Effects of Pedestrian Behavior, Time Pressure, and Repeated Exposure on Crossing Decisions in Front of Automated Vehicles Equipped with External Communication

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Figure 1: The automated vehicles and the external communication concepts used in the studies.

ABSTRACT

Automated vehicles are expected to substitute driver-pedestrian communication via LED strips or displays. This communication is expected to improve trust and the crossing process in general. However, numerous factors such as other pedestrians' behavior, perceived time pressure, or previous experience influence crossing decisions. Therefore, we report the results of a triply subdivided Virtual Reality study (*N*=18) evaluating these. Results show that external communication was perceived as hedonically pleasing, increased perceived safety and trust, and also that pedestrians' behavior affected participants' behavior. A timer did not alter crossing behavior, however, repeated exposure increased trust and reduced crossing times, showing a habituation effect. Our work helps better to integrate research on external communication in ecologically valid settings.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**.

KEYWORDS

External communication; Autonomous vehicles; Chicken Game; Pedestrian Behavior; eHMI.

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1 INTRODUCTION

Automated vehicles (AVs) will change traffic [36] and, most likely, interaction in traffic [17, 25, 57] fundamentally. The interaction will be altered because AVs could be equipped with loudspeakers [19], displays [16], LED strips [26], windshield displays [27] or other means for communicating with other road users. Other research investigated their, and found mostly positive, effects on trust, clarity, hedonic qualities, and crossing behavior. While most work assessed the communication in simple one AV-on-one pedestrian scenarios [22] and did not vary environmental factors [66], Colley et al. [21] stated that previous work has shown that there are at least **38** factors that influence crossing decisions. These can be grouped into physical context, dynamic factors, traffic characteristics, social factors, demographics, abilities, and characteristics. Some of these factors are person, culture-, or country-dependent (e.g., demographics, social norms, and law compliance) and some of these have been evaluated in the context of external communication of AVs (e.g., age [23]).

However, while external communication is designed with improved safety in mind and will be encountered with other pedestrians present, effects of *other Pedestrian Behavior* [37] and *Past experience* [66] have not yet been evaluated in the context of external communication of AVs. Especially the effect of *Past experience* is of interest with the Game theory approach of the "Chicken Game", which states that a cost function determines whether pedestrians will cross and that this cost function alters significantly with the introduction of AVs, thereby leading to pedestrians always crossing in front of AVs without hesitation [4, 5, 40]. Additionally, some external communication concepts propose to include information about an imminent start of the AV (see, for example, concept 6 "The Countdown Timer" [28]. While this increases behavior transparency to the pedestrian, its effects are unclear and could even lead to dangerous behavior as a potential effect of *Perceived Time Pressure* (e.g., quickly running in front of an AV to save time).

Therefore, we conducted a triply subdivided Virtual Reality (VR) study (*N*=18). In the three scenarios, participants crossed the street (1) with another pedestrian group crossing prematurely (evaluating the effect of *other Pedestrian Behavior*), (2) another person crossing in front of an AV equipped with a timer (evaluating the effect of *Perceived Time Pressure*), or (3) in front of an infinite number of non-yielding AVs (evaluating the effect of *Past experience*). We found that we could influence the participants' behavior via the other pedestrians and that external communication was considered useful. However, no interaction effects were found. The timer (used for *Perceived Time Pressure*) did not lead to more dangerous behavior but was seen as a useful tool for making an informed crossing decision. Repeated exposure towards non-yielding AVs showed a quick habituation and adjustment of behavior (e.g., faster crossing).

Contribution Statement: This work provides insights into three scenarios regarding the external communication of AVs. The scenarios include the behavior of another pedestrian group, another single pedestrian crossing in front of an AV with a timer, and non-yielding AVs. The results of a VR study with *N*=18 participants showed that eHMIs are useful, simulated pedestrian behavior affects participants, that a timer does not lead to dangerous behavior, and that repeated exposure will likely lead to quick habituation and behavior adjustment. Our work helps in introducing AVs safely into general traffic.

2 RELATED WORK

This work is based on research in the field of crossing and external communication of AVs.

2.1 Street Crossing Factors

While numerous factors influence the crossing [21, 66], in this work, we describe the effects of *other Pedestrian Behavior*, *Group Size*, *Social Status*, and *Past Experience*.

Yagil [77] showed that pedestrians obey (or disobey) the law depending on the presence of other pedestrians' behavior. While Lefkowitz et al. [56] showed this imitation to be dependent on the appearance of the other pedestrian. When the confederate wore a fancy outfit, imitation was more prevalent. However, Dolphin et al. [31] found that social status and gender do not affect imitation. They claim that the *group size* better predicts imitation (smaller group size, higher imitation). Nonetheless, we implemented our non-player characters to resemble middle- to upper-class citizens. Regarding group size, Heimstra et al. [44] found in a naturalistic study that children cross the street in more than 80% of the cases in groups. Crossing in a group lets pedestrians be more careless and accept shorter gaps between vehicles [42, 69, 73, 75]. Therefore, we simulated the behavior of other pedestrians to study whether the participants would rely on the external communication or would follow the group's behavior.

Deb et al. [24] and Hulse et al. [49] argue that the perceived risk of AVs could depend on factors such as pedestrians' age, gender, past experience, level of law compliance, location, and social norms. Therefore, these factors should be studied with the concepts developed in the novel research area of external communication of AVs.

2.2 External Communication of Automated Vehicles

Currently, unclear situations and traffic-related problems are often overcome via gestures and eye-contact [65]. While the frequency of necessary explicit communication might be low [55], external communication of AVs, also called external Human-Machine-Interfaces (eHMIs), is one proposed solution to enable such communication between a potentially driverless AV and pedestrians or other vulnerable road users [45].

External communication concepts have been grouped based on modality, message type, and communication location [17, 18]. Colley and Rukzio [17] distinguish eight message type classes: Instruction, Command, Advisory, Answer, Historical, Predictive, Question, and Affective. The *communication location* defines whether the communication occurs on the vehicle, the personal device, or the infrastructure (e.g., sidewalk). The position can be further broken down, for example, whether the communication occurs on the windshield, hood, or bumper. Dey et al. [29] showed that the eye-gaze of pedestrians shifts from the bumper to the windshield as a vehicle approaches. Additionally, situation parameters such as communication relationship (one-to-one, one-to-many, many-to-one, and many-to-many), acoustic noise, or communication partner (e.g., pedestrian or cyclist) should be considered [17]. Work on eHMI focused on children [7, 23], people with vision [19, 20] or mobility impairments [3], general pedestrians [2, 28, 57], and bicyclists [48]. Several modalities such as displays [39], LED strips [39, 58] (and windshield displays [27]), movement patterns [78], projections [1, 63], external devices such as smartphones [46], auditory or tactile cues [60] and combinations [60] or enhanced infrastructure [72] were proposed. Additionally, eHMIs were proposed for automated delivery trucks [15], to warn distracted pedestrians [14], and as personalization possibilities [13].

Most work found positive effects of eHMIs. For example, Dey et al. [27] evaluated an eHMI with distance-dependent information (i.e., indicating when the AV will come to a halt). This improved pedestrians' comprehension of the AV's intention and increased willingness to cross. Colley et al. [19] found that people with vision impairment preferred speech-based communication giving clear commands compared to only communicating the intention or no communication. Regarding the communication design, prior work found that polite (compared to dominant) [53] external communication and feedback communication [9] lead to higher trust and acceptance.

However, Deb et al. [23] found that children relied entirely on eHMIs, thereby revealing the necessity for "proper promotion and training to prepare children" [23, p. 155].

The focus on the research on eHMIs seems to shift towards unresolved questions such as overtrust [47] (i.e., pedestrians trust eHMIs even prior to their first encounter), scalability [22] (i.e., current evaluations focus mostly on one-on-one communication), or social aspects of eHMIs [9, 53, 67, 68].

While previous work showed positive effects of eHMIs, the question remains when they are necessary of when implicit cues (e.g., velocity changes) suffice [61, 62].

