Calibrating Pedestrians' Trust in Automated Vehicles

Does an Intent Display in an External HMI Support Trust Calibration and Safe Crossing Behavior?

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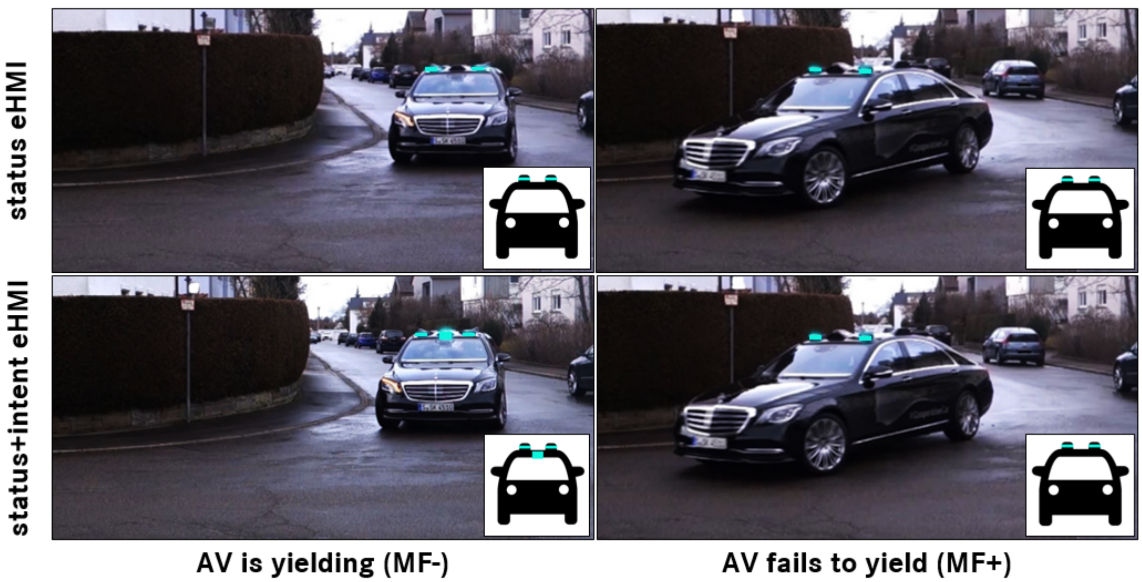

Figure 1: Pedestrians' trust development and crossing behavior during repeated encounters with an AV yielding to the pedestrian perfectly (no occurrence of a malfunction, MF-) or unreliably (failing to yield in one trial, i.e. occurrence of a malfunction, MF+) was investigated. Pedestrians' reactions for two eHMI concepts were explored: A status eHMI indicating automated driving mode and a status+intent eHMI indicating the AV's intent to additionally yield (providing transparency in the event of a malfunction through the non-activation of the yielding intent signal). The status signal indicates automated mode with two continuous lights on each sensor imitation. The intent signal is indicated by a slowly flashing light above the windshield.

ABSTRACT

Policymakers recommend that automated vehicles (AVs) display their automated driving status using an external human-machine interface (eHMI). However, previous studies suggest that a status eHMI is associated with overtrust, which might be overcome by an additional yielding intent message. We conducted a video-based laboratory study (N = 67) to investigate pedestrians' trust and crossing behavior in repeated encounters with AVs. In a 2x2 between-subjects design, we investigated (1) the occurrence of a malfunction (AV failing to yield) and (2) system transparency (status eHMI vs. status+intent eHMI). Results show that during initial

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encounters, trust gradually increases and crossing onset time decreases. After a malfunction, trust declines but recovers quickly. In the status eHMI group, trust was reduced more, and participants showed 7.3 times higher odds of colliding with the AV as compared to the status+intent group. We conclude that a status eHMI can cause pedestrians to overtrust AVs and advocate additional intent messages.

CCS CONCEPTS

• Human-centered computing; **• Interaction design;**; **• Empirical studies in HCI**;

KEYWORDS

Self-driving vehicles, automated vehicles, pedestrians, external human-machine interface, trust in automation, transparency, malfunction

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1 INTRODUCTION

The introduction of automated vehicles (AVs) contributes a significant change in the traffic system [35]. To ensure safe adaption of this technology, in addition to the driver-vehicle interaction via in-car HMIs, the interaction with other road users such as pedestrians also constitutes an essential challenge [8, 29, 39]. Vehicles that decide and move on their own without a human driver need to communicate with pedestrians in order to share the road. Nowadays, there is a complex array of communication between drivers and other road users — including honking, flashing, eye contact, waving or even verbal interaction — all of which must be integrated or re-invented in AV interaction concepts. In recent years, the endeavor to develop meaningful concepts for communication between AVs and pedestrians has been conducted under the concept of external human-machine interfaces (eHMIs). An eHMI displays information about the operation of the AV to surrounding traffic participants. Recent concepts vary in their information content and design. The focus of this paper lies on the type of information content of eHMIs. More specifically, the effects of a basic status message vs. a status+intent message were investigated under error-free and erroneous AV operation (Figure 1).

In this study, we implemented SAE Recommended Practice J3134 [86] by using two symmetrical, continuously lit blue-green "marker lamps" to indicate automated status. By means of such a status eHMI, pedestrians are informed about whether a vehicle is being conventionally steered by a driver (status eHMI is turned off) or is driving in automated mode (status eHMI is turned on). In addition to the SAE, policymakers in several states in the U.S. (e.g. California, Oregon, Pennsylvania) [71] and the American Association of Motor Vehicle Administrations (AAMVA) [3] mandate manufacturers to design AVs such that others recognize when a vehicle operates in automated driving mode. At this point, while the general idea of introducing a status eHMI has gained considerable empirical support, prior research indicates a tendency toward overtrust in such basic status eHMIs, which might be associated with severe consequences for pedestrian safety [32, 33] that in turn might result from the low transparency of system malfunctions.

The basic idea of this study is advancement of the current status eHMI concept by adding a yielding intent signal in the eHMI providing transparency of the planned maneuver, which has been shown to be effective in previous studies (e.g. [13, 32, 33]). An additional yielding intent signal might provide pedestrians with the possibility to calibrate their trust in the probability of an AV failing to yield. We implemented a slowly flashing blue-green light above the windshield which turns on the same time the vehicle starts yielding and remains on when the vehicle comes to a standstill and is waiting for a pedestrian to cross the street. The signal would only be activated if the AV intends to yield for another traffic participant but not if it brakes to adjust its speed. In this study, we implemented a flashing light in a sinusoidal fashion between 30 % and 100 % light intensity and a frequency at 0.5 Hz (design based on [31]). Regarding the general idea of eHMI design, we adopted blue-green lamps because they represent a neutral color that is not associated with a specific meaning in traffic communication at this point [5, 20, 25, 30].

In a simulation study with a realistic curb and video clips of vehicle encounters, we investigated how pedestrians' trust in AVs develops over time and quantified when and if pedestrians decide to cross the street. In four experimental groups, the two eHMI versions (basic status eHMI vs. status+intent eHMI) were crossed with either a flawless operating AV or a single system malfunction with the AV failing to yield to the pedestrian.

The results indicate that theoretical concepts and study procedures on drivers' trust development in regard to AVs can be transferred substantially to pedestrians' trust in AVs. Over repeated encounters, pedestrians' trust steadily increased and their crossing onset time (COT) decreased. After experiencing a system malfunction, trust declined temporarily but was quickly reinstated. Interestingly, while initial trust levels of the two eHMI versions were comparable, trust in the status only was three times more reduced than in the status+intent group following a system malfunction. Also, when the vehicle failed to yield, participants were 7.3 times more likely to choose to cross the street with a basic status than with a status+intent eHMI. These findings indicate that a status+intent eHMI provides a possibility to facilitate a calibrated level of pedestrians' trust in AVs. Thus, a trust level that is in accordance with the actual capabilities and error rates of the AV (e.g. [77]).

Viewed together, our study provides theoretical and practical insight into how pedestrians decide to cross in the presence of AVs, the role of trust in these situations, and the influence of an intent signal in an eHMI.

