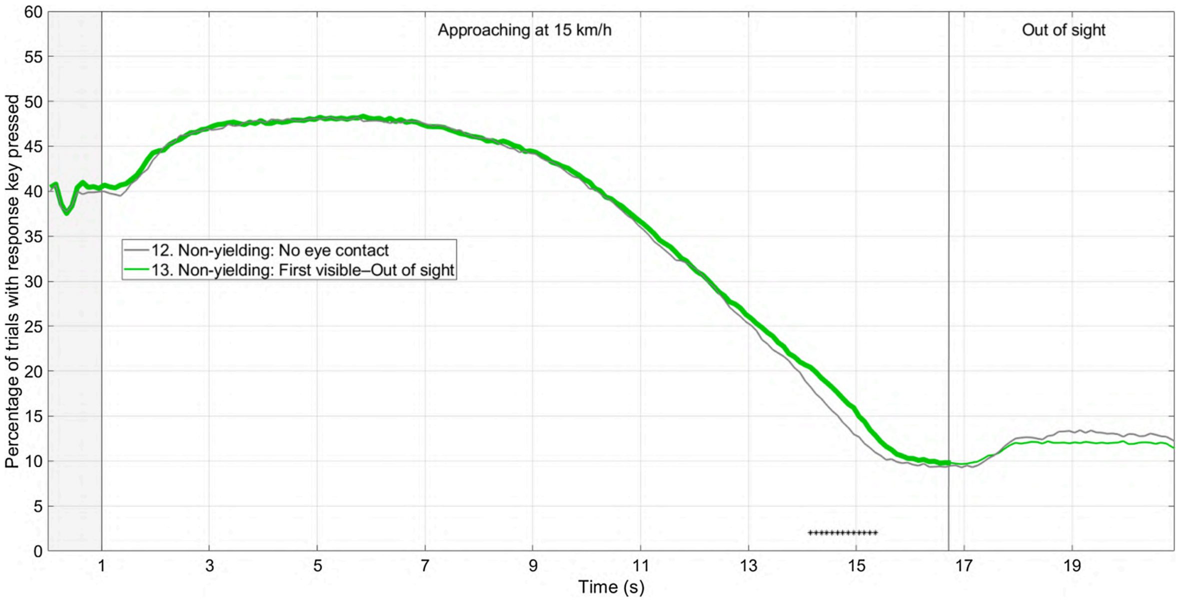

Fig. 3. Percentage of trials in which the response key was pressed for no driver's eye contact (Video 12) and driver's eye contact throughout (Video 13), for the videos in which the car did not yield. The bold sections of the lines indicate that there was eye contact at those moments. The asterisks at the bottom indicate significant differences between pairs of conditions, $p < 0.001$.

determine whether duplicate IPs were due to one person or multiple persons completing the experiment on one device or multiple devices connected to the same network. Out of the total number of 47,710 trials (1835 participants × 26 trials per person), 46,277 trials (97.0%) were retained, whereas the rest of the trials were excluded due to playback lags of more than 2 s.

The mean study completion time was 39.1 min ($SD = 18.8$ min, median = 33.0 min). The study yielded a mean satisfaction score of 4.4 on a scale of 1 (*very dissatisfied*) to 5 (*very satisfied*) by 86 people who completed the optional satisfaction survey offered by Appen. The five most represented countries were Venezuela ($n = 1098$), the United States ($n = 210$), Russia ($n = 70$), India ($n = 59$), and Egypt ($n = 57$). The participants consisted of 1159 males, 668 females, and 8 people who indicated 'I prefer not to respond'. The mean age was 34.9 years ($SD = 10.9$). A total of 100 participants indicated that they were 'never' pedestrians, 68 indicated 'less than once a

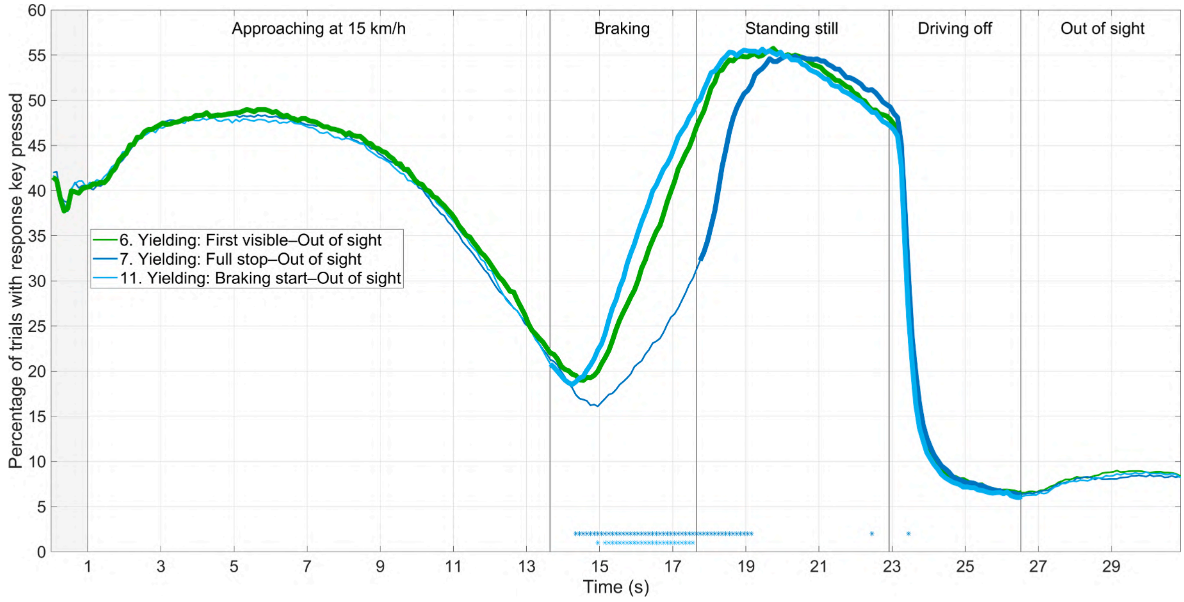

Fig. 4. Percentage of trials in which the response key was pressed for driver's eye contact throughout (Video 6), and eye contact initiation when the car started to brake (Video 11), and when the car came to a stop (Video 7). The bold sections of the lines indicate that there was eye contact at those moments. The asterisks at the bottom indicate significant differences with the video containing eye contact throughout (Video 6), $p < 0.001$.