Based on previous work, we, therefore, employed simulated LED strips. These are technologically feasible (compared to, e.g., projections or windshield displays) and do not necessitate language knowledge (compared to text). While *text* was reported to be least ambiguous [6, 23], this is not universally comprehensible, for example, for children or foreigners. As our primary goal was to evaluate the different scenarios with a general population, we avoided auditory and tactile eHMIs that were found to be best suited for people with impairments [19]. To be best of our knowledge, we are the first to incorporate the crossing-related behavior of other pedestrians and the effect of repeated exposure in research on external communication of AVs.

3 EXPERIMENT

To evaluate the effects of eHMIs, the behavior of other pedestrians, and non-yielding AVs, we designed and conducted a within-subject study with *N*=18. Our research was focused both on the objective behavior as well as the subjective assessment of the eHMIs. Therefore, this study was guided by the research questions (RQ):

- *RQ1: What impact do the variables "eHMI" and "pedestrian group behavior" have on pedestrians in terms of (1) behavior, (2) mental workload, (3) trust, (4) perceived safety, and (5) communication quality?*
- *RQ2: What impact does the variable "eHMI timer" have on pedestrians in terms of (1) behavior, (2) mental workload, (3) trust, (4) perceived safety, and (5) communication quality?*
- *RQ3: What impact does the variable "prior experience" have on pedestrians in terms of (1) behavior, (2) mental workload, (3) trust, (4) perceived safety, and (5) communication quality?*

3.1 Materials

To answer the three research questions and as briefly explained in the introduction, we designed three scenarios. We modeled the scenarios in Unity version 2020.3.1f10 [74]. The AVs are equipped with a turquoise LED attached in the center at the top of the windshield serves as a status indicator as suggested by Faas et al. [35]. Turquoise is a suggested color for AVs as it is highly visible and does not carry traffic-relevant meaning [76]. All scenarios take place in a city, and the pedestrian starts either at the curb of a street (scenarios "Pedestrian Group Behavior" and "Non-Yielding Automated Vehicles") or a little way back (scenario "Timer"). Due to space and tracking constraints, we added a gain factor in the straightforward and sideways (not height) axis. A gain of 1.7 (meaning 1 m traversed in reality equals 1.7m traversed in VR) was employed. This gain factor was only applied to the participant.

3.1.1 External Communication Concept. The external communication concept is based on a LED strip attached to the lower front of the AV. The entire LED strip blinks turquoise when the AV communicates that the pedestrian can cross (see Figure 1; based on work by Dey et al. [26]). The concept for communicating that the AV will drive through uses yellow and employs the animation starting in the center and moving to the edges (see Figure 1).

3.1.2 Scenario "Pedestrian Group Behavior". In this scenario, there is mixed traffic as it is likely that the introduction of AVs will be a continuous process. The pedestrian stands at the curb wanting to cross the street. We investigated two factors in this scenario: the presence of an eHMI on the AV (yes/no) and the presence of a group of pedestrians (yes/no). The group of pedestrians consisted of two men and one woman standing at the curb and directly starts to cross. The relation (friends, colleagues, strangers, etc.) to the other pedestrians is not introduced to the participant. The participant was placed left from the group to enable a clear view of the AV. The first vehicle approaching from the left is an AV. If in a condition with eHMI, this first AV indicates that it will not yield (see Figure 1). After 15s, the next approaching AV indicates to come to a halt (see Figure 1). The traffic on the far lane did not communicate to yield but vehicles came to a halt if the participants or the simulated group were on the road. The simulated pedestrian group ignores the AV's intention not to yield to determine if the effect of eHMI is higher than the behavior (and, thus, possible imitation) of the other pedestrians. This scenario is potentially dangerous. However, jaywalking despite oncoming traffic is common today (e.g., see [71]) and, especially in these scenarios, it is important to understand the effect eHMIs can have to improve traffic safety. The AV was introduced as follows (text in brackets: depending on the presence of an eHMI):

> *The autonomous vehicles will (not) communicate with you via an extra display.*

3.1.3 Scenario "Timer". External communication of AVs is intended to make traffic safe. Therefore, eHMIs should avoid provoking potentially dangerous behavior. For example, in the project "IQ Mobility" of Scania, the question arose which messages should be conveyed by an automated bus [33]. While the message "I am standing still" could help pedestrians cross safely, it was discussed whether this information should incorporate temporal information (i.e., how long will the vehicle stand still). This information could help pedestrians assess whether it is safe to cross and provoke them to cross the street quickly. Therefore, in the scenario "Timer", the participant sees another pedestrian crossing in front of a halted AV. The participant was placed a little further back to ensure the necessity to walk quickly to actually cross the street in front of the AV, thus, provoking potentially dangerous behavior. Here, there are two conditions, one, in which the AV is equipped with a "timer" on the hood as proposed by Dey et al. [28] (see Figure 1). The timer has a duration of 5 seconds, indicated by the 5 circles vanishing. In case of a pedestrian still crossing or standing in front of the AV, the timer could restart the countdown. However, this would lengthen the standing time. Nonetheless, the AV must not harm people, therefore, in our case, the AV would remain at its position but accelerate as soon as possible. In the other case, there is no timer present. The AV was introduced as follows (text in brackets only when a timer was present):

> *An autonomous vehicle stands at the road and lets a pedestrian cross. (The vehicle communicates the time until the pedestrian can continue with a timer.)*

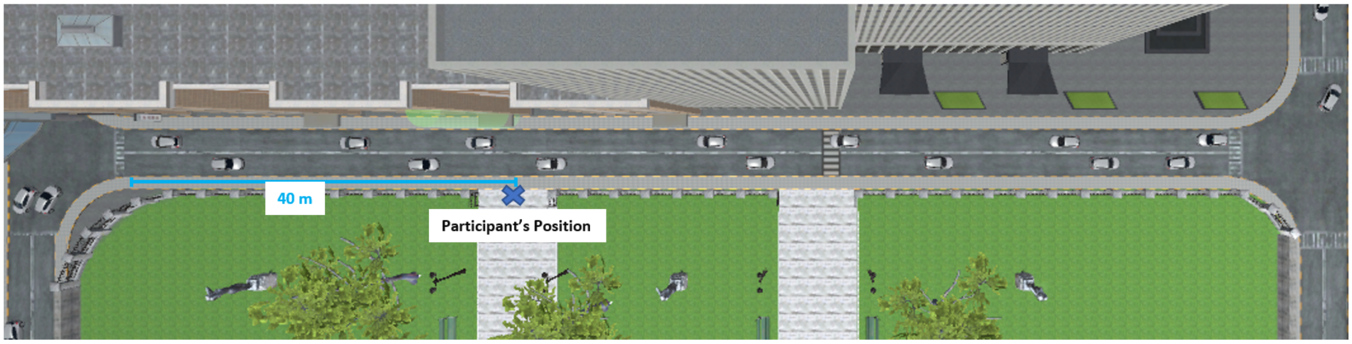

Figure 2: Overview of the scene used in the three scenarios.

3.1.4 Scenario "Non-Yielding Automated Vehicles". The Game Theory approach of the "Chicken Game" was already used to describe the interaction between AVs and pedestrians [4, 5, 40]. In this approach, there are two actors with different cost and benefit functions. In the case of an AV, stepping in front of an AV was postulated to have no cost, as the AV must stop. Therefore, it could be assumed that pedestrians will always cross in front of AVs. However, this theoretical approach was not yet empirically tested. Therefore, we designed the scenario "non-yielding automated vehicle". In this scenario, only AVs pass the pedestrian to be able to study solely the effect of eHMIs in conjunction with *Past experience*. All AVs signal that they do not want to yield to the pedestrian. The distance between the AVs per lane was at max 40m with a velocity of 50 km/h (see Figure 2). If a participant steps in front of an AV, the AV stops and flashes the LED strip red. The AVs were introduced as follows:

> *The autonomous vehicles equipped with an emergency braking system will communicate with you via an extra display. Whether the autonomous vehicles stop is random.*

Participants encountered this scenario three times to evaluate learning effects.