1.1 Contribution Statement

This study contributes to the body of knowledge in the design of eHMIs by introducing the use case of a malfunctioning AV with correctly operating eHMI. The findings of the eHMI evaluation suggest that a status eHMI can lead to overtrust and dangerous crossing behavior, while a status+intent eHMI provides more transparency and a chance for pedestrians to more efficiently calibrate their trust and adapt their crossing decisions. We found that the development of calibrated trust in AVs follows similar patterns in pedestrians as in drivers indicating a stronger transfer of theories and results between these two research areas.

2 RELATED WORK

This section presents related work in the context of trust in automation to establish a basis for understanding how pedestrians calibrate their trust in AVs. In addition, an overview over pedestrian-AV interaction is provided.

2.1 Trust in Automation

Trust in automation has been investigated for around three decades now since the transfer of interpersonal trust theories to the domain of human-technology interaction by Muir [75, 76] and Lee and Moray [64]. While many different definitions of trust in automation have been brought forward, currently the most commonly applied definition is the one by Lee and See [65] that conceptualizes trust in automation as an attitude that a technology benefits the goal and intention of a human interaction partner (agent) in a situation characterized by risk, uncertainty and vulnerability. Thereby, trust in automation has been found to considerably influence the usage decisions with and reliance on automated systems of various types (e.g., [9, 18, 48, 74]). Essentially, a calibrated level of trust – a situation in which the individual trust level of a user exactly reflects the actual capabilities and functional scope of a technical system – has been discussed as an important psychological prerequisite for efficient and safe interaction with various types of systems (e.g. [59, 75]). On the other hand, miscalibrated trust might lead to inappropriate system use and dangerous decisions. While too little trust in a system (system distrust) might lead to not taking account of the full advantages of a technical system (e.g. a pedestrian would hesitate to cross the street), excessive trust in a technical system (overtrust) can lead to using a system beyond its intended scope (system misuse; e.g. a pedestrian would "blindly" enter the street; [77]).

The process in which users adapt their trust levels in relation to available information is termed trust calibration (e.g., [54, 59, 76]). In this regard, calibrated trust is an ideal result of the process of trust calibration, in which available information is used to assess and learn about the trustworthiness of a system [60]. In this paper, we address this process of trust calibration and identify information and trust mechanisms pedestrians use to calibrate their trust in AVs. Thus, rather than directly assessing calibrated trust, we provide evidence for mechanisms and information guiding trust calibration which are therefore essential for pedestrians in arriving at a calibrated trust level. In order to understand how pedestrians' trust calibration in AVs can be facilitated by implementing eHMIs, the use of available information in trust formation and calibration must be considered. In this regard, the current research builds on the Three Stages of Trust framework [60] providing a theoretical process of three subsequent trust forms building on available information to calibrate one's trust in an automated system (see also Hoff & Bashir [49]). The framework suggests that trust is based on the individual propensity to trust in automation (first stage) — a generalized disposition to trust automated technology. Based on this, available information prior to and during the interaction with new systems is used to build up expectations about it which, in turn, influences learned trust. Prior to the first interaction, available system information provided by e.g. rumors, marketing and public information campaigns is used to build up initial learned trust (second stage). This, in turn, provides the basis for the formation of dynamic learned trust (third stage) during the interaction, which is then also influenced by actual system behavior and provided information during the interaction, for example, in user interfaces. In this regard, this research focuses on the joint roles of the observed system behavior and the available information in an eHMI to understand this behavior during trust calibration in the third stage of trust. The basic assumption of this research is it that pedestrians' trust in AVs is established in a process of collecting information and gaining experience with AVs in actual traffic situations, underlining the importance of a combined consideration of pedestrians' pre-knowledge, expectations, actual behavior of AVs and eHMI outputs. In this context, the importance of facilitating a calibrated level of trust in automation cannot be stressed enough. Essentially, if pedestrians are too trusting of the capabilities of automated vehicles, excessive trust (overtrust) beyond the intended scope of use might result in dangerous misuse, which potentially results in severe accidents such as those reported in recent years, in which excessive driver trust might have played a role [93]. In the same context, overtrust in pedestrians might result in comparable dangerous outcomes in mixed traffic. Against this background, this research aims at a transfer of some of the most recent findings on trust calibration in driver-vehicle interaction to the domain of pedestrian-vehicle interaction. Trust has been found to be a substantial subjective predictor for the usage behavior of automated driving systems (e.g. [48, 78, 80]). Several studies underline the importance of viewing trust formation and calibration in AVs as a history-based process over time. It has been shown that trust calibration is essentially influenced by prior information [6, 56, 61], driver states [58], and personality [57]. During the interaction, the temporal development of trust in automated driving has been investigated [48, 61] along with the influences of system limitations [47, 48], system malfunctions [61], and different designs of the AV's user interface [38].

More specifically, the current study aims at a transfer of the general research concept and some of the study hypotheses by the study of Kraus et al. [59], in which drivers' trust in an AV was shown to be dynamically calibrated on the basis of the combination of information about the AV prior to and during the interaction.

2.2 Automated Vehicles And Pedestrian Interaction

In today's traffic, to decide whether it is safe to cross a street, pedestrians rely on two established means of communication when a vehicle approaches: (1) Vehicle cues such as the distance, speed, and deceleration of the vehicle [21, 67, 87, 88, 91] and (2) driver cues such as eye contact, posture and gestures [43, 82, 91]. While in well-defined situations, pedestrians largely rely on vehicle cues [2, 23, 91], driver cues become particularly prominent as a subsequent form of communication in ambiguous, low-speed urban scenarios [24, 66, 72]. Following models of situation awareness [4, 27, 62], these cues constitute relevant situation elements a pedestrian perceives (perception level 1). However, AVs lack the driver cues of conventional vehicles (CVs). Also, with the introduction of AVs, navigating in traffic will become more complex for pedestrians as they need to interact with CVs (where driver cues will remain present) and AVs (where driver cues will become invalid) at the same time [53, 90]. A status eHMI incorporates the most general information that displays in a binary manner whether a vehicle moves in automated mode (status eHMI is turned on) or in conventional mode (status eHMI is turned off) [7]. A status eHMI facilitates mode awareness — that is, pedestrians can differentiate in mixed traffic between AVs (invalid driver cues) and CVs (valid driver cues) and adapt their expectations accordingly. Compared to AVs without eHMI, pedestrians feel safer, more trusting and more accepting of AVs when they are equipped with a status eHMI [32, 33]. Previous studies suggest that pedestrians feel unsafe if there is no driver on the driver's seat [32, 63, 68, 84], but a status eHMI explains the absence of a driver so that pedestrians no longer miss one [32]. The status eHMI supports pedestrians to comprehend that driver cues are invalid and must not be integrated into their holistic picture of the traffic situation, supporting the construction of an adequate situation model (comprehension level 2) [4, 27, 62]. However, in prior studies, concerns were raised that a status eHMI might lead to overtrust in an AV's capabilities [32, 33]. A status eHMI provides low system transparency since a potential malfunction is not displayed. Displaying only automated driving mode via an eHMI may lead to the assumption that the AV always stops, given their defensive and law-abiding driving style [73]. Such overtrust may result in pedestrians' over reliance on the AV and under reliance on vehicle cues, i.e. failing to monitor whether the AV actually yields.

An additional implementation of a yielding intent message constitutes a higher density of information [7]. With such an additional transparency display of the AV's intention to yield, pedestrians could more easily gain an understanding of the AV's next maneuver and, thus, more efficiently adapt their interaction with these vehicles. In this context, many research studies show that pedestrians feel safer, more trusting and more accepting and initiate street crossing sooner if the AV is equipped with a (status+) intent eHMI as opposed to no eHMI [1, 10, 15, 19, 44, 45, 52, 69] or a basic status eHMI [32, 33]. Following models of situation awareness [4, 27, 62], the intent eHMI supports pedestrians to anticipate future developments (anticipation level 3). This is particularly the case in the context of a malfunction with the AV failing to yield to a pedestrian, in which the yielding intent message would not be activated, making the combined message of status and intent signal clearly distinguishable from a non-malfunction situation. In this manner, the intent eHMI provides transparency and pedestrians are enabled to anticipate the malfunction. Following recent results on the effects of system transparency on trust development [59], a better situation anticipation should enable pedestrians to better calibrate their trust in an AV's behavior and adapt their behavior accordingly, i.e. to make safe street crossing decisions.