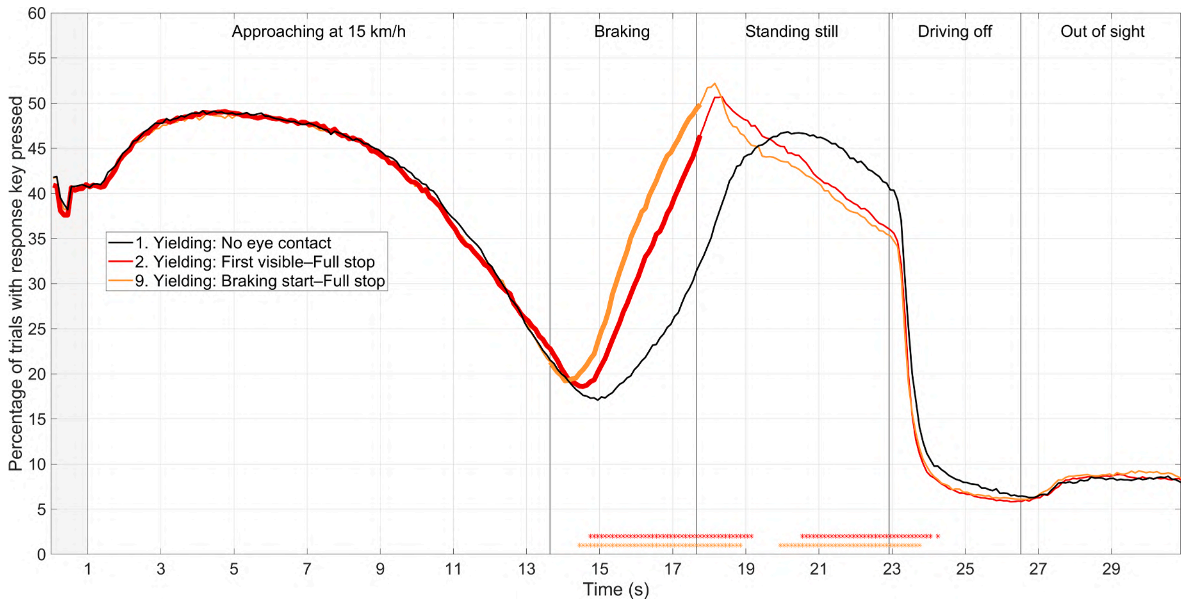

Fig. 5. Percentage of trials in which the response key was pressed for no driver's eye contact throughout (Video 1) and eye contact termination when the car came to a stop (Videos 2 and 9). The bold sections of the lines indicate that there was eye contact at those moments. The asterisks at the bottom indicate significant differences with the video containing no eye contact (Video 1), $p < 0.001$.

month', 166 'once a month to once a week', 487 '1 to 3 days a week', 376 '4 to 6 days a week', and 580 'every day' (58 participants indicated 'I prefer not to respond').

3.1. Keypress percentage as a measure of perceived safety to cross

Fig. 2 shows the mean keypress percentage for yielding cars for driver's eye contact throughout versus no driver's eye contact. It can be seen that pedestrians perceived the situation as less and less safe until the car began braking. As the car braked, perceived safety increased and remained high while the car was fully stopped, only to drop sharply after the car took off. This sharp drop started at

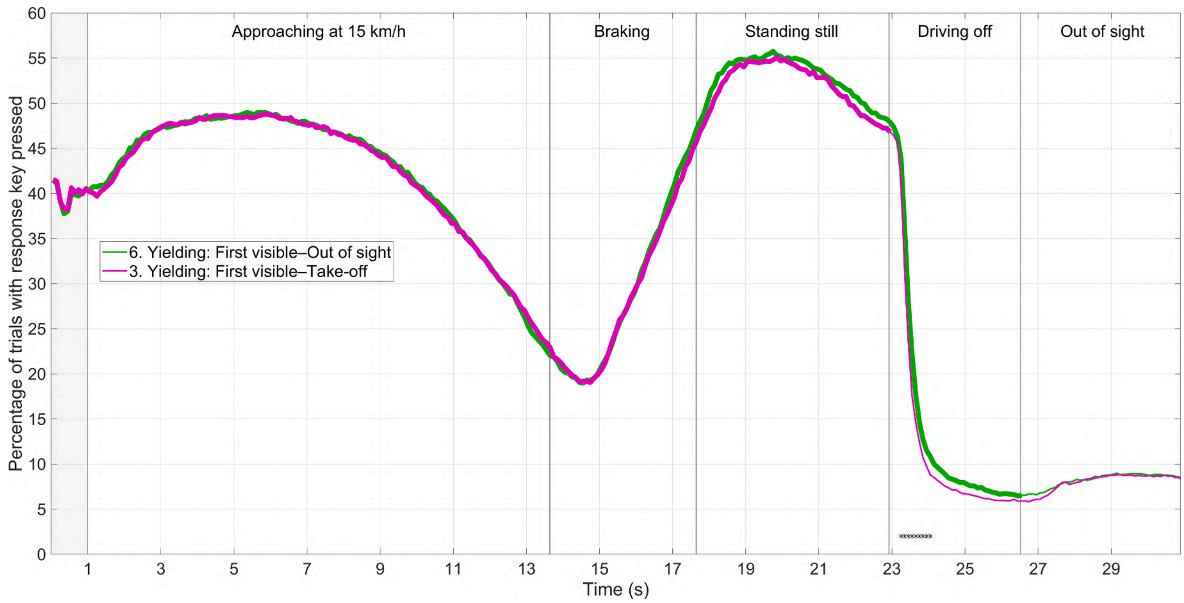

Fig. 6. Percentage of trials in which the response key was pressed for driver's eye contact throughout (Video 6) and eye contact termination when the car took off (Video 3). The bold sections of the lines indicate that there was eye contact at those moments. The asterisks at the bottom indicate significant differences, $p < 0.001$.