3.2 Measurements

The simulation logged the position with 50 Hz, the number of collisions with cars, the time in the park, on the sidewalk, on the street, and the total duration.

We employed the mental workload subscale of the raw NASA-TLX [43] on a 20-point scale ("How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?"; 1=Very Low to 20=Very High). Additionally, we used the subscales *Predictability/Understandability* (*Understanding* from here) and *Trust* of the *Trust in Automation* questionnaire by Körber [51]. Understanding is measured using agreement on four statements ("The system state was always clear to me.", "I was able to understand why things happened."; two inverse: "The system reacts unpredictably.", "It's difficult to identify what the system will do next.") using 5-point Likert scales (1=Strongly disagree to 5=Strongly agree). Trust is measured via agreement on equal 5-point Likert scales on two statements ("I trust the system." and "I can rely on the system."). Also, participants rated their perceived safety using four 7-point semantic differentials from -3 (anxious/agitated/unsafe/timid) to +3 (relaxed/calm/safe/confident) [34]. Regarding the communication quality, the short version of the User Experience Questionnaire (UEQ-S) [70] with the subscales pragmatic and hedonic quality was used. Additionally, participants were asked on 7-point Likert scales about several aspects of the communication: unfriendly/friendly, impolite/polite, ambiguous/unambiguous, unnatural/natural, machine-like/human-like (see [64]), inadequate/adequate (see [67]).

Finally, participants assessed the communication (intention to stop, intention not to stop, and timer) regarding necessity and reasonability on individual 7-point Likert scales and gave open feedback.

3.3 Procedure

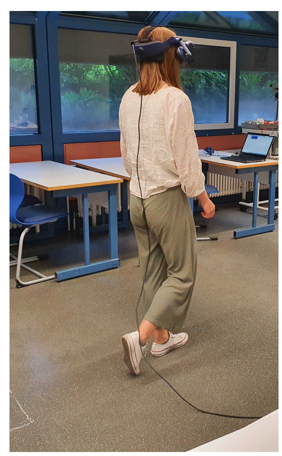

Figure 3: Participant walking with the Vive Pro Eye headset.

First, participants were introduced to the study procedure and the VR scene. Here, the eHMIs for coming to a halt (see Figure 1) and driving through (see Figure 1) were explained to avoid novelty effects. Then, we introduced the setting as:

> *You are standing on a two-lane road. There are only electric cars on this road. In addition, there is mixed traffic on this road, i.e., there are both manually controlled*

and highly automated vehicles on the road. One of the vehicles will stop to let you cross the road. This vehicle will communicate with you differently depending on the condition. The automated vehicles are equipped with an emergency braking system.

They then signed informed consent and could adjust the headset. Afterward, participants first experienced the four conditions of the scenario "Pedestrian Group Behavior", then the two of scenario "Timer", and finally the three of scenario "Non-Yielding Automated Vehicles" (see Figure 4). This order was chosen so that participants were most familiar with AVs in the last scenario. Within the scenarios "Pedestrian Group Behavior" and "Timer", the order of the conditions was based on a balanced Latin square. Participants were instructed in every scenario as follows:

You want to cross the road. Your destination is the green marked zone on the other side of the road.

After each trial, participants answered the questionnaires described in subsection 3.2 on a separate laptop shown in the background of Figure 3. Therefore, participants answered the same questionnaire nine times (four times for scenario "Pedestrian Group Behavior", two times for scenario "Timer", and three times for scenario "Non-Yielding Automated Vehicles". The conditions are listed in Table 1.

The study took approximately 55 min. Participants were compensated with 10€. The study was conducted in German. The hygiene concept for studies regarding COVID-19 (ventilation, disinfection, wearing masks) involving human subjects of our university was applied.

4 RESULTS

In the following, we report the results per scenario.

4.1 Data Analysis

We analyzed each of the three scenarios "Pedestrian Group Behavior", "Timer", and "Non-Yielding Automated Vehicles" independently. Prior to every statistical test, we checked the required assumptions (normality distribution and homogeneity of variance assumption). Conditions were either compared via Friedman's (non-parametric) or a repeated-measures ANOVA. For non-parametric data, we used the non-parametric ANOVA (NPAV) as implemented by Lüpsen [59]. We used Bonferroni correction for post-hoc tests. R in version 4.1.1 and RStudio in version 1.4.1717 was employed. All packages were up to date in September 2021.

4.2 Participants

We determined the required sample size via an a-priori power analysis using G*Power in version 3.1.9.7 [38]. To achieve a power of .8 with an alpha level of .05, 18 participants should result in an anticipated medium to high effect size (0.29 [41]) in a within-factors repeated-measures ANOVA with four measurements.

Therefore, we recruited N=18 participants (7 female, 11 male). Participants were, on average, M=31.28 (SD=10.53; range: 21 to 56) years old. Participants stated that their highest educational level was College (7), High School (7), secondary school (2), or Vocational training (2). Regarding their employment status, nine participants stated to be students at a university, while nine indicated to be employees. On 5-point Likert scales (*1 = Strongly Disagree — 5 = Strongly Agree*), participants showed medium interest in AVs (M=3.78, SD=1.31), believed AVs to ease their lives (M=3.78, SD=0.94), and were rather positive whether AVs become reality by 2031 (M=3.72, SD=1.78).

4.3 Scenario "Pedestrian Group Behavior"

4.3.1 Mental Workload, Trust, Perceived Safety. The NPAV found a significant main effect of *eHMI* on mental workload ($F(1, 17) = 7.35$, p=0.015). Mental workload was significantly lower with (M=6.28, SD=3.99) than without an eHMI (M=8.53, SD=5.19). The NPAV also found a significant main effect of *eHMI* on trust ($F(1, 17) = 12.78$, p=0.002). Trust was significantly higher with (M=3.89, SD=0.90) than without an eHMI (M=3.08, SD=1.24). A repeated-measures ANOVA found a significant effect of *eHMI* on understanding ($F(1, 17) = 8.22$, p=0.01). Understanding was significantly higher with (M=3.95, SD=0.73) than without an eHMI (M=3.15, SD=1.13). The NPAV found no significant effect on perceived safety.

4.3.2 Communication Quality. The NPAV found a significant main effect of *eHMI* on hedonic quality ($F(1, 17) = 24.56$, p<0.001). Hedonic quality was significantly higher with (M=5.27, SD=1.07) than without an eHMI (M=4.03, SD=1.42).

The NPAV also found a significant main effect of *eHMI* on pragmatic quality ($F(1, 17) = 10.03$, p=0.006). Pragmatic quality was significantly higher with (M=5.81, SD=1.15) than without an eHMI (M=4.33, SD=1.37).

Additionally, the NPAV found a significant main effect of *eHMI* on friendliness ($F(1, 17) = 10.03$, p=0.006), politeness ($F(1, 17) = 4.51$, p=0.049), human-likeness ($F(1, 17) = 5.25$, p=0.035), unambigousness ($F(1, 17) = 14.54$, p=0.001), naturalness ($F(1, 17) = 5.44$, p=0.032), and appropriateness ($F(1, 17) = 41.65$, p<0.001). In all cases, the values were significantly higher with the eHMI.

The NPAV found a significant main effect of *pedestrian presence* on friendliness ($F(1, 17) = 8.24$, p=0.011). Friendliness of communication was rated higher with (M=5.39, SD=1.29) than without (M=4.56, SD=1.36) pedestrians present. The NPAV also found a significant main effect of *pedestrian presence* on politeness ($F(1, 17) = 9.07$, p=0.008). Politeness of communication was rated lower with (M=2.69, SD=1.37) than without (M=3.44, SD=1.40) pedestrians present. The NPAV found a significant main effect of *pedestrian presence* on naturalness ($F(1, 17) = 5.58$, p=0.03). Naturalness of communication was rated higher with (M=4.61, SD=1.40) than without (M=4.11, SD=1.24) pedestrians present.

