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HACKING NONVERBAL COMMUNICATION BETWEEN PEDESTRIANS AND VEHICLES IN VIRTUAL REALITY

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Summary: We use an immersive virtual reality environment to explore the intricate social cues that underlie non-verbal communication involved in a pedestrian's crossing decision. We "hack" non-verbal communication between pedestrian and vehicle by engineering a set of 15 vehicle trajectories, some of which follow social conventions and some that break them. By subverting social expectations of vehicle behavior we show that pedestrians may use vehicle kinematics to infer social intentions and not merely as the state of a moving object. We investigate human behavior in this virtual world by conducting a study of 22 subjects, with each subject experiencing and responding to each of the trajectories by moving their body, legs, arms, and head in both the physical and the virtual world. Both quantitative and qualitative responses are collected and analyzed, showing that, in fact, social cues can be engineered through vehicle trajectory manipulation. In addition, we demonstrate that immersive virtual worlds which allow the pedestrian to move around freely, provide a powerful way to understand both the mechanisms of human perception and the social signaling involved in pedestrian-vehicle interaction.

INTRODUCTION

One of the challenging aspects in the design of autonomous vehicles is their communication with other, non-autonomous participants in traffic. Specifically the interaction with pedestrians requires clear communication of intent to allow for safe interactions (Rasouli et al., 2017). If autonomous vehicles will be more prevalent in the future, yielding to pedestrians under all circumstances (i.e. conservative driving behavior) may no longer be feasible as an interaction strategy. It has been shown that communicating the intention not to yield to pedestrians in certain traffic situations can significantly increase traffic flow (Gupta et al., 2018). Finding ways to communicate such intentions to pedestrians in a way that is easy to understand and assertive but safe for the pedestrian remains an open challenge of autonomous driving. In this paper we investigate how vehicle kinematics can be "hacked" to project intent and manufacture non-verbal communication cues that are actionable and interpretable by the interacting pedestrian.
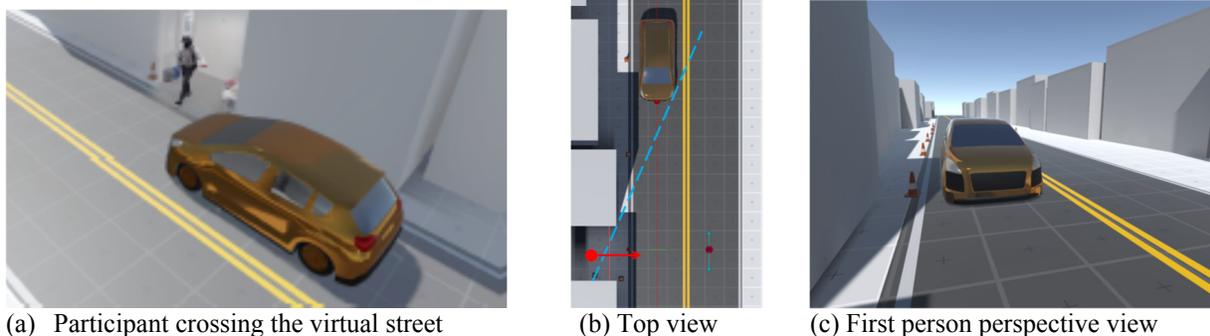
| (a) Participant crossing the virtual street | (b) Top view | (c) First person perspective view |

Figure 1: Visualization from various perspectives of the pedestrian crossing scenario in virtual reality. Fig. 1a visualizes the crossing experience. Fig. 1b shows a top down view of the intersection where the red dot indicates starting position and the blue dashed line indicates the line of sight threshold where the vehicle becomes visible. Fig. 1c provides the first person view of the subject in virtual reality based on the orientation of their head.