Previous studies have examined the effects of a malfunctioning eHMI that indicates erroneous information; that is, an advice cue to cross via a green walking man symbol [50] or a yielding intent message via a slowly flashing white light [52], although the AV was not giving way to the pedestrian. Both studies showed that a single eHMI malfunction leads to a strong decline in trust, yet trust recovered immediately in a subsequent trial with a correct eHMI. During the failure trial, pedestrians may collide with the AV [50, 52]. In addition to this, our approach assumes a functioning eHMI but malfunctioning AV.

3 RESEARCH QUESTIONS AND HYPOTHESES

To the best of our knowledge, no research has systematically examined the effects of eHMIs in the event of an AV malfunction. In this study, we aim to address this research gap with the following research question: ***Does a status+intent eHMI lead to a better trust calibration in the AV and safe crossing behavior (i.e. less misuse/collisions) than a status eHMI?***

This study examined pedestrians' trust and crossing behavior during repeated encounters with an AV. We aimed to study the effects of a single high-risk malfunction (no malfunction vs. malfunction) and the level of system transparency provided by an eHMI (status eHMI vs. status+intent eHMI). The study hypotheses were as follows:

H1: Trust is negatively associated with crossing onset time. It is hypothesized that the more trust pedestrians have in an AV, the earlier they start crossing a street. H1 is based on the assumption that trust development in AVs can be transferred from drivers to pedestrians, i.e. it has been shown that trust is negatively associated with the time drivers monitor an automated driving system [48].

H2: If the automated driving system operates without malfunctions, trust increases (H2.1) and crossing onset time decreases (H2.2) over the course of AV encounters. It is hypothesized that the experience of a functioning AV (AV always yields to the pedestrian according to traffic laws) leads to a gradual increase in trust and decrease in COT over time. H2.1 and H2.2 are based on both prior research with regard to pedestrian-AV interaction [32] and a transfer perspective from driver-AV interaction [48, 59].

H3: An unexpected malfunction of the automated driving system leads to a significant temporary decrease in trust (H3.1). Trust recovers in the event of continued error-free operation (H3.2). It is hypothesized that the experience of a single high-risk malfunction (AV fails to yield to the pedestrian as mandated by traffic laws) leads to a temporary decline in trust, but it recovers quickly over the course of further error-free system operation. H3.1 and H3.2 are based on both prior research studies on pedestrian-AV interaction with a malfunctioning eHMI but functioning AV [50, 52] and with regard to a transfer perspective from driver-AV interaction [59].

H4: In the event of an automated driving system malfunction, knowing the intention of an AV leads to less trust reduction (H4.1) and fewer collisions (H4.2) rather than when the intention is not communicated by an eHMI. As the non-activation of the yielding intent message in the event of a malfunction in the status+intent eHMI allows for detection of the malfunction, it is hypothesized that pedestrians' trust decreases in more pronounced fashion for the status eHMI than for the status+intent eHMI and that the status+intent eHMI minimizes the risk of collisions with the AV. H4.1 is based on a transfer perspective from driver-AV interaction [59]. H4.2 is based on concerns raised in prior studies on pedestrian-AV interaction [32, 33, 73].

4 PEDESTRIAN STUDY

In a video-based lab study, participants acting as pedestrians encountered a number of street-crossing scenarios in which CVs and AVs approached an unsignaled intersection. Participants were instructed to cross the street when they felt safe to do so. In a between-subject design, the two independent variables (malfunction and eHMI version) were manipulated, and the dependent variables (subjective trust and objective crossing behavior) were measured repeatedly.

4.1 Independent Variables

The first independent variable is the occurrence of a single high-risk malfunction. In a failure trial, the AV failed to yield to the pedestrian when making a right turn. In real traffic, pedestrians could experience this type of 'failure' if an AV fails to detect a pedestrian. While in two groups, participants were always exposed to AVs that give way when making a right turn (MF-), the other two groups experienced such a malfunction (MF+) in the 19^{th} trial.

As a second independent variable, the eHMI version was manipulated. By means of a status eHMI, continuously lit blue-green lights on each sensor imitation indicated if a vehicle was in automated driving mode. In addition to the status information, a status+intent eHMI indicated if the AV intended to yield to a pedestrian. In this case, a slowly flashing blue-green light above the windshield was turned on (design based on [31]).

Consequently, a 2 (malfunction: MF- vs. MF+) x 2 (eHMI version: Status eHMI vs. status+intent eHMI) experimental design with four study groups resulted: *Status eHMI/MF-*, *status eHMI/MF+*, *status+intent eHMI/MF-*, and *status+intent eHMI/MF+*.

4.2 Participants

Due to the Covid-19 pandemic, only Daimler AG employees were invited to participate in the study to minimize contact to externals. To this end, we recruited participants using the Daimler AG employee participant pool. The study was approved by the RD Ethical Clearing Committee of Daimler AG. Informed consent was obtained from each participant. The participants received monetary compensation.

Five participants were excluded due to not moving as a pedestrian in traffic (2), exceeding the experiment's time limit (1), somnolence (1), and an unwillingness to complete the questionnaire (1). The final sample consisted of $N = 67$ participants (32 male, 35 female) ranging in age from 20 to 63 years ($M = 38.87$ years, $SD = 12.39$ years), with $N = 16$-17 for each test condition (*status eHMI/MF-* ($N = 17$), *status eHMI/MF+* ($N = 16$), *status+intent eHMI/MF-* ($N = 17$), and *status+intent eHMI/MF+* ($N = 17$)). The participants were randomly assigned to the four experimental groups, controlling for age, $F(3, 63) = 0.01$, $p = .998$, and gender, $\chi^2(3) = 0.04$, $p = .998$. Participants had no constraints in personal mobility, normal or corrected-to-normal vision, no self-reported color blindness, and no self-reported expertise in automated driving. To ensure that the participants moved in traffic as pedestrians and believed that the vehicle drove in automated mode, we conducted manipulation checks. In the pre-experimental questionnaire, participants were asked which modes of transportation they used during a typical workweek (vehicle, taxi, public transit, bike, walking). The participant reported to move in traffic as pedestrians between 0.25 and 11 hours a week ($M = 3.39$ hours; $SD = 2.74$ hours). In the post-experimental questionnaire, participants were asked "Expressed as a percent, to what extent do you think the vehicle you encountered in the video clips was driving in automated mode?". All participants believed that the vehicle was driving in automated mode at least to some extent ($M = 58.37\%$, $SD = 9.76\%$; range: 30% - 80%).

4.3 Apparatus

The study was conducted in the lab of the Mercedes-Benz Research & Development department in Böblingen, Germany. We adapted a validated setup (see [34]) that allows measuring eHMI effects on pedestrians' crossing behavior in a natural manner while not creating any danger for participants (Figure 2). Participants watched video clips of real traffic conditions on two TV screens (65"). By offsetting the screen positions by 130 degrees and stitching the videos together, we enabled the participants to have a panoramic field of vision, thus increasing immersion. The left TV screen showed the approaching vehicle, while the right TV screen showed the intersection. We constructed a sidewalk by covering a wooden pallet (47.2 in x 31.5 in x 3.5 in) with a linoleum surface in asphalt look. We attached two quadratic force sensors (Interlink FSR 406 0.2 N - 20 N) with the dimensions 43.7 mm x 43.7 mm x 0.46 mm (L x W x H) between the EUR pallet and the linoleum surface. The force sensors were used as trigger spots to start the video and initiate the time measurement automatically. The pressure sensors were wired to an Arduino Uno microcontroller using a 1 k Ohm resistor. Figure 3 shows the hardware architecture.