200–300 ms and has the highest slope at 300–600 ms after the car drove off. This drop is consistent with the reaction time distribution to a discrete stimulus (e.g., Ratcliff, 1993), which in this case would be the onset of motion of the car. Fig. 2 further shows that there was also a small increase in the mean keypress percentage after the car went out of sight.

It can also be seen from Fig. 2 that the driver's eye contact did not significantly affect perceived safety before the car started braking and for most of the car's take-off. The driver's eye contact substantially increased perceived safety compared to a lack of it in a time window starting soon after the car started braking and ending shortly after the car took off again.

For non-yielding cars (Fig. 3), perceived safety decreased throughout the video, which is explained by the fact that the car got closer and closer to the pedestrian but without slowing down. Similar to Fig. 2, a slight increase in perceived safety can be seen after the non-yielding car went out of sight after passing the pedestrian.

Fig. 4 shows that if the driver started making eye contact when the car started to brake (Video 11), perceived safety during the braking phase was significantly higher compared to when eye contact was already present at the beginning of the video (Video 6). In other words, the initiation of eye contact alongside the initiation of braking positively affected pedestrians' perceived safety compared to eye contact throughout the encounter. From Fig. 4, it can be seen that eye contact while braking had a strong effect: when the car came to a stop, the keypress percentage was 31.3% for Video 7 but 49.7% for Video 11 (i.e., a 59% increase).

Fig. 4 further shows that the initiation of eye contact when the car came to a stop (Video 7) gave a small boost to perceived safety, so that in parts of the standing still and driving off phases, it was higher compared to eye contact throughout (Video 6). So again, the initiation of eye contact had a reinforcing effect on the keypress percentage compared to continuous eye contact from the beginning of the video.

If the driver stopped making eye contact when the car came to a full stop (Videos 2 and 9), this was seen by pedestrians as a sign that they should not cross when the car was standing still, compared to no eye contact at all (Video 1), as seen in Fig. 5. In other words, just like the initiation of eye contact was a cue that pedestrians should cross, the termination of eye contact was a cue that they should not cross. It is interesting that the effects of eye contact termination at full stop carried forward until after take-off. It is also worth noting that the drop in mean keypress response due to termination of eye contact was not as steep as the drop due to the car's initial approach or its take-off, suggesting that the car's motion was a more dominant cue.

The above figures show that participants' perceived safety reduced abruptly when the car started to drive away, regardless of eye contact. In other words, implicit communication (i.e., vehicle motion) was more dominant. There was, however, a delayed response for cases when the driver retained eye contact while driving away (e.g., Video 6) compared to when eye contact ended when the car drove off (e.g., Video 3), as seen by the presence of significant differences in Fig. 6. Thus again, the termination of eye contact was perceived as a sign that the pedestrian should not cross.

Figs. 2–6 showed results for selected videos. The results for all 11 videos involving a yielding car are available in the Supplementary material (Fig. S1).

3.2. Relationships between self-reported intuitiveness, self-reported driver's eye contact, and objective performance

Fig. 7 provides an indication of concurrent validity by depicting the mean scores across participants for self-reported intuitiveness, self-reported driver's eye contact, and objective performance. From Fig. 7 (left), it can be seen that for videos in which there was eye contact, self-reported eye contact was high (i.e., close to 100%), suggesting that participants were generally attentive.

Fig. 7 (left) also shows that the false-positive rate was 15–20% for the videos without eye contact (Videos 1 and 12). These values are relatively far from 0%, which can be explained by the fact that it is difficult to ascertain that there was no eye contact at all during the entire video because of the low signal-to-noise ratio when the car is still far away. That is, when the car is far away, participants have to guess whether there is eye contact or not since they cannot see the driver clearly.

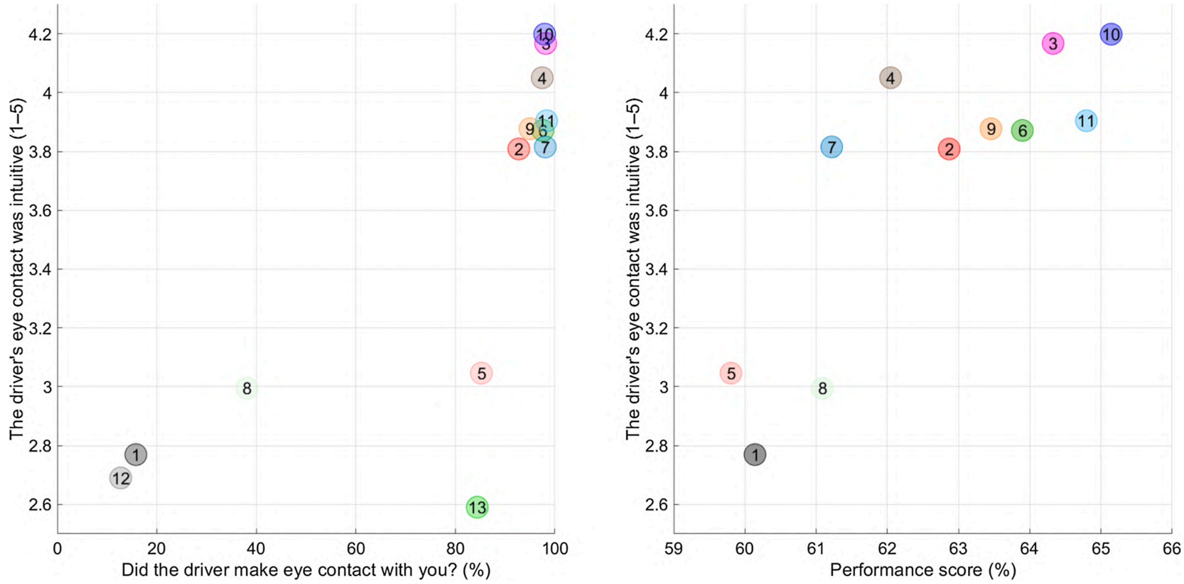

Fig. 7. Mean self-reported intuitiveness of eye contact per video versus self-reported occurrence of eye contact per video (left), and mean self-reported intuitiveness of eye contact per video versus performance score per video with a yielding car (right).