RELATED WORK

Pedestrian-vehicle-interactions in the form of road crossings have thus far mostly been studied as a problem of gap size and time to arrival, among the methods used are two-dimensional as well as curved screens (Oxley et al., 2005), announcing crossing intent while observing actual intersections (Schwebel et al., 2008) and immersive Virtual Reality (VR) (Clancy et al., 2006; Simpson et al., 2003). While these studies do of course consider vehicle movement, it is taken in a physical context and explored in terms of remaining distance or time for the pedestrian to reach the other side of the road.

Current research regarding the general interaction between autonomous vehicles and pedestrians has been focused on external Human Machine Interfaces (EHMIs). These concepts revolve around variations of displays, lights or projections placed inside or outside of the vehicle (Clamann et al., 2017; Deb et al., 2018; Dey et al., 2018; Mahadevan et al., 2018; Risto et al., 2017). Such mechanisms are intended to replace explicit gestures from the driver towards pedestrians intending to cross (Mahadevan et al., 2018; Risto et al., 2017). Such mechanisms have previously also been studied using virtual reality (Deb et al., 2018).

Table 1. Trajectories

Trajectory	Dist. (m)	TTA(s)	Velocity	Group	Description
deterrent_50kph_2s	27.78	2.0	constant	DETERRENT	Constant speed, low tta. Intended to deter participants from crossing.
deterrent_40kph_4s	11.11	4.0	constant	DETERRENT	Constant speed, low tta. Intended to deter participants from crossing.
rolling_yield_5m	14.58	9.0	decelerate	YIELD	Deceleration from 20 km/h to 3 km/h in 3s, deceleration completes 5m from the intersection with 6s remaining tta.
rolling_yield_8m	18.75	9.0	decelerate	YIELD	Deceleration from 20 km/h to 3 km/h in 3s, deceleration completes 8m from the intersection with 6s remaining tta.
15kph_acceleration	27.50	8.0	accelerate	15_KPH_SET	The vehicle accelerates from 1 km/h to 15 km/h in 3s.
15kph_deceleration	45.83	8.0	decelerate	15_KPH_SET	The vehicle decelerates from 45 km/h to 15 km/h in 3s.
15kph_uniform_speed	33.33	8.0	constant	15_KPH_SET	The vehicle approaches at a constant speed of 15 km/h with a tta of 8s
40kph_deceleration	162.67	8.0	decelerate	40_KPH_SET	The vehicle decelerates from 106.4 km/h to 40 km/h over 8 seconds.
40kph_acceleration	61.11	8.0	accelerate	40_KPH_SET	The Vehicle will accelerate from 15 km/h to 40 km/h over 8 seconds.
40kph_uniform speed	88.89	8.0	constant	40_KPH_SET	The vehicle drives by at a constant speed of 15 km/h with a tta of 8 s.
breaking_on_enter	12.00	4.8	other	OTHER	If the pedestrian enters the lane the vehicle decelerates 1.8 km/h with -1.3 m/s^2
conf_jump_rolling	12.00	15.0	other	SUBVERSION	The vehicle moves at a constant, slow pace. Looking at the vehicle or stepping short of 0.8 m from the curb will cause the vehicle to accelerate from 0.8 km/h to 3 km/h with 3.5 m/s^2 and then immediately decelerate back 0.8 m/s^2. This is repeated if the participant takes their gaze of the vehicle and then looks at it again.
conf_jump_stopped	6.00	NaN	other	SUBVERSION	The vehicle is stopped 6 m from the intersection. Looking at the vehicle or stepping short of 0.8 m from the curb will cause the vehicle to accelerate from to 3 km/h with 3.5 m/s^2 and then immediately decelerate back to a stop. This is repeated if the participant takes their gaze of the vehicle and then looks at it again.
conf_malicious_acc	20.00	NaN	other	SUBVERSION	The vehicle starts of moving steadily at 2 km/h from 20 m distance, which leads to a perceived tta of 36s. If the pedestrian is in the lane of travel and not looking at the vehicle it will accelerate with 3.5 m/s^2 to 8 km/h. This trajectory was designed to be openly malicious.
conf_distance_mirr	NaN	NaN	other	SUBVERSION	The vehicle mirrors the movements of the pedestrian. It will take the rolling average of the pedestrian's position over 0.66s with a delay of 1.8s and position itself at twice the pedestrian's distance from the point of intersection at that time. The vehicle "mirrors" the actions of the participant with a slight delay.