The NPAV also found a significant interaction effect of *pedestrian presence* X *eHMI* on naturalness ($F(1, 17) = 4.48$, p=0.049; see Figure 5). While naturalness was approximately equal with and without eHMI without pedestrians, with pedestrians, the naturalness of the communication was rated higher with an eHMI.

4.3.3 Collisions and Duration. In total, six collisions with cars occurred. A Friedman's ANOVA (χ^2 (3)=1.22, p=0.748) found no significant differences between the conditions on the number of collisions. Also, an NPAV found no significant effects (*eHMI*, *pedestrian presence*, or interaction effects) on the number of collisions. A Friedman's ANOVA found no significant differences between the

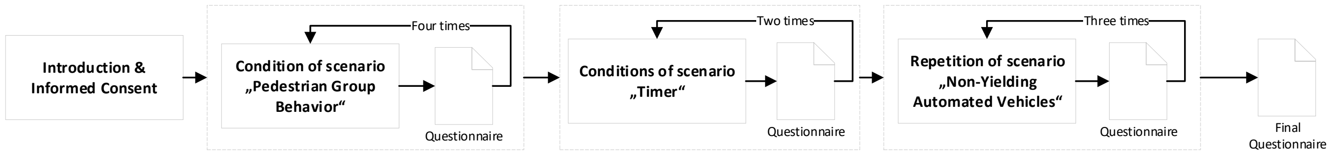

Figure 4: The study procedure.

Scenario	Condition 1	Condition 2	Condition 3	Condition 4
"Pedestrian Group Behavior"	no eHMI no group	with eHMI no group	no eHMI with group	with eHMI with group
"Timer"	without Timer	with Timer		
"Non-Yielding Automated Vehicles"	Run 1	Run 2	Run 3	

Table 1: Conditions of the three scenarios.

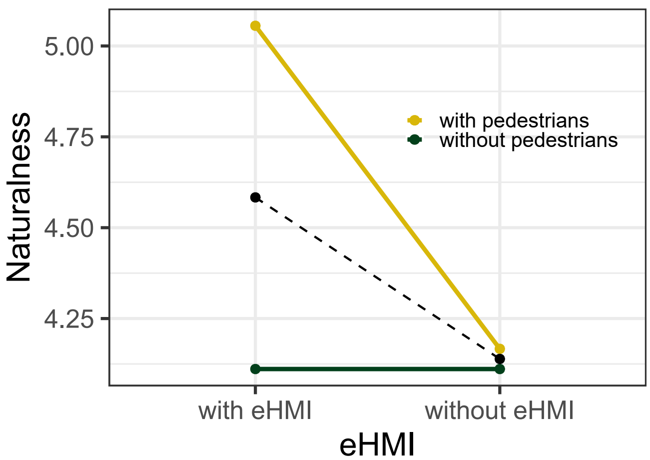

Figure 5: IE of *pedestrian presence* X *eHMI* on naturalness.

conditions on the spent time in the park or on the street. The NPAV also found no significant effects on the spent time in the park or on the street.

The NPAV found a significant main effect of *pedestrian presence* on time on the sidewalk ($F(1, 17) = 26.34$, p<0.001). Participants spent significantly more time on the sidewalk when no pedestrians were present (*M*=14.62, *SD*=9.74) than with pedestrians (*M*=9.23, *SD*=6.40).

The NPAV also found a significant main effect of *pedestrian presence* on total duration ($F(1, 17) = 5.23$, p=0.035). Total time was significantly higher without (*M*=22.00, *SD*=11.39) than with pedestrians (*M*=16.50, *SD*=6.92). Finally, the NPAV found a significant main effect of *eHMI* on total duration ($F(1, 17) = 4.64$, p=0.046). Total time was significantly higher without (*M*=20.62, *SD*=8.75) than with an eHMI (*M*=17.89, *SD*=10.63).

4.4 Scenario "Timer"

4.4.1 Mental Workload, Trust, Perceived Safety. A student's t-test (t(17)=2.42, p=0.027) showed that mental workload was significantly lower with the timer (*M*=6.00, *SD*=4.43) than without (*M*=8.44, *SD*=4.89). A Wilcoxon signed-rank test showed no significant differences for perceived safety (p=0.099). A student's t-test showed no significant differences for trust (p=0.582). A Wilcoxon signed-rank test showed no significant differences for understanding (p=0.067).

4.4.2 Communication Quality. A student's t-test (t(17)=-2.81, p=0.012) showed that hedonic quality was rated significantly higher with the timer (*M*=5.13, *SD*=1.24) than without (*M*=4.06, *SD*=1.29). A student's t-test (t(17)=-2.30, p=0.034) also showed that pragmatic quality was rated significantly higher with the timer (*M*=5.07, *SD*=1.55) than without (*M*=4.11, *SD*=1.39).

A Wilcoxon signed-rank test (p=0.009) showed that politeness was rated significantly lower with (*M*=2.33, *SD*=1.14) than without (*M*=3.61, *SD*=1.46) the timer.

Student's t-tests and Wilcoxon signed-rank tests found no significant differences for friendliness (p=0.149), human-likeness (p=0.968), unambiguousness (t(17)=-2.05, p=0.056; with timer higher), naturalness (p=1.00), and appropriateness (p=0.261).

4.4.3 Collisions and Duration. One collision with a car occurred in the condition without the timer. Therefore, no significant differences between the conditions with and without a timer were found.

Wilcoxon signed-rank and student's t-tests showed no significant differences for time in the park (p=0.571), on the sidewalk (p=0.408), on the street (p=0.459), or the total time (t(17)=0.65, p=0.523).

4.5 Scenario "Non-Yielding Automated Vehicles"

4.5.1 Mental Workload, Trust, Perceived Safety. A repeated-measures ANOVA found a significant difference in the mental workload ($F(1.94, 33.04) = 5.85$, p=0.007) between the three repetitions in the scenario "Non-Yielding Automated Vehicles". Post-hoc tests showed that the mental workload was significantly lower in the third repetition (*M*=7.89) compared to the first (*M*=10.50) and the second (*M*=10.06) repetition.

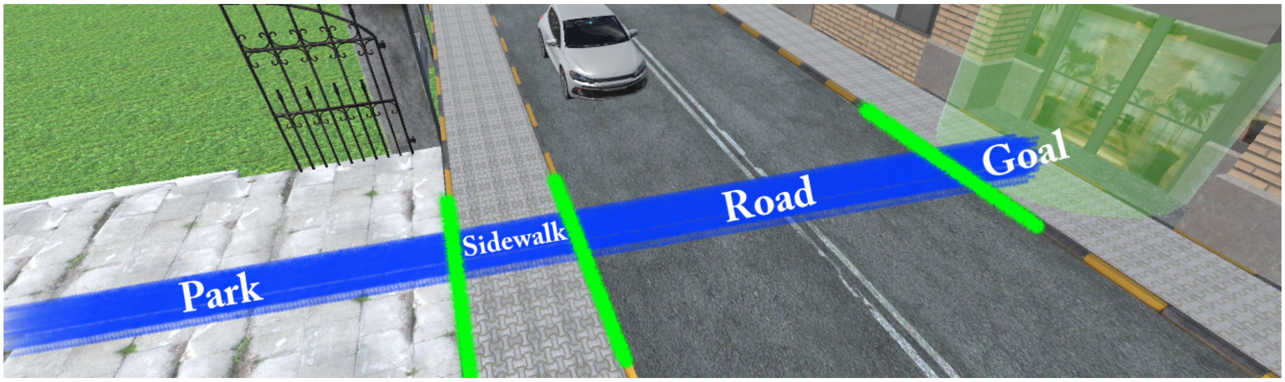

Figure 6: Triggers we used for the logging of the crossing durations. The sidewalk is 1.8m, the road 6.5m wide.