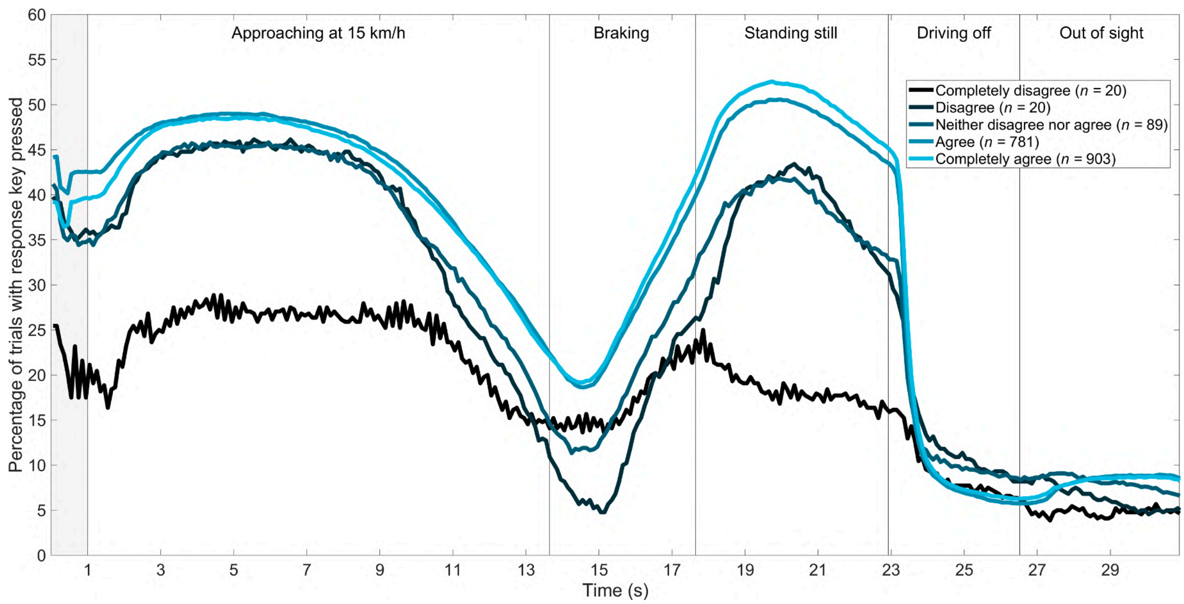

Fig. 8. Percentage of trials in which the response key was pressed for different self-reported concentration levels.

Table 2
Means, standard deviations, and Pearson product-moment correlation coefficients of means per video ($n = 13$ for intuitiveness ratings, and $n = 11$ for performance scores, which were computed for videos with a yielding car) for participants from different countries.

		M	*SD*	1	2	3	4	5	6	7	8	9	10	11
1	Intuitive (1–5) (All)	3.52	0.60											
2	Intuitive (1–5) (VEN)	3.56	0.62	0.999										
3	Intuitive (1–5) (USA)	3.53	0.54	0.998	0.999									
4	Intuitive (1–5) (RUS)	3.47	0.78	0.987	0.981	0.978								
5	Intuitive (1–5) (IND)	3.46	0.54	0.981	0.978	0.971	0.978							
6	Intuitive (1–5) (EGY)	3.44	0.50	0.987	0.987	0.981	0.972	0.979						
7	Performance (%) (All)	62.62	1.87	0.827	0.823	0.830	0.805	0.760	0.830					
8	Performance (%) (VEN)	62.71	1.74	0.834	0.832	0.836	0.803	0.772	0.837	0.997				
9	Performance (%) (USA)	62.84	1.70	0.776	0.768	0.777	0.771	0.693	0.789	0.980	0.964			
10	Performance (%) (RUS)	61.45	3.22	0.871	0.864	0.875	0.869	0.800	0.861	0.963	0.950	0.957		
11	Performance (%) (IND)	61.42	2.05	0.788	0.779	0.786	0.795	0.725	0.807	0.925	0.905	0.959	0.915	
12	Performance (%) (EGY)	60.75	1.70	0.749	0.748	0.739	0.703	0.731	0.776	0.866	0.884	0.814	0.844	0.729