METHODS

As stated before our crossing scenarios were designed to gauge participant reactions towards different kinds of vehicle behaviors, with the goal to identify a difference in participant reactions between vehicle behaviors designed to comply with social expectations and vehicle behaviors designed to subvert social expectations.

To achieve this, the vehicles in our crossing scenarios followed different *trajectories*. For our purposes a trajectory describes the behavior of an approaching vehicle by determining the vehicle speed and acceleration for any given point in time. Some of these trajectories were interactive, while others were following a predetermined acceleration curve.
For the purpose of the aforementioned comparison we created two distinct groups of trajectories:

YIELD (green): Trajectories intended to comply with social expectations. These trajectories were designed to encourage pedestrians to cross the street. The vehicle slows down aggressively at a certain distance from the pedestrian but keeps rolling at a slow speed in order to elicit a decision for or against crossing.

SUBVERSION (red); Trajectories in this category were designed with the intention to subvert social expectations. The trajectories display varying degrees of unusual vehicle behaviors, some are just confusing while other are outright malicious. Trajectories in this set are dynamic and react to the actions of the pedestrian, in many cases by accelerating towards them.

In addition to these basic attempts at communication we included two sets of trajectories to study if basic changes in acceleration would yield different reactions. Each of these two sets consists of three trajectories with a common final approach velocity and identical TTA. One of the trajectories starts at a lower velocity and accelerates towards the terminal velocity, one trajectory which starts at a higher velocity and decelerates towards the terminal velocity and finally one trajectory with no acceleration change for comparison.

15 KPH SET (light blue): Three trajectories with 15 km/h as the final approach velocity of the vehicle, all with a TTA of 8s.
40 KPH SET (dark blue): Three trajectories with the final approach speed of 40 km/h and a TTA of 8s.
All trajectories up to this point shared a time to arrival between 8s and 9s, in order to make crossing decisions comparable between them. In addition to these we tested some trajectories with a lower TTA:

DETERRENT (grey): Trajectories designed to be challenging to impossible to cross safely, with a time to arrival as low as two seconds. As trajectories from almost all other groups have a TTA of 8s or more or more these are interspersed to prevent participants form believing that crossing the street is possible for all interactions, forcing them to carefully consider the decision to cross each time.