A Friedman's ANOVA found a significant difference for perceived safety (χ^2 (2)=6.32, p=0.042) between the three repetitions in the scenario "Non-Yielding Automated Vehicles". Post-hoc tests showed that perceived safety was significantly higher in the third (M=1.44) than in the second (M=0.64) repetition.

A Friedman's ANOVA found a significant difference for trust (χ^2 (2)=6.47, p=0.039) between the three repetitions in the scenario "Non-Yielding Automated Vehicles". Post-hoc tests showed that trust was significantly higher in the third (M=3.67) than in the first (M=3.28) repetition.

A repeated-measures ANOVA found no significant differences in understanding ($F(1.68, 28.50) = 0.08$, p=0.892) between the three repetitions in the scenario "Non-Yielding Automated Vehicles".

4.5.2 Communication Quality. A repeated-measures ANOVA neither found a significant difference in hedonic ($F(1.76, 29.92) = 1.07$, p=0.348) nor in pragmatic quality ($F(1.38, 23.42) = 3.00$, p=0.085) between the three repetitions in the scenario "Non-Yielding Automated Vehicles".

A Friedman's ANOVA found a significant difference for human-likeness of the communication (χ^2 (2)=10.75, p=0.005). Post-hoc tests showed that human-likeness was significantly higher in the third (M=3.33) than in the second (M=2.83) or the first (M=2.78) repetition.

Repeated-measures and Friedman's ANOVAs found no significant differences for friendliness (χ^2 (2)=0.76, p=0.682), politeness ($F(1.68, 28.60) = 0.94$, p=0.389), unambiguousness (χ^2 (2)=3.49, p=0.175), naturalness (χ^2 (2)=1.00, p=0.607), or appropriateness (χ^2 (2)=0.21, p=0.900) between the three repetitions in the scenario "Non-Yielding Automated Vehicles".

4.5.3 Collisions and Duration. In total, four collisions occurred. No significant differences between the three conditions for crossing in front of non-yielding AVs were found.

In **every** repetition (i.e., in 18 x 3 = 54 repetitions), the AV had to perform an emergency brake and flash the warning light.

A Friedman's ANOVA found a significant difference for the time on the sidewalk (χ^2 (2)=7.11, p=0.029). Post-hoc tests showed that the time on the sidewalk was significantly lower in the third (M=17.86) than in the first (M=25.07) repetition. A Friedman's ANOVA found no significant difference for the time on the street (χ^2 (2)=4.00, p=0.135). A Friedman's ANOVA found a significant difference for the total time (χ^2 (2)=8.33, p=0.016). Post-hoc tests showed that the total time was significantly lower in the third (M=27.48) than in the second (M=33.82) or the first repetition (M=34.19).

4.6 Open Feedback

After all nine conditions, participants gave open feedback about positive and negative aspects of the communication. They were also asked how they would behave if they encountered the scenario "non-yielding automated behavior".

Participants highlighted that the communication and the usage of different colors were well designed. Five participants especially highlighted the timer (e.g., "The timer was good. You could know how fast you should cross the road.") as good communication.

Three participants stated that the timer was not visible enough, especially on the pale hood.

Eleven participants stated that they would wait in a real scenario resembling the "non-yielding automated vehicles" scenario. One participant stated "I would be more careful than in the simulation. After all, it's my life that's at stake, and I would look three times." Nonetheless, five participants stated that they would also cross in front of the AV (e.g., "I would just run straight into the road as soon as 5-9 cars wouldn't let me cross" or "I would still cross the road because the vehicle would stop anyway").

5 DISCUSSION

In this work, we presented a VR study with N=18 participants that was subdivided into three scenarios to investigate the effects of (1) other pedestrians crossing the street with and without an eHMI attached to an AV (*other Pedestrian Behavior*), (2) the effects of a timer on the hood of the AV as main communication modality (*Perceived Time Pressure*), and (3) the effect of repetition (*Past experience*) on the crossing decision and evaluation. In line with previous work [2, 9, 16, 34, 57], we found that eHMIs increased trust and perceived communication quality significantly.

5.1 External Communication in the Light of Other Pedestrians

In the scenario "Pedestrian Group Behavior", we were able to show that the behavior of other pedestrians influenced the participants' behavior (e.g., via the time on the sidewalk), which is in line with previous work showing that pedestrians cross more likely when others had already started to cross [37]. Previous work by Colley et al. [9] showed that a standing pedestrian group did not influence the crossing duration. Therefore, we can conclude that the actual behavior and not the mere presence of other pedestrians altered participants' behavior. We also found that the eHMI let participants cross the road more quickly. However, we could not show significant interaction effects besides the assessment of communication naturalness (see Figure 5). Therefore, we are not able to assess which factors influenced the behavior more strongly. As no interaction effects were found, our data indicate that the two factors do not necessarily interfere. Nonetheless, the data suggest that an eHMI helps to increase trust, reduce mental workload, and positively influences the assessed communication quality. This is in line with previous work and further highlights the potential benefits of external communication of AVs.

5.2 Potential Dangers of Timer-Based External Communication

The scenario "Timer" was used to assess the possibility of pedestrians feeling the need to quickly cross the street in front of an AV before the AV starts to accelerate. Our data do not suggest that the timer affected the decision to cross nor on the actual crossing behavior (e.g., speed). The observed collision occurred in the condition without the timer, further indicating that the timer did not affect potentially dangerous behavior. While previous work indicated over-reliance on eHMIs as a potential drawback [23, 47], an additional timer seemed not to have negative effects. The timer can be seen as an element of increased transparency as it provides additional information on the planned movement. Work on transparent systems from a perspective *within the AV* [8, 10–12, 32, 50, 54] already showed the positive effects of this transparency and enables pedestrians to plan their actions. Nonetheless, as the participants were not presented with incentives to cross the road quickly, it is unclear how a timer will affect pedestrians when there is a cost of crossing late (e.g., running late for a meeting).

5.3 On the "Chicken Game" Theory

The scenario "non-yielding automated vehicles" was designed to evaluate the effect of repeated exposure to AVs. Our data support the existence of a habituation effect. Pedestrians crossed quicker, felt safer, reported lower mental workload, and trusted the AV more in later repetitions. This is in line with the longitudinal study of Faas et al. [34] showing that crossing onset was significantly reduced and trust significantly increased over time. While eleven participants stated that they would wait in a realistic scenario, five participants claimed they would cross the street in front of AVs in such a scenario. Therefore, we argue that our experiment showed that already after three exposures to AVs, pedestrian behavior is significantly altered. We believe that this alteration will only become more significant with time. Our results indicate that there is a preference towards time-saving over (perhaps perceived as low probability) crash avoidance and is, therefore, in line with other work studying this in the more artificial setting of a board game [5]. Therefore, appropriate measures such as how AVs are introduced to the general public have to be considered. It was already shown that introduction matters with AVs (as a passenger [52]). In our introduction, we stated that the AV is equipped with an "emergency braking system". While not giving specific information and not exaggerating the capabilities of the AV (which already happens frequently [30]), this already seemed to suffice for participants to cross the street in front of AVs that indicated they would not yield. While the potential benefits of eHMIs increase over time (increased trust, lowered crossing times for pedestrians) [34], there are drawbacks such as increased waiting times for AVs (potentially leading to traffic jams) or the formation of overtrust in the eHMI [47]. Future work should evaluate **when** these effects occur and **how** they could be reduced or even avoided.

5.4 Limitations

A moderate number of participants took part (N=18). As mostly younger participants (on average 31.28 years old) took part, it is unclear whether this work's findings are transferable to other age groups. Transferability to a real-world scenario is difficult to assess. While we were able to show that participants crossed the road quicker with other pedestrians present (thereby confirming related work on quicker crossing in groups), especially in the scenario "non-yielding automated vehicles", we assume that participants would have been more cautious in the real world. Nonetheless, we argue that the results provide the first evidence on how pedestrians would behave in scenarios with eHMIs, other pedestrians, and after repeated exposure to AVs. As we employed a gain factor for the movement of the participants, the absolute numbers for traversing the road can not be directly compared to real-world crossings. Nonetheless, as the gain factor was applied in every condition, the relative differences (i.e., the statistical analyses) are still valid.