Participants initially stood on the starting position marked with white tape. To start a trial, the participants aligned their feet with the footprints on the sidewalk. As soon as both sensors registered a pressure, the Arduino sent a code word via a serial interface to the main controller. The main controller interpreted the code word, started the measurement and sent an HTTP message to the clients. After receiving this HTTP message, the screen clients synchronously launched. As soon as the test person lifted one foot (right or left) from either force sensor (participant enters the street), a code word was once again sent to the MainController via the serial interface, and the MainController automatically stopped the timing. After crossing the street, the participants returned to the starting position for a new trial.

In addition to the fully automated control of the videos by the pressure sensors, the experimentor was provided with the option to manually remote control the videos via a Bluetooth remote control presenter. The remote control signals were interpreted by the main controller and broadcasted to the clients. Both the computer with the MainController software and the clients with the PowerPoint-ControllerClient software were in a non-interference local network so that we could maintain a low latency of HTTP communication of below 50 ms. For each participant, the completed measurement iteration was automatically extracted into a log file. The architecture and code are available at GitHub (see [89]).

For the trials, we used real-life video clips of a suburban, unsignaled four-way intersection, an approaching vehicle, and no other moving traffic (see Figure 1). The videos were recorded on

Figure 2: Study setup. Participants watched real traffic video clips with an AV approaching an intersection. The pedestrians' task was to cross when they feel safe. Force-sensitive resistor sensors captured pedestrians' crossing onset time (COT).

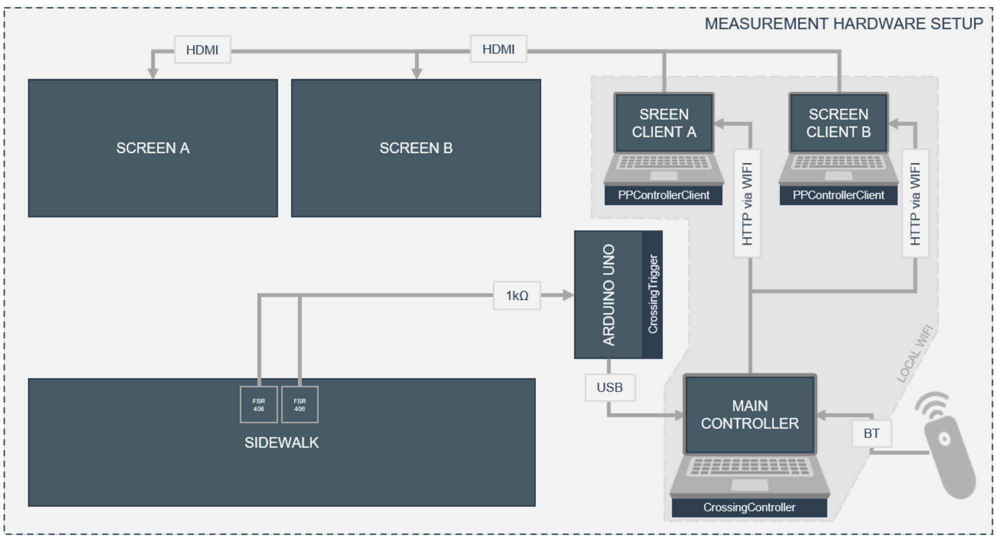

Figure 3: Hardware architecture. The setup consists of the main computer and two client computers. The participant's feet are recognized by force sensors that are serially connected to the main computer via the Arduino Uno. The main computer addresses the two clients via HTTP in a local WIFI network.

a cloudy day on a public road from the viewpoint of a pedestrian standing on a sidewalk attempting to cross. The vehicle was a black Mercedes-Benz S-Class (model series V222) with a Wizard-of-Oz setup of an AV [17]. To promote the impression that the vehicle is able to drive in automated mode (see [1]), we mounted a fake sensor construction on its roof resembling test-driven AVs on public roads (e.g. [40, 81]). In addition, for the AV trials, the driver controlling the vehicle wore a seat costume to create the deception of a driverless vehicle (adapted from [84]). For the CV trials, the driver was visible. Right turn and yielding videos were cropped to a length of 15 s (+ 3 s countdown), right turn and non-yielding videos to a length of 12 s (+ 3 s countdown), and driving-straight videos to a length of 12 s (+ 3 s countdown). The indicator and the eHMI light signals were animated in a subsequent step.

4.4 Experimental Design

Each participant completed 25 trials. The participants experienced four blocks (t_1, t_2, t_3, t_4), which consisted of six trials each (see Table 1; Figure 4). The order of the trials was randomized with a Latin square design within each block, for all blocks, and for all participants. In addition, after block 3, the MF+ groups experienced a single malfunction trial in which the AV made a right turn but failed to yield to the pedestrian (in violation of traffic laws), while the MF- groups experienced a further error-free single trial in which

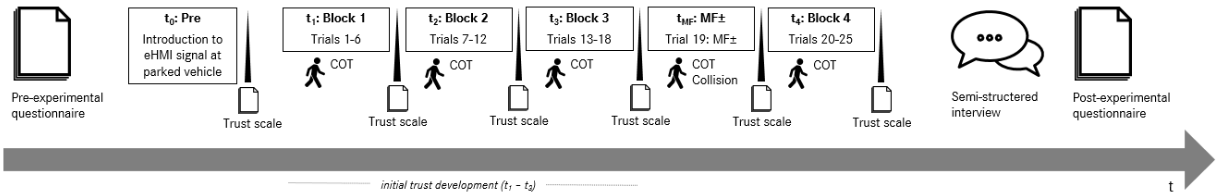

Figure 4: Study procedure.

Table 1: Number of trials per 6-trial block. *Independent variable eHMI.

Behavior	Driving mode	eHMI	Number of trials per block
Right turn – yielding	AV (driverless)	Status eHMI/status+intent eHMI*	2
Right turn – yielding	CV (visible driver)	Off	1
Right turn – non-yielding	CV (visible driver)	Off	1
Straight	AV (driverless)	Status eHMI	1
Straight	CV (visible driver)	Off	1

the AV made a right turn and yielded to the pedestrian (as mandated by traffic laws).

All trials started with a three-second countdown, followed by the vehicle approaching the same unsignaled intersection from the same direction and driving at an initial speed of 30 km/h in accordance with the speed limit of most residential areas in Germany [28, 36]. The vehicle distance at the beginning of each video was approximately 62 m from the pedestrian. This onset of the videos was determined by four experts with the aim of provoking an ambiguous and uncertain situation — neither too far away, nor too close (see [15]). This was done to increase the role of trustworthiness information (e.g. vehicle dynamics or eHMI) and trust in arriving at a crossing decision.

For the right turn and yielding trials, the vehicle activated the indicator, decelerated to come to a standstill and waited for the pedestrian to cross. For the AV trials of the status eHMI groups, the status eHMI was on (activated). For the AV trial of the status+intent eHMI groups, the status eHMI was on and the intent eHMI was activated when the vehicle started to brake (see Figure 1). For the CV trial, the eHMI was off (deactivated). For the right turn and non-yielding trials, the vehicle indicated that it was planning to turn right via the indicator, slightly decelerated to make a right turn, but did not stop for the pedestrian. For the AV, this case constitutes the malfunction trial (MF+). The experimental groups *status eHMI/MF+* and *status+intent eHMI/MF+* experienced this malfunction after block 3. In both groups, only the status eHMI was on. For the CV trial, the eHMI was off. If participants nevertheless entered the crosswalk, a red screen with the message "not safe to cross!" was triggered. For the driving straight trials, the vehicle slightly decelerated when approaching the intersection and then drove straight across the intersection. The paths of the vehicle and the pedestrian did not cross. For the AV trial, the status eHMI was on. For the CV trial, the eHMI was off.