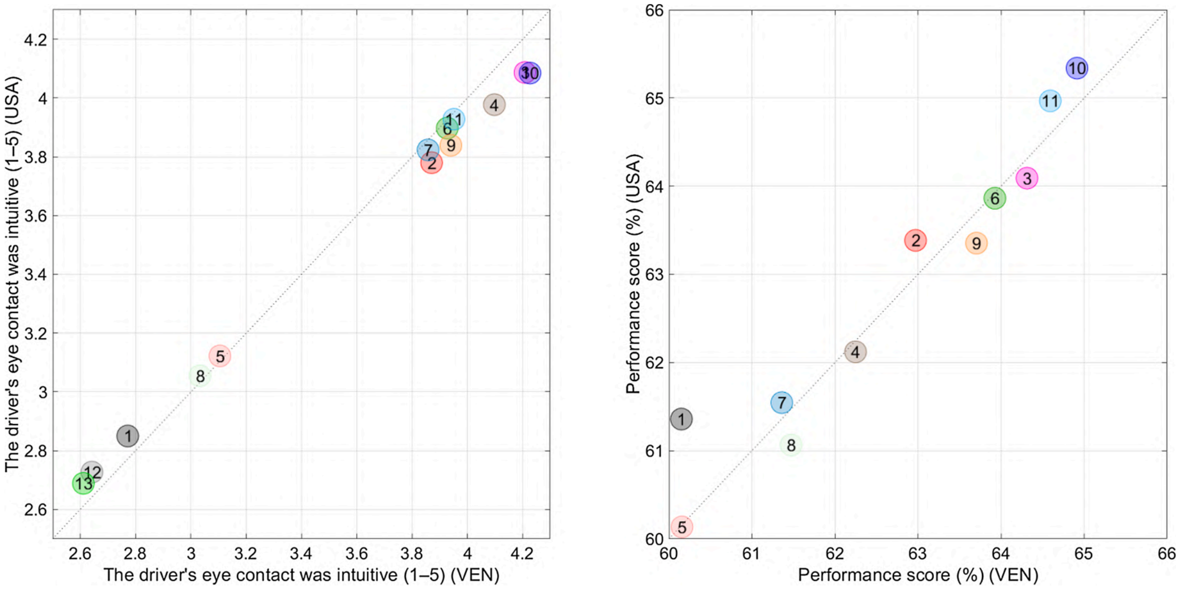

Fig. 9. Mean self-reported intuitiveness of eye contact per video for participants from the United States and Venezuela (left, $r = 0.999$), and mean performance score per video involving a yielding car for participants from the United States and Venezuela (right, $r = 0.964$). The diagonal lines are lines of unity.

Intermediate percentages of self-reported eye contact were observed for Video 5 (85%), Video 8 (38%), and Video 13 (84%). These relatively low percentages may be because eye contact occurred late in the video, only when the car drove off (Video 5), occurred very early, in which case eye contact is hard to detect (Video 8), or because the car did not stop, which may have also made it difficult to detect eye contact (Video 13).

Fig. 7 (left) further shows clear differences between the intuitiveness ratings of the 13 videos. From the 78 pairs of comparisons between the 13 videos, only 7 pairs were not significantly different from each other, i.e., p greater than 0.005 (Video pairs 1–12, 2–7, 3–10, 5–8, 6–9, 6–11, and 9–11), indicating that our study was adequately powered to detect small differences in the intuitiveness ratings. The highest intuitiveness ratings were found for Videos 3 and 10, which were videos in which the driver terminated eye contact upon driving away, whereas the highest performance scores were obtained for Videos 10 and 11 (Fig. 7, right), which were videos in which the driver initiated eye contact when the car started braking.

Among the videos in which the driver made eye contact, Video 5 was the least intuitive and yielded the lowest performance by a substantial margin (Fig. 7, right). In this video, the driver started looking at the pedestrian when the car started to drive off. Another counterintuitive video that yielded low performance was Video 7. This video was similar to Video 5 as the driver started to make eye contact upon take-off.

3.3. *Effects of self-reported concentration*

An issue in online studies such as the present one is that inattentive participants may contaminate the data. A small positive correlation was observed between self-reported concentration and objective performance ($r = 0.10$, $p < 0.001$, $n = 1813$ participants with a response to this question). The association between self-reported concentration and keypress behavior for videos with yielding cars is illustrated in Fig. 8, showing that non-concentrated participants were less likely to hold the key than concentrated participants. More specifically, the mean keypress percentages from the start of the video until the car went out of sight were 20, 31, 32, 37, and 37% for concentration levels 1 (*Completely disagree*) to 5 (*Completely agree*).

3.4. *Cross-cultural consistency*

A common question in the analysis of eye contact and other road user gestures is whether there may exist cross-cultural differences (Ranasinghe et al., 2020). In an attempt to address this question, we computed the means and standard deviations, as well as correlations of the means of videos ($n = 13$) for participants from the five most represented countries.

The results in Table 2 suggest that outcomes for participants from different countries were highly similar. More specifically, the average ratings of driver's eye contact intuitiveness were similar (between 3.44 for Egypt and 3.56 for Venezuela, on the scale of 1–5), and the average performance scores were similar as well (between 61% for Egypt and 63% for the United States). Also, the correlations of the mean intuitiveness ratings were all high ($r > 0.97$, $n = 13$) and correlations for the mean performance scores were high as well ($r > 0.90$, $n = 11$), with the exception of participants from Egypt, whose performance scores showed a more modest correlation with the performance scores of participants from the four other countries. Nonetheless, correlations between intuitiveness ratings and performance scores were all around $r = 0.75$ ($n = 11$), indicating that the results presented in Fig. 7 (right) are cross-nationally robust. The correlation coefficients for the two most highly represented countries (Venezuela and the United States) are illustrated in Fig. 9.

The performance scores were computed based on whether the participants pressed the key when the key should be pressed and released the key when the key should not be pressed. Although performance scores were similar, the base rates of key presses were different between countries, with mean keypress percentages from the start of the video until the car went out of sight being 36, 33, 47, 39, and 33% for Venezuela, United States, Russia, India, and Egypt, respectively. These differences in base rates, which are illustrated in the Supplementary material (Fig. S2), may be caused by some participants from particular countries misunderstanding the task or not taking the task seriously (e.g., holding the key throughout the trial). Such anomalies were, however, not of concern for the relative effects between videos, as was demonstrated in Table 2.

4. Discussion

This study aimed to examine the effect of drivers' eye contact on pedestrians' perceived safety to cross a road. Through an online experiment with a large sample size, we varied the start and end times of a driver's eye contact, yielding a total of ten different eye contact intervals for an approaching car that slowed down to a full stop and subsequently drove off. In addition, we included a video with no eye contact as a baseline and two videos in which the approaching car did not yield: one with eye contact throughout and one without eye contact.

The results of this study unambiguously indicated that a driver's eye contact made pedestrians feel safer to cross. This finding confirms the scarce evidence so far that suggests that eye contact increases the feeling of safety and willingness to cross (Bazilinskyy et al., 2021; Malmsten Lundgren et al., 2017; Yang, 2017). The studies so far, however, did not provide insight into the effects of drivers' eye contact on pedestrians as a function of time during the car's approach.