6 CONCLUSION

Overall, this work presents a triply subdivided VR study with N=18 participants. The three scenarios were used to evaluate the effect of (1) other pedestrians' behavior, (2) a timer-based external communication, and (3) repeatedly being exposed to non-yielding AVs. The results indicate that other pedestrians influence the crossing of the participants even in VR and that eHMIs are helpful. Potentially negative aspects of a timer, such as time pressure-induced dangerous behavior, were not observed. Finally, with repeated exposure to non-yielding AVs, participants quickly adapted their behavior and crossed the street despite warning messages. Our work investigated relevant factors related to the crossing scenario and can help to inform the safe introduction of AVs.

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REFERENCES

[1] Claudia Ackermann, Matthias Beggiato, Sarah Schubert, and Josef F Krems. 2019. An experimental study to investigate design and assessment criteria: what is important for communication between pedestrians and automated vehicles? *Applied ergonomics* 75 (2019), 272–282.

[2] Sander Ackermans, Debargha Dey, Peter Ruijten, Raymond H. Cuijpers, and Bastian Pfleging. 2020. The Effects of Explicit Intention Communication, Conspicuous Sensors, and Pedestrian Attitude in Interactions with Automated Vehicles. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376197

[3] Ashratuz Zavin Asha, Christopher Smith, Georgina Freeman, Sean Crump, Sowmya Somanath, Lora Oehlberg, and Ehud Sharlin. 2021. Co-Designing Interactions between Pedestrians in Wheelchairs and Autonomous Vehicles. In *Designing Interactive Systems Conference 2021* (Virtual Event, USA) *(DIS '21)*. Association for Computing Machinery, New York, NY, USA, 339–351. https://doi.org/10.1145/3461778.3462068

[4] Fanta Camara, Serhan Cosar, Nicola Bellotto, Natasha Merat, Charles Fox, et al. 2020. Continuous Game Theory Pedestrian Modelling Method for Autonomous Vehicles.

[5] Fanta Camara, Richard Romano, Gustav Markkula, Ruth Madigan, Natasha Merat, and Charles Fox. 2018. Empirical game theory of pedestrian interaction for autonomous vehicles. , 238–244 pages.

[6] Chia-Ming Chang, Koki Toda, Takeo Igarashi, Masahiro Miyata, and Yasuhiro Kobayashi. 2018. A Video-Based Study Comparing Communication Modalities between an Autonomous Car and a Pedestrian. In *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Toronto, ON, Canada) *(AutomotiveUI '18)*. Association for Computing Machinery, New York, NY, USA, 104–109. https://doi.org/10.1145/3239092.3265950

[7] Vicky Charisi, Azra Habibovic, Jonas Andersson, Jamy Li, and Vanessa Evers. 2017. Children's Views on Identification and Intention Communication of Self-Driving Vehicles. In *Proceedings of the 2017 Conference on Interaction Design and Children* (Stanford, California, USA) *(IDC '17)*. Association for Computing Machinery, New York, NY, USA, 399–404. https://doi.org/10.1145/3078072.3084300

[8] Mark Colley, Ali Askari, Marcel Walch, Marcel Woide, and Enrico Rukzio. 2021. ORIAS: On-The-Fly Object Identification and Action Selection for Highly Automated Vehicles. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Association for Computing Machinery, New York, NY, USA, 79–89. https://doi.org/10.1145/3409118.3475134

[9] Mark Colley, Jan Henry Belz, and Enrico Rukzio. 2021. Investigating the Effects of Feedback Communication of Autonomous Vehicles. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Association for Computing Machinery, New York, NY, USA, 263–273. https://doi.org/10.1145/3409118.3475133

[10] Mark Colley, Christian Bräuner, Mirjam Lanzer, Walch Marcel, Martin Baumann, and Rukzio Rukzio. 2020. Effect of Visualization of Pedestrian Intention Recognition on Trust and Cognitive Load. In *Proceedings of the 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '20)*. ACM, Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3409120.3410648

[11] Mark Colley, Benjamin Eder, Jan Ole Rixen, and Enrico Rukzio. 2021. Effects of Semantic Segmentation Visualization on Trust, Situation Awareness, and Cognitive Load in Highly Automated Vehicles. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Article 155, 11 pages. https://doi.org/10.1145/3411764.3445351

[12] Mark Colley, Svenja Krauß, Mirjam Lanzer, and Enrico Rukzio. 2021. How Should Automated Vehicles Communicate Critical Situations? A Comparative Analysis of Visualization Concepts. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5, 3, Article 94 (2021), 23 pages. https://doi.org/10.1145/3478111

[13] Mark Colley, Mirjam Lanzer, Jan Henry Belz, Marcel Walch, and Enrico Rukzio. 2021. Evaluating the Impact of Decals on Driver Stereotype Perception and Exploration of Personalization of Automated Vehicles via Digital Decals. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Association for Computing Machinery, New York, NY, USA, 296–306. https://doi.org/10.1145/3409118.3475132

[14] Mark Colley, Surong Li, and Enrico Rukzio. 2021. Increasing Pedestrian Safety Using External Communication of Autonomous Vehicles for Signalling Hazards. In *Proceedings of the 23rd International Conference on Mobile Human-Computer Interaction*. Association for Computing Machinery, New York, NY, USA, Article 20, 10 pages. https://doi.org/10.1145/3447526.3472024

[15] Mark Colley, Stefanos Mytilineos, Marcel Walch, Jan Gugenheimer, and Enrico Rukzio. 2022. Requirements for the Interaction With Highly Automated Construction Site Delivery Trucks. *Frontiers in Human Dynamics* 4 (2022), 8 pages. https://doi.org/10.3389/fhumd.2022.794890

[16] Mark Colley, Stefanos Can Mytilineos, Marcel Walch, Jan Gugenheimer, and Enrico Rukzio. 2020. Evaluating Highly Automated Trucks as Signaling Lights. In *Proceedings of the 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '20)*. ACM, Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3409120.3410647

[17] Mark Colley and Rukzio Rukzio. 2020. A Design Space for External Communication of Autonomous Vehicles. In *Proceedings of the 12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI '20)*. ACM, Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3409120.3410646

[18] Mark Colley and Rukzio Rukzio. 2020. Towards a Design Space for External Communication of Autonomous Vehicles. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, Hawaii USA) *(CHI '20)*. ACM, Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3334480.3382844

[19] Mark Colley, Marcel Walch, Jan Gugenheimer, Ali Askari, and Enrico Rukzio. 2020. Towards Inclusive External Communication of Autonomous Vehicles for Pedestrians with Vision Impairments. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376472

[20] Mark Colley, Marcel Walch, Jan Gugenheimer, and Enrico Rukzio. 2019. Including People with Impairments from the Start: External Communication of Autonomous Vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 307–314. https://doi.org/10.1145/3349263.3351521

[21] Mark Colley, Marcel Walch, and Enrico Rukzio. 2019. For a Better (Simulated) World: Considerations for VR in External Communication Research. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications: Adjunct Proceedings* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 442–449. https://doi.org/10.1145/3349263.3351523

[22] Mark Colley, Marcel Walch, and Rukzio Rukzio. 2020. Unveiling the Lack of Scalability in Research on External Communication of Autonomous Vehicles. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, Hawaii USA) *(CHI '20)*. ACM, Association for Computing Machinery, New York, NY, USA. https://doi.org/10.1145/3334480.3382865

[23] Shuchisnigdha Deb, Daniel W. Carruth, Muztaba Fuad, Laura M. Stanley, and Darren Frey. 2020. Comparison of Child and Adult Pedestrian Perspectives of External Features on Autonomous Vehicles Using Virtual Reality Experiment. In *Advances in Human Factors of Transportation*, Neville Stanton (Ed.). Springer International Publishing, Cham, 145–156.