OTHER (purple): This group consists only of the trajectory BREAKING_ON_ENTER. Vehicles following this trajectory have a comparatively low TTA of 4.8s, but will slow down if the participant steps into the lane of travel.
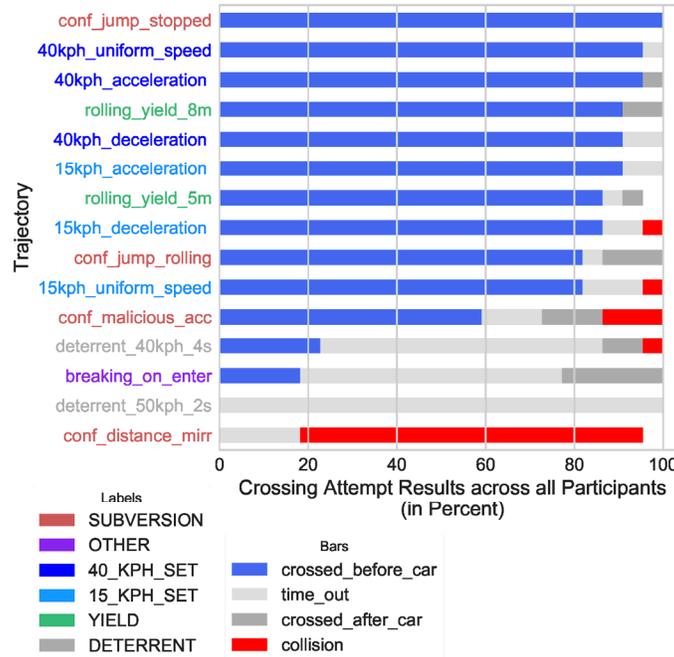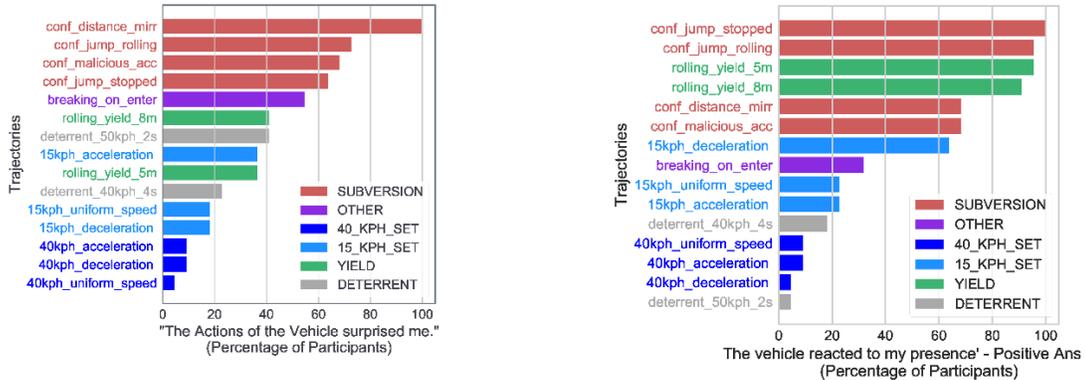
Figure 2: Results of crossing attempts. Label color indicates trajectory group.

(a) Participants perception of vehicle's reaction to their presence.

(b) Participants surprised by vehicle behavior.

Figure 3: Participant reaction towards trajectories.

Excluding our introductory scenarios we tested a total of 15 trajectories. The individual trajectories are described in Table 1. Participants completed each trajectory once. The number of trajectories was limited to keep the duration of one session within thirty minutes.

RESULTS AND DISCUSSION

Road Crossing Decisions

We recorded a total of 328 individual crossing attempts, excluding two training attempts per participant. Two crossing attempts could not be recorded due to technical issues and were excluded from analysis.

Excluding trajectories from the *DETERRENT* (grey) group as well as the trajectory CONF_DISTANCE_MIRR, as those trajectories were designed to inhibit road-crossing, that left 263 individual crossing opportunities to study crossing decisions. Out of those 263 attempts

participants crossed in front of the approaching vehicle 81.75% of the time. Four of the remaining cases resulted in collisions, the remainder are cases were participants decided not to cross or crossed after the vehicle.

In the following, "successful crossing" will refer to crossing attempts completed by entering the street in front of the approaching vehicle without any collisions.

This high success-rate for crossing opportunities fits the circumstances as for all of these interactions the TTA was 8s and participants were primed to cross if possible.

It is further consistent with the real-world observations in Rothenb¨ucher et al. (2016) where the majority of pedestrians crossed in front of a seemingly autonomous vehicle even if it had shown a transgression towards them during its approach.

Fig. 2 provides the success-rate for each trajectory, showing which percentage of participants crossed in front of the approaching vehicle, which percentage crossed after the vehicle had passed (or not at all) and which percentage of participants collided with the vehicle. Crossing decisions are an important metric given the long-term goal of influencing pedestrian crossing decisions as stated in. Furthermore deciding not to cross despite a sufficient gap-distance could be interpreted as a strong signal of a participant's reaction to the vehicle behavior in the given trajectory.