The 1:1 ratio of CVs that made a right turn and gave way to the pedestrian (as mandated by traffic laws) compared to those who did not yield to the pedestrian (in violation of traffic laws) within each block was based on a prior study of pedestrians' experiences when they encountered CVs in traffic (not reported here). In contrast, since AVs are programmed to adhere to traffic laws, a well-functioning AV would yield to a pedestrian when making a right turn. The CV trials were included to account for mixed traffic. The driving-straight trials were included to ensure participants' understanding of the intent eHMI (experimental groups "status+intent eHMI"), given that the intent eHMI would only be activated when the AV brakes to yield for another traffic participant (making a right turn and yielding trial) but not if it brakes to adjust its own speed (driving-straight trial, MF+ trial).

4.5 Procedure

The study procedure is illustrated in Figure 4. After welcoming the participants, the researcher explained that the experiment was aimed at studying pedestrians' perceptions and crossing behavior when interacting with CVs and AVs as well as the need for an eHMI. Participants then filled in a pre-experimental questionnaire regarding demographics and their traffic preferences.

After this, the researcher introduced the vehicle that was parked in the lab (same vehicle as in the videos). Participants were instructed that the vehicle has two driving modes — conventional and automated. For automated driving mode, participants were provided with the definition of highly automated driving (SAE Level 4). For the introduction to the eHMI message(s), the experimenter demonstrated the corresponding eHMI. All experimental groups were introduced to the status eHMI. During the introduction, it was mentioned that if the status eHMI is on, it means that the vehicle is in automated driving mode, and if the status eHMI is off, a driver is steering the vehicle conventionally. In addition, participants of the status+intent groups were introduced to the intent eHMI. The description included the following text: "In addition, the vehicle will indicate that it is braking when it intends to yield to you. As soon as the vehicle starts to brake, the blue-green center light on the windshield will pulsate. [. . .] this lamp only lights up when the vehicle has detected a pedestrian and intends to come to a complete stop. The lamp would not light up if the vehicle brakes only slightly, for example, to adjust its speed". Then, in a manipulation check, participants' understanding of the lighting concepts was tested. Following this introduction, participants completed the trust questionnaire to evaluate their first expression of the vehicle and their corresponding eHMI (t_0).

Participants were then introduced to the experimental setup. In a demonstration trial, they saw an AV making a right turn and yielding to the pedestrian with their corresponding eHMI. They were told that they will encounter both CVs steered by an actual driver and AVs that are driverless. Participants were required to cross when they felt safe to do so. Their task was described as follows: "Your task is to cross the street as soon as you feel safe to do so. You must cross the street in all scenarios. For vehicles that do not stop for you, you can cross the road after the vehicle has passed." They were also told that AVs are programmed to adhere to traffic laws; thus, if a pedestrian is detected, they will yield when making a turn. Within each block (t_1, t_2, t_3, $t_{MF\pm}$, t_4), for all trials with the AV making a right turn, the COT was measured. For the MF+ trial ($t_{MF\pm}$), the occurrence of a collision was measured. After each block, participants rated their level of trust toward CVs and AVs. The pedestrians' ratings toward CVs do not fall within the scope of this paper.

Following all blocks, a semi-structured interview was conducted. The participants then completed a post-experimental questionnaire, including the estimated percentage of AV trials (manipulation check). After the study, the participants were debriefed. The experiment lasted approximately one hour for each participant.

4.6 Measurements

In the following, the measurements utilized are defined, and all subjective dependent variables were assessed with a 7-point Likert scale from 1 ("not at all") to 7 ("extremely").

Propensity to trust: Upon arrival, we measured participants' propensity to trust (based on Körber [55]). Reliability was questionable with $\alpha = .66$ [41].

Trust (H1, H2, H3, H4): After each block, participants' trust in the AV was assessed with a German 11-item version [79] of the Automation Trust Scale by Jian et al. [51]. The English version of this scale is widely used to assess trust in automated driving [32, 42, 46, 85]. In line with the original definition of trust in automation as a unidimensional construct, we recoded negatively framed items to report a single trust measure (e.g. [51]). Reliability was good to excellent, with $\alpha = .87$ to $.96$ [41].

Crossing onset time (COT; H1, H2): For all AV trials that turned right and yielded to the pedestrian, COT was measured. COT indicates the time, in seconds, between the vehicle yielding and the pedestrian entering the street. Shorter times indicate an earlier crossing decision. We checked the data for extreme cases, defined as more than three times the interquartile range greater than the upper or lower quartile, resulting in no exclusions. Within each block, we calculated the mean COT of the two trials in which the AV turned right and yielded.

Collision (H4): For the MF+ trial ($t_{MF\pm}$), the occurrence of a collision was measured based on the difference between the COT relative to the time the AV passed the pedestrian. A crossing onset before the AV had passed (negative COT values) indicated a misuse, whereas a crossing onset after the AV had passed (positive COT values) represented a safe crossing decision.

Semi-structured interviews (H4): After all trials, to understand the opportunities and risks associated with each eHMI version, we asked participants of the MF+ groups how they felt about the malfunction. Based on Mayring [70], we chose inductive category formation as an analytic technique. All interviews were audio-recorded and transcribed, resulting in a total scope of 2,371 words. The first coder coded the interview transcripts by defining a codebook in a step-by-step procedure of reduction and abstraction. Subsequently, the second coder coded the interview transcripts with the codebook. The inter-rater reliability was excellent, Cohen's K = .75, $p < .001$ [14]. Conflicts were resolved via discussion, and the coders agreed on one coding for the reported final category system. The categories were then assigned to one of the following three levels: emotional (evoked feelings), cognitive (evoked thoughts) and conative (evoked behavior).

5 RESULTS

Figure 5 shows trust and Figure 6 shows COT development over time in the different experimental groups.

To establish comparability of the study groups, a series of one-way ANOVAs between the four experimental groups was conducted. Between the groups, participants did not differ in their propensity to trust, $F(3, 63) = 1.28$, $p = .289$, their time moving in traffic as pedestrians, $F(3, 63) = 0.53$, $p = .662$, or their evaluation of the percentage of trials the vehicle was driven in automated mode, $F(3, 63) = 0.81$, $p = .493$. Prior to the experimental trials (t_0), no significant group differences in trust were found, $F(3,63) = 2.63$, $p = .058$. However, as the p-value closely missed significance, to ensure comparability of the study groups, additional post-hoc t-tests were conducted which revealed no differences between the experimental groups (all ps > 0.1). In addition, the participants between groups did not differ in their trust ratings at t_1, $F(3, 63) = 0.55$, $p = .648$, t_2, $F(3, 63) = 0.85$, $p = .473$, or t_3, $F(3, 63) = 1.14$, $p = .342$.

Overall, participants rated both their propensity to trust with $M = 4.47$ ($SD = 1.06$; range: 1 to 7) and their initial trust following the introduction of the corresponding eHMI concept at the parked vehicle at t_0 with $M = 3.87$ ($SD = 0.59$; range: 1 to 7) rather intermediate.

5.1 Analysis Method Of Hypothesis Testing

To test H1, we calculated a Pearson product-moment correlation. To test H2 and H3, we used mixed ANOVAs. We checked the data for sphericity via Mauchly's test and, where violated ($p < .05$), Greenhouse-Geisser (if Greenhouse-Geisser estimate of sphericity is $\epsilon \leq .75$) or Hyunh-Feldt (if Greenhouse-Geisser estimate of sphericity is $\epsilon > .75$) corrections were applied (as recommended by [37]). In addition, as both hypotheses H2 and H3 predicted specific shapes of trust development over time, polynomial contrast analyses were used to investigate if linear (first order, i.e. constantly increasing/decreasing mean), quadratic (second order, i.e. U-shape) and cubic (third order, i.e. peak-and-valley pattern) trends match the trust development at the respective points of measurement (see [12, 83]). To test H4, we calculated simple contrast analyses and