[24] Shuchisnigdha Deb, Lesley Strawderman, Daniel W Carruth, Janice DuBien, Brian Smith, and Teena M Garrison. 2017. Development and validation of a questionnaire to assess pedestrian receptivity toward fully autonomous vehicles. *Transportation research part C: emerging technologies* 84 (2017), 178–195.

[25] Debargha Dey, Azra Habibovic, Andreas Löcken, Philipp Wintersberger, Bastian Pfleging, Andreas Riener, Marieke Martens, and Jacques Terken. 2020. Taming the eHMI jungle: A classification taxonomy to guide, compare, and assess the design principles of automated vehicles' external human-machine interfaces. *Transportation Research Interdisciplinary Perspectives* 7 (2020), 100174.

[26] Debargha Dey, Azra Habibovic, Bastian Pfleging, Marieke Martens, and Jacques Terken. 2020. *Color and Animation Preferences for a Light Band EHMI in Interactions Between Automated Vehicles and Pedestrians.* Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376325

[27] Debargha Dey, Kai Holländer, Melanie Berger, Berry Eggen, Marieke Martens, Bastian Pfleging, and Jacques Terken. 2020. Distance-Dependent EHMIs for the Interaction Between Automated Vehicles and Pedestrians. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Virtual Event, DC, USA) *(AutomotiveUI '20)*. Association for Computing Machinery, New York, NY, USA, 192–204. https://doi.org/10.1145/3409120.3410642

[28] Debargha Dey, Marieke Martens, Chao Wang, Felix Ros, and Jacques Terken. 2018. Interface Concepts for Intent Communication from Autonomous Vehicles to Vulnerable Road Users. In *Adjunct Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Toronto, ON, Canada) *(AutomotiveUI '18)*. Association for Computing Machinery, New York, NY, USA, 82–86. https://doi.org/10.1145/3239092.3265946

[29] Debargha Dey, Francesco Walker, Marieke Martens, and Jacques Terken. 2019. Gaze Patterns in Pedestrian Interaction with Vehicles: Towards Effective Design of External Human-Machine Interfaces for Automated Vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 369–378. https://doi.org/10.1145/3342197.3344523

[30] Liza Dixon. 2020. Autonowashing: the greenwashing of vehicle automation. *Transportation research interdisciplinary perspectives* 5 (2020), 100113.

[31] J Dolphin, L Kennedy, S O'Donnell, and GJS Wilde. 1970. Factors influencing pedestrian violations.
[32] Na Du, Jacob Haspiel, Qiaoning Zhang, Dawn Tilbury, Anuj K. Pradhan, X. Jessie Yang, and Lionel P. Robert. 2019. Look who's talking now: Implications of AV's explanations on driver's trust, AV preference, anxiety and mental workload. *Transportation Research Part C: Emerging Technologies* 104 (2019), 428–442. https://doi.org/10.1016/j.trc.2019.05.025 ID: 271729.
[33] Frida Eriksson, Angelos Malikoutis, Adeliina Aho Tarkka, Potus Unger, Pedram Nayeri, Anders Bäckman, Maria Kougioumoutzi, Karolina Söderberg, Julia andIngre, and Stas Krupenia. 2020. External HMI for Autonomous Buses - Results of the IQ Mobility project in preparation for Project Qatar Mobility.
[34] Stefanie M. Faas, Andrea C. Kao, and Martin Baumann. 2020. A Longitudinal Video Study on Communicating Status and Intent for Self-Driving Vehicle – Pedestrian Interaction. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376484
[35] Stefanie M Faas, Lesley-Ann Mathis, and Martin Baumann. 2020. External HMI for self-driving vehicles: Which information shall be displayed? *Transportation Research Part F: Traffic Psychology and Behaviour* 68 (2020), 171–186.
[36] Daniel J Fagnant and Kara Kockelman. 2015. Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice* 77 (2015), 167–181.
[37] Jolyon J Faria, Stefan Krause, and Jens Krause. 2010. Collective behavior in road crossing pedestrians: the role of social information. *Behavioral ecology* 21, 6 (2010), 1236–1242.
[38] Franz Faul, Edgar Erdfelder, Axel Buchner, and Albert-Georg Lang. 2009. Statistical power analyses using G* Power 3.1: Tests for correlation and regression analyses. *Behavior research methods* 41, 4 (2009), 1149–1160.
[39] Evelyn Florentine, Mark Adam Ang, Scott Drew Pendleton, Hans Andersen, and Marcelo H. Ang. 2016. Pedestrian Notification Methods in Autonomous Vehicles for Multi-Class Mobility-on-Demand Service. In *Proceedings of the Fourth International Conference on Human Agent Interaction* (Biopolis, Singapore) *(HAI '16)*. Association for Computing Machinery, New York, NY, USA, 387–392. https://doi.org/10.1145/2974804.2974833
[40] Charles Fox, Fanta Camara, Gustav Markkula, Richard Romano, Ruth Madigan, Natasha Merat, et al. 2018. When should the chicken cross the road?: Game theory for autonomous vehicle-human interactions.
[41] David C. Funder and Daniel J. Ozer. 2019. Evaluating Effect Size in Psychological Research: Sense and Nonsense. *Advances in Methods and Practices in Psychological Science* 2, 2 (2019), 156–168. https://doi.org/10.1177/2515245919847202 arXiv:https://doi.org/10.1177/2515245919847202
[42] W Andrew Harrell. 1991. Factors influencing pedestrian cautiousness in crossing streets. *The Journal of Social Psychology* 131, 3 (1991), 367–372.
[43] Sandra G Hart and Lowell E Staveland. 1988. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In *Advances in psychology*. Vol. 52. Elsevier, Amsterdam, The Netherlands, 139–183.
[44] Norman W Heimstra, James Nichols, and Gary Martin. 1969. An experimental methodology for analysis of child pedestrian behavior. *Pediatrics* 44, 5 (1969), 832–838.
[45] Kai Holländer, Mark Colley, Enrico Rukzio, and Andreas Butz. 2021. A Taxonomy of Vulnerable Road Users for HCI Based On A Systematic Literature Review. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Association for Computing Machinery, New York, NY, USA, Article 158, 13 pages. https://doi.org/10.1145/3411764.3445480
[46] Kai Holländer, Andy Krüger, and Andreas Butz. 2020. Save the Smombies: App-Assisted Street Crossing. In *22nd International Conference on Human-Computer Interaction with Mobile Devices and Services* (Oldenburg, Germany) *(MobileHCI '20)*. Association for Computing Machinery, New York, NY, USA, Article 22, 11 pages. https://doi.org/10.1145/3379503.3403547
[47] Kai Holländer, Philipp Wintersberger, and Andreas Butz. 2019. Overtrust in External Cues of Automated Vehicles: An Experimental Investigation. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 211–221. https://doi.org/10.1145/3342197.3344528
[48] Ming Hou, Karthik Mahadevan, Sowmya Somanath, Ehud Sharlin, and Lora Oehlberg. 2020. Autonomous Vehicle-Cyclist Interaction: Peril and Promise. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376884
[49] Lynn M Hulse, Hui Xie, and Edwin R Galea. 2018. Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age. *Safety science* 102 (2018), 1–13.
[50] Jeamin Koo, Jungsuk Kwac, Wendy Ju, Martin Steinert, Larry Leifer, and Clifford Nass. 2015. Why did my car just do that? Explaining semi-autonomous driving actions to improve driver understanding, trust, and performance. *International Journal on Interactive Design and Manufacturing (IJIDeM)* 9, 4 (2015), 269–275.
[51] Moritz Körber. 2019. Theoretical Considerations and Development of a Questionnaire to Measure Trust in Automation. In *Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018)*, Sebastiano Bagnara, Riccardo Tartaglia, Sara Albolino, Thomas Alexander, and Yushi Fujita (Eds.). Springer International Publishing, Cham, 13–30.
[52] Moritz Körber, Eva Baseler, and Klaus Bengler. 2018. Introduction matters: Manipulating trust in automation and reliance in automated driving. *Applied ergonomics* 66 (2018), 18–31. https://doi.org/10.1016/j.apergo.2017.07.006
[53] Mirjam Lanzer, Franziska Babel, Fei Yan, Bihan Zhang, Fang You, Jianmin Wang, and Martin Baumann. 2020. Designing Communication Strategies of Autonomous Vehicles with Pedestrians: An Intercultural Study. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Virtual Event, DC, USA) *(AutomotiveUI '20)*. Association for Computing Machinery, New York, NY, USA, 122–131. https://doi.org/10.1145/3409120.3410653
[54] Mirjam Lanzer, Tanja Stoll, Mark Colley, and Martin Baumann. 2021. Intelligent mobility in the city: the influence of system and context factors on drivers' takeover willingness and trust in automated vehicles. *Frontiers in Human Dynamics* 3 (2021), 42. https://doi.org/10.3389/fhumd.2021.676667
[55] Yee Mun Lee, Ruth Madigan, Oscar Giles, Laura Garach-Morcillo, Gustav Markkula, Charles Fox, Fanta Camara, Markus Rothmueller, Signe Alexandra Vendelbo-Larsen, Pernille Holm Rasmussen, et al. 2021. Road users rarely use explicit communication when interacting in today's traffic: implications for automated vehicles. *Cognition, Technology & Work* 23 (2021), 367–380.
[56] Monroe Lefkowitz, Robert R Blake, and Jane Srygley Mouton. 1955. Status factors in pedestrian violation of traffic signals. *The Journal of Abnormal and Social Psychology* 51, 3 (1955), 704.
[57] Andreas Löcken, Carmen Golling, and Andreas Riener. 2019. How Should Automated Vehicles Interact with Pedestrians? A Comparative Analysis of Interaction Concepts in Virtual Reality. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 262–274. https://doi.org/10.1145/3342197.3344544
[58] Victor Malmsten Lundgren, Azra Habibovic, Jonas Andersson, Tobias Lagström, Maria Nilsson, Anna Sirkka, Johan Fagerlönn, Rikard Fredriksson, Claes Edgren, Stas Krupenia, and Dennis Saluäär. 2017. Will There Be New Communication Needs When Introducing Automated Vehicles to the Urban Context?. In *Advances in Human Aspects of Transportation*, Neville A. Stanton, Steven Landry, Giuseppe Di Bucchianico, and Andrea Vallicelli (Eds.). Springer International Publishing, Cham, 485–497.
[59] Haiko Lüpsen. 2020. R-Funktionen zur Varianzanalyse. http://www.uni-koeln.de/~luepsen/R/. [Online; accessed 25-SEPTEMBER-2020].
[60] Karthik Mahadevan, Sowmya Somanath, and Ehud Sharlin. 2018. Communicating Awareness and Intent in Autonomous Vehicle-Pedestrian Interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3174003
[61] Dylan Moore, Rebecca Currano, and David Sirkin. 2020. Sound Decisions: How Synthetic Motor Sounds Improve Autonomous Vehicle-Pedestrian Interactions. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Association for Computing Machinery, New York, NY, USA, 94–103.
[62] Dylan Moore, Rebecca Currano, G. Ella Strack, and David Sirkin. 2019. The Case for Implicit External Human-Machine Interfaces for Autonomous Vehicles. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 295–307. https://doi.org/10.1145/3342197.3345320
[63] Trung Thanh Nguyen, Kai Holländer, Marius Hoggenmueller, Callum Parker, and Martin Tomitsch. 2019. Designing for Projection-Based Communication between Autonomous Vehicles and Pedestrians. In *Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Utrecht, Netherlands) *(AutomotiveUI '19)*. Association for Computing Machinery, New York, NY, USA, 284–294. https://doi.org/10.1145/3342197.3344543
[64] Aaron Powers and Sara Kiesler. 2006. The Advisor Robot: Tracing People's Mental Model from a Robot's Physical Attributes. In *Proceedings of the 1st ACM SIGCHI/SIGART Conference on Human-Robot Interaction* (Salt Lake City, Utah, USA) *(HRI '06)*. Association for Computing Machinery, New York, NY, USA, 218–225. https://doi.org/10.1145/1121241.1121280
[65] Amir Rasouli, Iuliia Kotseruba, and John K Tsotsos. 2017. Understanding pedestrian behavior in complex traffic scenes. *IEEE Transactions on Intelligent Vehicles* 3, 1 (2017), 61–70.
[66] Amir Rasouli and John K Tsotsos. 2019. Autonomous vehicles that interact with pedestrians: A survey of theory and practice. *IEEE Transactions on Intelligent Transportation Systems* 21, 3 (2019), 900–918.
[67] Shadan Sadeghian, Marc Hassenzahl, and Kai Eckoldt. 2020. An Exploration of Prosocial Aspects of Communication Cues between Automated Vehicles and Pedestrians. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Virtual Event, DC, USA) *(AutomotiveUI '20)*.