Looking at trajectories with a lower TTA (see Table 1 in Fig. 2 we can see observations of previous studies regarding crossing decisions hold true in our environment, as these trajectories with a low TTA (five seconds or less), such as the *DETERRENT* (grey) trajectories as well as BRAKING_ON_ENTER show the least amount of crossings completed successfully. This is an argument towards the perceived realism of our simulation.

CON_DISTANCE_MIRR has a high number of "collisions" as this trajectory did not offer any other solution to the scenario except waiting for the time limit to pass.

Reacting to Presence
Given the overall goal of using vehicle kinematics as a means for communicating with pedestrians it is important that pedestrians perceive actions taken by the vehicle as a reaction to their presence, otherwise communication cannot occur, at least on a conscious level.

Fig. 3a shows which percentage of participants believed the actions of the vehicle were a reaction to their presence for each trajectory. This was self reported by participants after each crossing attempt.

It can be observed that the trajectories belonging to the two sets designed to communicate with pedestrians, the *SUBVERSION* (red) set as well as the *YIELD* (green) set, were indeed perceived as interactive by the largest percentage of participants. Furthermore we see that trajectories designed without the intention to communicate, such as the *DETERRENT* (grey) trajectories as well as a trajectories featuring a "uniform speed" rank a lot lower in comparison. This strongly supports the possibility that trajectories can be used to intentionally convey information.

Looking closer at the four trajectories belonging to the *SUBVERSION* (red) set, we a difference between the trajectories meant to be irritating CONF_JUMP_STOPPED, CONF_JUMP_STOPPED and the hostile trajectories CONF_DISTANCE_MIRR and CONF_MALICIOUS_ACC, with the latter ones ranking lower in perceived interactivity. This is consistent with comments made by some participants who did not consider malicious behavior to be a possibility, providing statements such as "*The fact that it accelerated into my path made me believe that was [originally] stopping for a factor that was not me*" (CONF_DISTANCE_MIRR). Instead, such behavior was often attributed to negligence. In terms of breaking social conventions this would imply that the malicious behavior is so far removed from the expected norm that it is not even considered as a possibility for these interactions, which points towards the existence of a social norm.

Subverted Expectations. To determine if we succeeded in subverting the expectations of street-crossing interactions we queried our participants after every attempt if they were surprised by the behavior of the vehicle. Fig. 3b shows for each trajectory which percentage of participants were surprised by the actions of the vehicle.

The trajectories from the *SUBVERSION* (red) set were perceived as surprising by a greater percentage of participants than all other trajectories. I can therefore be stated that the *SUBVERSION* (red) trajectories succeeded in their design goal of subverting pedestrian expectations, which in combination with the participant feedback we received suggests a social component in the interpretation of vehicle kinematics exists.

15_KPH_ACCELERATION was perceived as surprising by twice as many participants than the other two trajectories from the same set (*15_KPH_SET*, light blue), suggesting that accelerating in the presence of pedestrians might be considered to be outside of the social norm, however multiple participants also cited the slow initial speed of the vehicle as being unusual and the reason for their confusion.

CONCLUSION

Our goal was to study if pedestrians derive social clues from vehicle kinematics, if such interactions could be studied in virtual reality and to estimate the potential in using vehicle kinematics for effective communication in autonomous vehicles. We confronted our participants with different vehicle kinematics, some of which were designed to subvert social expectations while others were intended to conform with expectations. We were able to show that our participants perceived the changes in vehicle motion as a direct reaction to their presence. We were able to show that vehicles following intentionally atypical trajectories let to confusion and in some cases mistrust among participants, while more conventional trajectories did not. Previously vehicle kinematics in the context of pedestrian interactions have been viewed as a matter of physics, with pedestrians assessing if the approaching vehicle leaves them enough time to cross its path of travel (evaluation of gap distance). We believe that future work will enable the use of vehicle kinematics to communicate driving intentions to pedestrians.

ACKNOWLEDGMENT

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