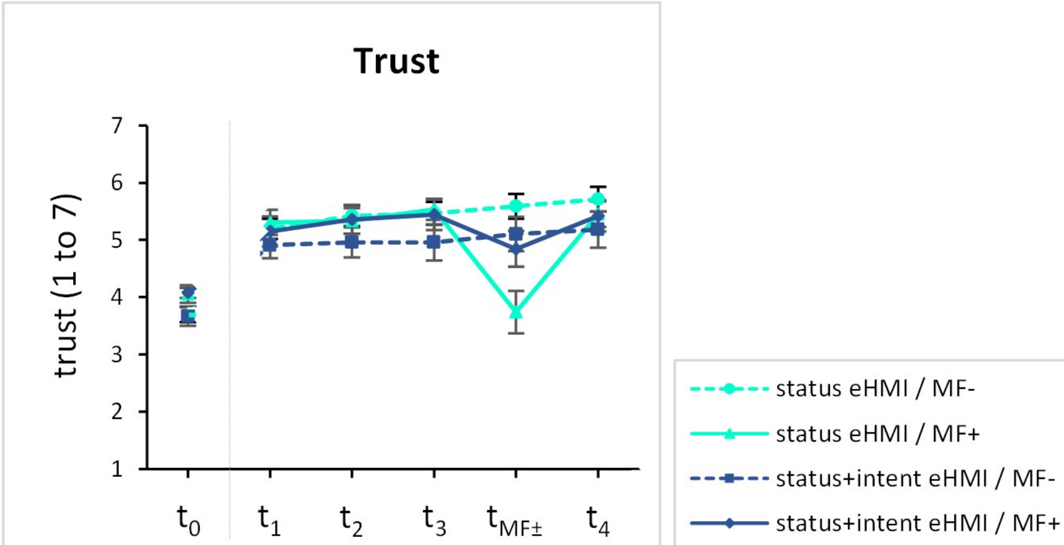

Figure 5: Trust development over the course of the experiment. At t_0, participants rated their first impression after being introduced to the eHMI. The time from t_1 to t_3 reflects initial trust development. At $t_{MF\pm}$, the MF+ groups experienced a malfunction of the AV. The MF- groups experienced a further error-free trial with the AV yielding to them. Error bars: ± 1 SE.

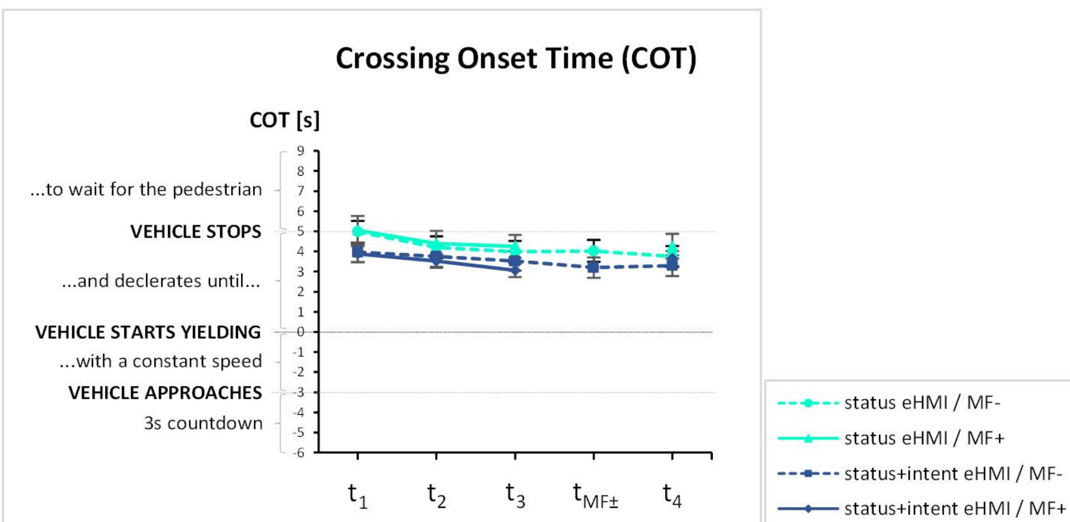

Figure 6: COT development. At $t_{MF\pm}$, only the COT for the MF- groups is shown. Error bars: ± 1 SE.

Fisher's exact test. For standardized effect size for all analyses, we calculated Pearson's r (r = 0.1, small effect, r = 0.3, medium effect, and r = 0.5, large effect; [11, 16, 37]).

5.2 Correlation Between Trust and COT

To test H1 that trust is negatively associated with COT, we calculated a Pearson product-moment correlation between trust and COT for all measuring times with a perfectly yielding AV (t_1, t_2, t_3, t_{MF-}, t_4). A significant negative correlation between trust and COT was found; that is, the more pedestrians trust the AV, the earlier they initiate street crossing — r = -.27, p < .001 — indicating a medium effect in line with H1 (see Figure 7).

5.3 Trust Development in the AV Over Time

H2.1 hypothesized that trust increases over time with additional experiences of an error-free AV. For testing H2.1, we conducted a mixed ANOVA with regard to initial trust development (before MF± trial) for all experimental groups with the independent variables of time (t_1, t_2, t_3), eHMI version (status eHMI, status+intent eHMI), and malfunction (MF-, MF+) and trust ratings as the dependent

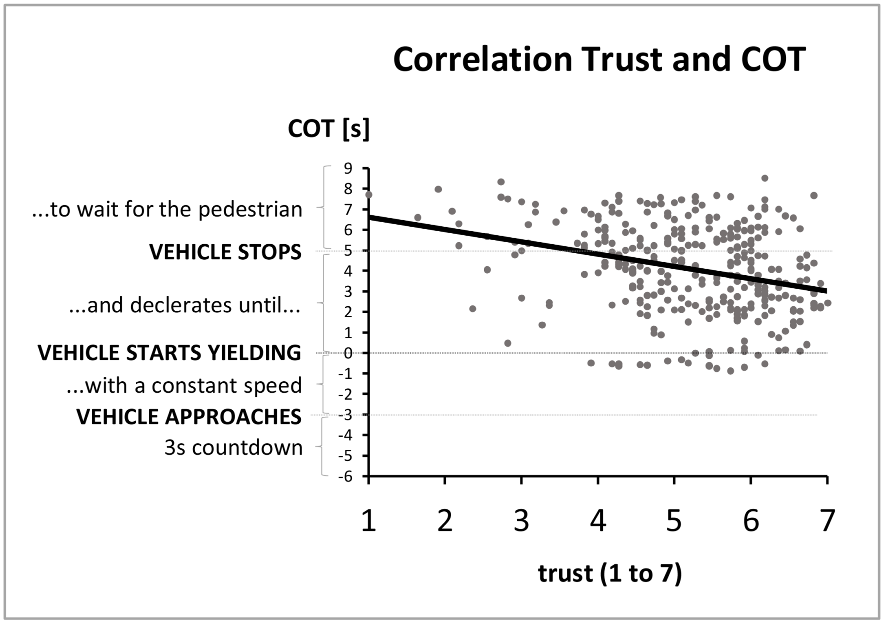

Figure 7: Correlation between trust ratings and COT for all measuring times (t_1, t_2, t_3, t_{MF-}, t_4).

Table 2: Mixed ANOVAs for initial trust development (t_1 to t_3).

Hypothesis	Measurement	Effect	df_1	df_2	F-value	p-value	R
H2.1	Trust	Time	1.82	114.45	5.94	$p = .005^{**}$	.29
		eHMI	1	63	1.22	$p = .274$	.14
		MF	1	63	0.82	$p = .369$	.11
		eHMI x MF	1	63	0.59	$p = .444$	.10
		Time x eHMI	1.82	114.45	0.27	$p = .746$	.07
		Time x MF	1.82	114.45	0.57	$p = .552$	.09
		Time x eHMI x MF	1.82	114.45	1.19	$p = .304$	.14
H2.2	COT	Time	1.73	108.93	17.87	$p < .001^{***}$	.47
		eHMI	3	63	3.10	$p = .083$	.22
		MF	1	63	0.01	$p = .929$	.01
		eHMI x MF	1	63	1.96	$p = .660$	.17
		Time x eHMI	1.73	108.93	1.42	$p = .246$	.15
		Time x MF	1.73	108.93	0.08	$p = .898$	.04
		Time x eHMI x MF	1.73	108.93	0.61	$p = .523$	.10

variable. A significant effect of time on trust, $F(1.82, 114.45) = 5.94$, $p = .006$, $r = .29$, was found (see Table 2). Polynomial contrast analysis showed that trust development from t_1 to t_3 matched a positive linear trend, $F(1, 63) = 8.20$, $p = .006$, $r = .34$, but not a quadratic trend, $F(1, 63) = 0.32$, $p = .572$, thus supporting H2.1 — i.e. a linear trust increase over time. There was no effect of the eHMI version, no effect of malfunction, and no interaction effects, all ps > .05, again indicating that the experimental groups did not differ in their initial trust development from t_1 to t_3.