In our study, the effects of different eye contact timings were investigated, and the results can be summarized by stating that not only eye contact but also the initiation and termination of eye contact affect perceived safety. That is, the initiation of eye contact alongside braking was found to be a more powerful cue for pedestrians to cross compared to eye contact throughout, and conversely, the termination of eye contact alongside take-off was a stronger deterrent to cross than no eye contact at all. This argument may be extended to say that there exists a time window between a car's braking and its subsequent take-off where eye contact is a strong cue to help resolve crossing conflicts.

Previous research made a case against the importance of eye contact and the usefulness of eHMIs, by arguing that implicit communication alone is sufficient for pedestrians, without any need for explicit communication, such as eye contact (Moore et al., 2019). The present study does not dispute that a car's motion is a more dominant cue than eye contact; in fact, it confirms this. However, it also provides counterevidence to the claim that eye contact is dispensable by showing that eye contact initiation while braking increased the perceived safety, with an increase from 31% to 50% of participants feeling safe to cross the road when the car came to a stop. These findings have implications for research into substituting eye contact in the context of AVs, i.e., that replacements may indeed be required to maintain the safety of pedestrians.

As pointed out above, our study showed that implicit communication could override the effect of eye contact. For example, the driver's eye contact did not have much of an effect if the car did not slow down. This finding can be explained by the fact that crossing will lead to collision in this scenario and is therefore intuitively unsafe. Similarly, after the car drove off from a standstill, participants consistently released the response key, and eye contact had a comparatively small effect. These results can be summarized by the common-sense notion that eye contact, although a compelling cue, is not compelling enough to cause participants to get run over by the car. Our study further showed that eye contact failed to have an effect when eye contact could not be detected with certainty, that is, when the vehicle was still far away. If the driver's eyes or head movement cannot be seen because of the large distance, pedestrian behavior cannot be affected.

The current study investigated the effect of drivers' eye contact on pedestrians' perceived safety. The converse topic, namely the effect of pedestrians' eye contact on drivers' perceived safety, would be of interest as well. Several early studies showed that drivers slowed down or stopped more often when staged pedestrians/hitchhikers looked at the approaching vehicle compared to when they did not (Katz, Zaidel, & Elgrishi, 1975; Morgan, Lockard, Fahrenbruch, & Smith, 1975; Snyder, Grather, & Keller, 1974). Similarly, Ren et al. (2016) observed that drivers braked earlier and approached more slowly when staged pedestrians made eye contact with them as opposed to when they did not. Naturalistic driving studies suggest that pedestrians' gaze/eye contact combined with other pedestrian behaviors such as facial expression and assertiveness have important roles in successfully resolving driver-pedestrian interactions (Kong, Das, Zhang, & Xiao, 2021; Nathanael, Portouli, Papakostopoulos, Gkikas, & Amditis, 2018; Uttley, Lee, Madigan, & Merat, 2020). The relatively small number of studies so far suggests that more research is needed in the area of the effect of pedestrians' eye contact on drivers. Apart from investigating one-way communication (i.e., driver → pedestrian, pedestrian → driver), it would be worthwhile to examine reciprocal effects of eye contact on both drivers and pedestrians, taking into consideration that eye contact is both an input (i.e., reading the other agent's intentions) and a cue (i.e., signaling one's own intentions), cf. Myllyneva and Hietanen (2016). The notion of mutual attention in traffic is a topic that is receiving increased attention nowadays (Kotseruba, Rasouli, & Tsotsos, 2016; Onkhar et al., 2021).

Some limitations have to be acknowledged. In particular, participants were looking at a monitor, were not immersed in actual traffic, and did not experience physical risk. In real traffic, pedestrians might overlook drivers' eye contact or have particular incentives to cross the road, for example, being in a hurry (Cefkin, Zhang, Stayton, & Vinkhuyzen, 2019). The detectability of eye contact in our study may be better or worse than the detectability of eye contact in real traffic. In our study, participants watched videos with a resolution of 1280 × 720 pixels. Based on a side-by-side comparison of video frames, eye contact (i.e., head turn) was already distinguishable from no eye contact when the car was about 50 m away. However, when eye contact was present from the video start until a 20 m distance, only 38% of participants reported noticing it (see Video 8 in Fig. 7, left), which is modestly higher than the video without eye contact (Video 1, with 16% of participants reporting eye contact). These findings are supported by Fig. S3 in the Supplementary material, showing the percentage of trials in which the response key was pressed as a function of vehicle–pedestrian distance. It can be seen that the earliest deviation between eye contact from the video start and no eye contact arose at a distance of about 25 m. In other words, although eye contact may have been theoretically detectable at farther distances, in our experiment, pedestrians started noticing and reacting to the driver's eye contact at a vehicle–pedestrian distance of 20–25 m or less. Research in real-life conditions shows that the detectability of eye contact (Martin & Jones, 1982; examined distances between 0.6 and 4.0 m), facial affect (Hager & Ekman, 1979; examined distances between 30 m and 45 m) and the recognizability of individuals (Lampinen, Erickson, Moore, & Hittson, 2014; examined distances between 3.7 and 37 m) decreases with increasing distance. In the real world, pedestrians are not hampered by restrictions of screen resolution, but other factors may impair the detectability of eye contact at a distance, such as smog, blinding headlamps at night, shadows, and windshield glare (e.g., AlAdawy et al., 2019; Schneemann & Gohl, 2016). Thus, it remains to be investigated how well the present findings are applicable to actual on-road settings.

It is to be noted that the speed of the car was 13 km/h, representative of speeds in residential areas and shared spaces. At this low speed, there is presumably substantial uncertainty about what the car will do. It can be expected, based on related findings in the literature (Schneemann & Gohl, 2016), that if the car would approach at higher speeds, then perceived safety would be lower, and the effect of eye contact relative to implicit communication would be smaller or effective across a shorter time interval. It needs to be investigated how the results generalize to high-speed interactions.