Association for Computing Machinery, New York, NY, USA, 205–211. https://doi.org/10.1145/3409120.3410657

[68] Hatice Sahin, Heiko Mueller, Shadan Sadeghian, Debargha Dey, Andreas Löcken, Andrii Matviienko, Mark Colley, Azra Habibovic, and Philipp Wintersberger. 2021. Workshop on Prosocial Behavior in Future Mixed Traffic. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. Association for Computing Machinery, New York, NY, USA, 167–170. https://doi.org/10.1145/3473682.3477438

[69] P Schioldborg. 1976. Children, traffic and traffic training: analysis of the Children's Traffic Club. *The Voice of the Pedestrian* 6 (1976), 12–19.

[70] Martin Schrepp, Andreas Hinderks, and Jörg Thomaschewski. 2017. Design and Evaluation of a Short Version of the User Experience Questionnaire (UEQ-S). *International Journal of Interactive Multimedia and Artificial Intelligence* 4, 6 (2017), 103–108. https://doi.org/10.9781/ijimai.2017.09.001

[71] Nirajan Shiwakoti, Richard Tay, and Peter Stasinopoulos. 2017. Exploring jaywalking at intersections.

[72] Andreas Sieß, Kathleen Hübel, Daniel Hepperle, Andreas Dronov, Christian Hufnagel, Julia Aktun, and Matthias Wölfel. 2015. Hybrid City Lighting-Improving Pedestrians' Safety through Proactive Street Lighting. In *2015 International Conference on Cyberworlds (CW)*. IEEE, New York, NY, USA, 46–49.

[73] Matus Sucha, Daniel Dostal, and Ralf Risser. 2017. Pedestrian-driver communication and decision strategies at marked crossings. *Accident Analysis & Prevention* 102 (2017), 41–50.

[74] Unity Technologies. 2021. *Unity*. Unity Technologies.

[75] Tianjiao Wang, Jianping Wu, Pengjun Zheng, and Mike McDonald. 2010. Study of pedestrians' gap acceptance behavior when they jaywalk outside crossing facilities. In *13th International IEEE Conference on Intelligent Transportation Systems*. IEEE, IEEE, New York, NY, USA, 1295–1300.

[76] Annette Werner. 2018. New Colours for Autonomous Driving: An Evaluation of Chromaticities for the External Lighting Equipment of Autonomous Vehicles. https://doi.org/10.25538/tct.v0i1.692 Number: 1.

[77] Dana Yagil. 2000. Beliefs, motives and situational factors related to pedestrians' self-reported behavior at signal-controlled crossings. *Transportation Research Part F: Traffic Psychology and Behaviour* 3, 1 (2000), 1–13.

[78] Raphael Zimmermann and Reto Wettach. 2017. First Step into Visceral Interaction with Autonomous Vehicles. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Oldenburg, Germany) *(AutomotiveUI '17)*. Association for Computing Machinery, New York, NY, USA, 58–64. https://doi.org/10.1145/3122986.3122988