H2.2 predicted that COT would decrease in the course of the experience of an error-free AV. To test this, we conducted a mixed ANOVA with the independent variables of time (t_1, t_2, t_3), eHMI version (status eHMI, status+intent eHMI), and malfunction (MF-, MF+) and COT as the dependent variable. Again, a significant effect of time on COT, $F(1.73, 108.93) = 17.87$, $p < .001$, $r = .47$ was found. Polynomial contrasts showed that COT development from t_1 to t_3 matched a negative linear trend, $F(1, 63) = 24.86$, $p < .001$, $r = .53$, but not a quadratic one, $p > .05$. In line with H2.2, this supports a decrease in COT in the course of the experience of an error-free AV. While no significant effect of eHMI version, malfunction or interaction effects were found, all ps > .05, a trend for eHMI version, $F(3, 63) = 3.10$, $p = .083$, $r = .22$, shows into the direction that participants might initiate street crossing sooner with a status+intent eHMI ($M = 3.61$, $SD = 1.76$) than with a status eHMI ($M = 4.48$, $SD = 2.36$).

Table 3: Mixed ANOVAs for trust development prior to (t_3), after the MF± trial ($t_{MF\pm}$), and after a further error-free block (t_4).

Hypothesis	Effect	df_1	df_2	*F*-value	*p*-value	*r*
H3.1, H3.2	Time	1.31	82.92	25.98	$p < .001^{***}$	.54
	eHMI	1	63	0.13	$p = .722$	.05
	MF	1	63	1.11	$p = .297$	.13
	eHMI x MF	1	63	2.82	$p = .098$	.21
	Time x eHMI	1.31	82.92	6.86	$p = .006$	.31
	Time x MF	1.31	82.92	28.13	$p < .001^{***}$	.56
	Time x eHMI x MF	1.31	82.92	6.16	$p = .009$	.30

Table 4: Polynomial contrast analyses for trust development prior to (t_3), after the MF± trial ($t_{MF\pm}$), and after a further error-free block (t_4).

Hypothesis	Group	Trend	df_1	df_2	*F*-value	*p*-value	*r*
H3.1, H3.2	Status eHMI/MF-	Linear	1	16	10.19	$p = .006^{**}$	.62
		Quadratic	1	16	0.00	$p = 1.000$	.00
	Status eHMI/MF+	Linear	1	15	0.49	$p = .497$	.18
		Quadratic	1	15	18.74	$p = .001^{**}$	.75
	Status+intent eHMI/MF-	Linear	1	16	4.39	$p = .052$	.46
		Quadratic	1	16	0.36	$p = .557$	.15
	Status+intent eHMI/MF+	Linear	1	16	0.06	$p = .813$	.06
		Quadratic	1	16	14.32	$p = .002^{**}$	.69

5.4 Malfunction

H3.1 predicted that trust temporarily decreases after a malfunction, and H3.2 predicted that trust consequently re-establishes to the level prior to the malfunction (positive quadratic trend). H3 was inspected with a mixed ANOVA on the three points of trust measurement prior to (t_3), directly after the MF± trial ($t_{MF\pm}$), and after a further error-free block (t_4) with the independent variables of time (t_3, $t_{MF\pm}$, t_4), eHMI version, and malfunction and trust ratings as the dependent variable. The effect of time, $F(1.31, 82.92) = 25.98$, $p < .001$, $r = .54$, and the interactions of time x eHMI, time x MF, and time x eHMI x MF, all *p*s < .05, $r = .30$ - .56 were found to be significant (see Table 3). To break down the interaction effects, we calculated polynomial contrasts for each experimental group, examining pedestrians' trust dynamics at the three points of measurement (see Table 4). For the MF- groups, a significant positive linear trend in trust development was found ($p = .006$ -.052, $r = .46$ - .62), while a quadratic trend was not significant (*p*s > .05). In line with H2, this indicates a further increase in trust over time. For the MF+ groups, a significant positive quadratic trend was found ($p =$ .001 -.002, $r = .69$ - .75), and a linear trend was not significant (*p*s > .05) (see Table 4). In line with H3.1 and H3.2, it can be concluded that a malfunction leads to a temporary decline in trust, but that trust is rebuilt quickly. Furthermore, a one-way ANOVA showed no significant differences in trust ratings at t_4 between experimental groups, $F(3, 63) = 0.70$, $p = .554$, again suggesting that the malfunction did not have a long-term effect on pedestrians' trust (in line with H3.2).

Furthermore, for the MF+ groups, a significant positive cubic trend for trust development from t_1 to t_4 was found (*p*s = .001, $r =$ .70 - .72). In line with H2 and H3, this indicates an initial increase in trust (H2.1), while a malfunction leads to a temporary trust decline (H3.1) which subsequently recovers (H3.2). In the *status eHMI/MF+* group, the slope of change in trust was 0.11 from t_1 to t_3, -1.80 from t_3 to t_{MF+}, and 1.71 from t_{MF+} to t_4. In the *status+intent eHMI/MF+* group, the slope of change in trust was 0.15 from t_1 to t_3, -0.60 from t_3 to t_{MF+}, and 0.58 from t_{MF+} to t_4. Thus, the rate of change from t_3 to t_{MF+} was three times lower for the status+intent eHMI (-0.60) than for the status eHMI (-1.80).

5.5 Transparency Through Additional Yielding Intent Message in eHMI

H4.1 proposed that pedestrians' trust would be more decreased in the *status eHMI/MF+* than in the *status+intent eHMI/MF+* group. For testing H4.1, we conducted a simple contrast analysis for the interaction effect of time (t_3, $t_{MF\pm}$) and eHMI version with trust ratings as the dependent measure. A significant interaction between time and eHMI version was found, $F(1, 31) = 7.35$, $p = .011$, $r = .44$. The interaction effect indicates — in line with H4.1 — that the decrease in trust in the *status+intent eHMI/MF+* group is significantly smaller than the decrease in trust in the *status eHMI/MF+*. It follows, then, that system transparency through an additional yielding intent message does not prevent, but mitigates a trust decline after a malfunction.

H4.2 proposed that pedestrians in the *status eHMI/MF+* group would be more likely to collide with the AV in the MF+ trial than pedestrians in the *status+intent eHMI/MF+* group. H4.2 was examined with Fisher's exact test for comparing the two groups regarding the proportion of collisions. From Figure 8, it can be seen that in the MF+ trial, 5 of 16 participants (31.3%) from the *status eHMI/MF+* group and 1 of 17 participants (5.9%) from the *status+intent*

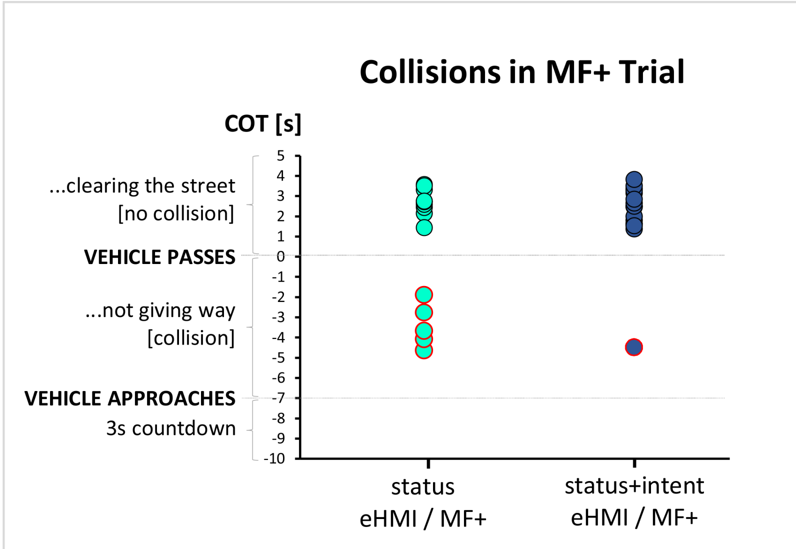

Figure 8: Crossing onset time (COT) in MF+ trial for groups *status eHMI/MF+* and *status+intent eHMI/MF+*. A crossing onset before the AV had passed (negative COT values) represents a misuse, i.e. a collision with the AV (circled in red). A crossing onset after the AV had passed (positive COT values) represents a safe crossing decision (circled in black).