It should also be noted that all conditions included a male driver with a presumed neutral or somewhat authoritative expression on his face. It would be relevant to investigate whether the results apply to different types of drivers as well. Previous research indicates that emotional expression (e.g., happy, sad, angry) has a strong effect on perceived dominance (Sutton, Herbert, & Clark, 2019) and may be interpreted differently cross-culturally (Arapova, 2016). Another limitation is that most of the participants were from Venezuela, followed by the United States, which may be regarded as an idiosyncratic subset of the world population. While the current study showed that the effects of drivers' eye contact generalize well between participants from different countries (see also Bazilinskyy et al., 2021), cultural differences in vehicle–pedestrian interactions may still exist. Norman (1992) anecdotally reflected on eye contact in Mexico City traffic: "*it was essential to avoid eye contact with other drivers. In the traffic circles of the city, the trick was to avoid letting the other drivers see that you had seen them. Once the other drivers knew that you knew they were there, they would proceed at high speed around the circle, completely ignoring your presence, because they knew that you knew that they were there, so they expected you to stop or slow down. … Most places in the United States don't let you get away with such games.*" (also see Vanderbilt, 2008, making the same point about driving in Mexico City). It would be interesting to explore these and other cultural differences in future research.

In relation to the above, some eye contact behaviors by the driver in our videos may be perceived as unnatural. Continuous eye contact by the driver throughout the car's approach is one such example. However, in the interest of systematically varying eye contact across the videos, it was necessary to include this scenario. Additionally, some eye contact behaviors by the driver that one might find realistic were deliberately excluded in our videos, such as multiple back-and-forth looks by the driver during the car's approach. These were undesirable in our experiment's design as they introduced a confounding variable – the number of eye contact attempts in a single interaction, which would have taken the focus away from eye contact duration and initiation/termination.

Another point of attention is that some participants may not have concentrated on the task or may have misunderstood the task. In particular, the results showed that about 8% of the participants inappropriately held the key when it was unsafe to cross, that is, when the vehicle drove away. The test questions and self-reports, on the other hand, revealed committed participants, with only 16 of 2000 participants failing the test questions (more than 2 mistakes out of 10 questions), and correct detection rates of eye contact close to 100% for videos in which there was eye contact when the car was close. Even though not all participants were fully committed to the task, this should not affect relative comparisons between the results for the different videos.

Finally, while not a shortcoming per se, it is worth noting that the current study is another entry in a series of papers we have published on pedestrians' crossing behavior that employed online crowdsourcing and our open-source simulator (Oudshoorn, De Winter, Bazilinskyy, & Dodou, 2021; Sripada, Bazilinskyy, & de Winter, 2021). As such, this paper bears similarities in its methods with its predecessors but also retains its novelty as an attempt to further the understanding of eye contact in traffic, since the prior works were instead concerned with eHMIs and vehicle motion.

In conclusion, this experiment demonstrated for the first time how drivers' eye contact and its timing affect the perceived safety of pedestrians. Results indicate that the presence and initiation of eye contact increase perceived safety, whereas the absence and termination of eye contact reduce perceived safety. The results also suggest that eye contact helps resolve crossing conflicts during a time window starting from the car's braking and ending with its subsequent take-off, and that a replacement for eye contact may be needed in the context of AVs. Future research could repeat the present study in a staged on-road design. Future research could also examine whether the driver's eye rotation or the driver's head rotation is a more dominant factor in pedestrians' perceived safety.

Author contributions

Onkhar, De Winter, Bazilinskyy, and Dodou jointly designed the experiment. Onkhar generated the videos, and Bazilinskyy set up and launched the study online. The analyses were performed by De Winter and Bazilinskyy. The manuscript was written by Onkhar and De Winter, with input provided by Dodou and Bazilinskyy. All authors read and approved the final manuscript.

Data availability

The videos shown, questions posed, data collected, and MATLAB code used for the analysis are available at: https://doi.org/10.4121/16866709.

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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Supplementary material

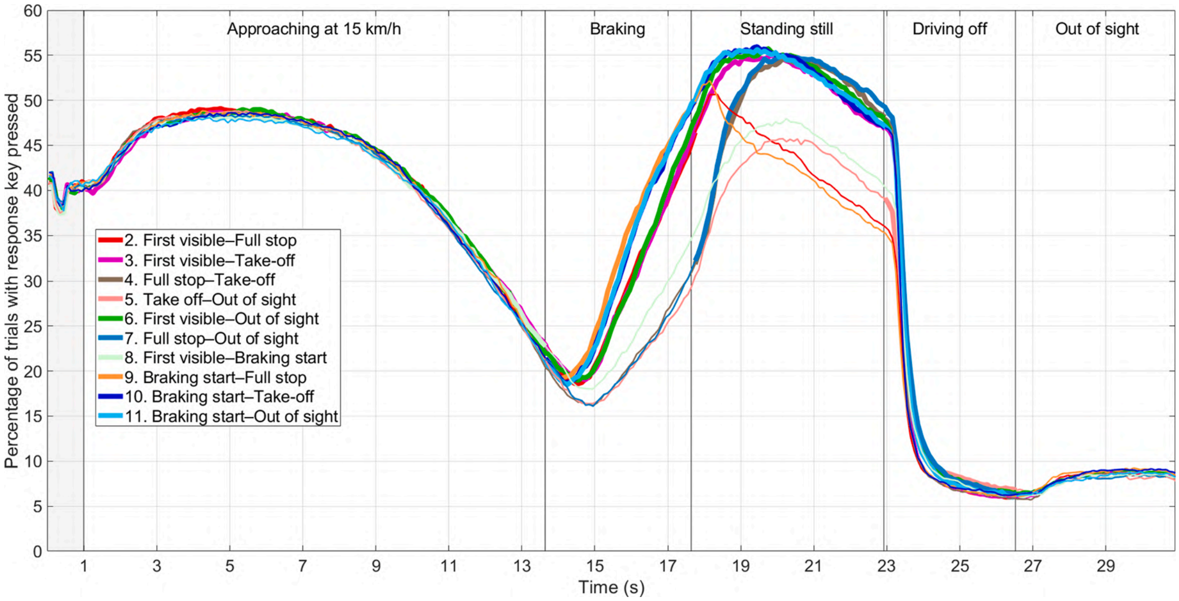

Fig. S1. Percentage of trials in which the response key was pressed for the videos that depict a yielding car. The bold sections of the lines indicate that there was eye contact at those moments.

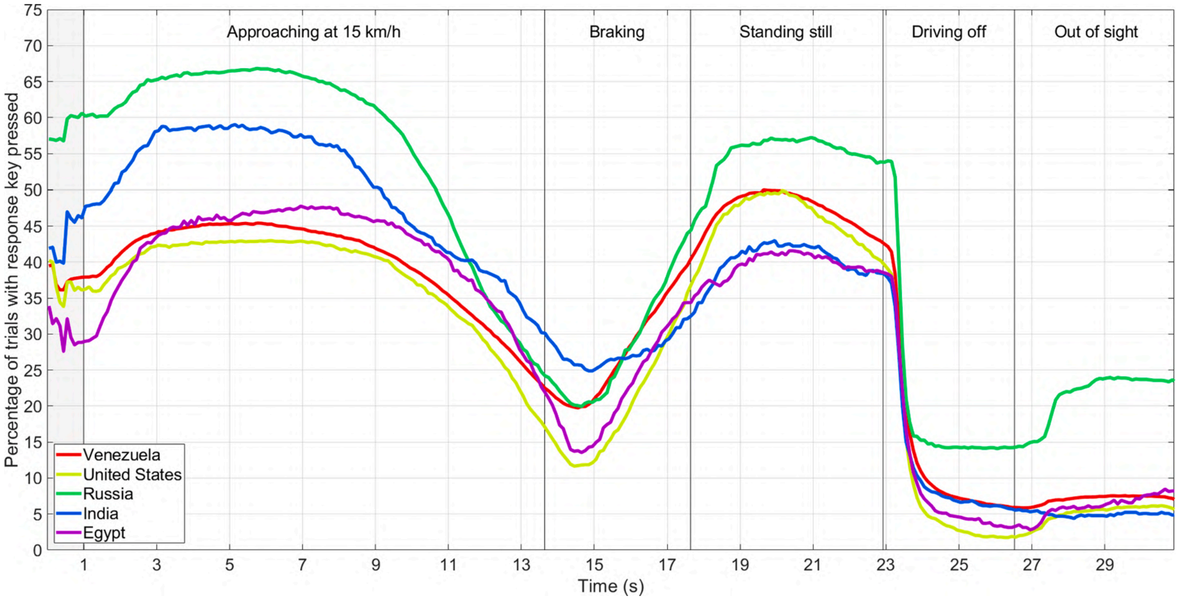

Fig. S2. Percentage of trials in which the response key was pressed for the videos that depict a yielding car for participants from different countries. The responses for the 11 videos were averaged.

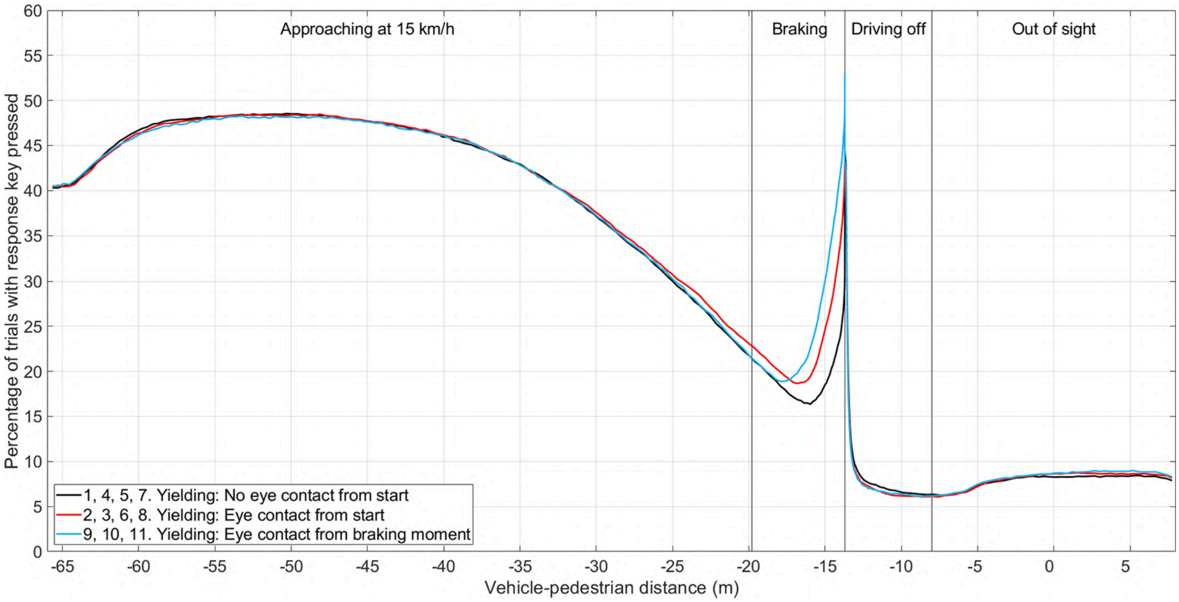

Fig. S3. Percentage of trials in which the response key was pressed for no driver's eye contact from the start of the video (Videos 1, 4, 5, and 7 averaged), driver's eye contact from the start of the video (Videos 2, 3, 6, and 8 averaged), and eye contact initiation when the car started to brake (Videos 9, 10, and 11 averaged) vs. vehicle-pedestrian distance.

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