eHMI/MF+ group entered the street before the vehicle had passed, thereby resulting in a collision. A trend between the eHMI version and whether pedestrians would collide with the malfunctioning AV that fails to yield to the pedestrian was found, $p = .087$, $r = .48$. Although the p-value is not significant, the effect size indicates a large effect in line with H4.2. This is further supported by the odds ratio indicating that the odds of pedestrians colliding with the AV was 7.3 times higher with a status eHMI than with a status+intent eHMI.

5.6 Qualitative Data

Following all trials, we asked participants of the MF+ groups how they felt about the trial in which the AV failed to yield to them. Table 5 shows the categories derived from the interviews.

On the affective level, the malfunction evokes negative emotions of *confusion* and *frustration*. SP111+ said, "for me, it [the status eHMI] meant that the vehicle would yield. But it did not. That was quite confusing". Furthermore, pedestrians report a *decline in perceived safety* and a *decline in trust* following the malfunction. For example, SP210+ said, "I felt insecure and asked myself if I could rely on the vehicle". Of particular note was that pedestrians in the *status eHMI/MF+* experimental group reported more negative emotions than pedestrians in the *status+intent eHMI/MF+* group, which might resemble the affective side of the associated trust decline.

On the cognitive level, the most frequently stated category in the *status+intent eHMI/MF+* group is the *transparency* provided by the yielding intent message. For example, SP204+ said, "I noticed OK, the indicator is blinking, but the light at the top is missing, so something is wrong." In addition, SP201+ said, "It did not indicate that the vehicle was stopping, so it was clear to me that it would continue". Analogously, pedestrians in the *status eHMI/MF+* group reported the *intransparency* of the status eHMI, as shown in the following exemplarity statement: "The light has not changed and remained the same the entire time" (SP115+).

On the conative level, foremost pedestrians in the *status+intent eHMI/MF+* group reported that they were *waiting for the AV to pass*. For example, SP213+ said, "I stayed because the signal light was not activated. [. . .] The signal light was good. It supported me. If it were not for the signal lamp, I might have just crossed". Some pedestrians who collided with the AV, reported that they were *entering the street because of overtrust*. For example, SP112+ said, "I saw the turquoise light and just walked". SP217+ said, "I didn't pay attention to the pulsing light [intent eHMI], that it didn't light up. I only paid attention to the other lights [status eHMI]".

Beyond this, there was a small number of participants with a *neutral attitude towards malfunctions* who emphasized the importance of a *constant vigilance in traffic* and the *reliance on vehicle dynamics*. For example, SP101+ said, "So with a normal [conventional] driver, I don't know whether he will stop for me or not, and then I thought, whether the automated vehicle stops or not, I don't know that either. For both, I have to wait and see how the vehicle or the driver reacts. [. . .] I believe that as a pedestrian, you should always be vigilant and always be careful what the vehicle does, regardless of whether a driver is in it or not".

6 DISCUSSION

This paper reports on the findings of an experimental lab study. Our results show that a basic status eHMI can lead to overtrust in AVs, associated with unsafe crossing behavior (i.e. collisions in the event of a malfunction), while a status+intent eHMI reduces such overtrust and might facilitate trust calibration of pedestrians in regard to AVs, which leads to safe crossing behavior (i.e. fewer collisions in the event of a malfunction).

Table 5: Categories derived from qualitative analysis of semi-structured interviews with MF+ groups. C = number of participants in a category, % of SP = number of category codings over all participants of each experimental group

		Status eHMI		Status+intent eHMI	
Level	Category	C	% of SP	C	% of SP
Affective	Confusion	7	44%	3	18%
	Frustration	6	38%	3	18%
	Decline in perceived safety	6	38%	2	12%
	Decline in trust	2	13%	3	18%
Cognitive	Transparency	0	0%	16	94%
	Intransparency	5	31%	0	0%
	Neutral attitude towards malfunctions	3	19%	2	12%
	Constant vigilance in traffic	2	13%	2	12%
	Reliance on vehicle dynamics	2	13%	2	12%
Conative	Waiting for AV to pass	3	19%	7	41%
	Entering street because of overtrust (misuse)	2	13%	1	6%

6.1 General Discussion

To summarize, all study hypotheses gained substantial support in the collected data. Our results add credibility to prior studies by showing that an intent eHMI is associated with positive effects [1, 10, 15, 19, 44, 45, 52, 69]. More specifically, while a basic status eHMI may have negative consequences in the context of a potential malfunction and lead to pedestrians' overtrust in the system, additional incorporation of an intent signal might prevent such negative effects. Furthermore, the reported findings underline that the nature of the formation of dynamic learned trust in AVs of pedestrians follows a similar mechanism as in actual drivers of AVs. Pedestrians build their trust with the accumulated information and experience they gather from repeat interactions with AVs, and transparent information about system operation is used to make sense of the actual experienced behavior of the AV. Before practical implications for eHMI design and the introduction of AVs to everyday traffic are discussed, evidence for the investigated study hypotheses is discussed in more detail.

H1: Trust is negatively associated with crossing onset time. In this study, higher levels of pedestrians' trust in the AV were associated with earlier COT. An earlier COT suggests that pedestrians less monitor vehicle cues such as the actual yielding behavior. This finding is comparable to driver-AV interactions, where prior research found that the more trust drivers have in the AV, the less they monitor it [48]. This suggests that pedestrians' trust in the AV might be a potential predictor for actual behavioral decisions of pedestrians. This, in turn, provides an important argument for the validity of our results in terms of trust dynamics over time in the familiarization process of pedestrians with AVs and a closer investigation of how pedestrians' trust is influenced by different eHMI designs.

H2: If the automated driving system operates without malfunctions, trust increases (H2.1) and crossing onset time decreases (H2.2) over the course of AV encounters. We confirmed that the experience of an error-free AV (i.e. the AV always yields to the pedestrian according to traffic laws) leads to a gradual increase in trust and decrease in COT during the early phase of interaction. In the reported study, participants in the MF+ groups were also able to gain experience in how the AV should operate and build up trust before the MF+ trial occurred. In summary, these results replicate previous research on repeat interactions of pedestrians with a correctly operating AV that showed an increase in trust and decrease in COT over three weeks [32].

H3: An unexpected malfunction of the automated driving system leads to a significant temporary decrease in trust (H3.1). Trust recovers in the event of continued error-free operation (H3.2). Study findings provide evidence that the experience of a single high-risk malfunction (e.g. the AV fails to yield to the pedestrian as mandated by traffic laws) leads to a temporarily decline in trust. Furthermore, in following error-free interaction with AVs, pedestrians recovered their trust in a relatively short period of time following the malfunction. This is in line with the findings from previous research on pedestrian-AV interaction with a malfunctioning eHMI [50, 52] and driver-AV interaction with a malfunction [59]. The combined evidence for H2 and H3 underlines that pedestrians form and calibrate their trust in AVs in crossing situations along the observed vehicle behavior on a dynamic basis.

H4: In the event of an automated driving system malfunction, knowing the intention of an AV leads to less trust reduction (H4.1) and fewer collisions (H4.2) rather than when the intention is not communicated by an eHMI. In this study, pedestrians in the *status eHMI/MF+* group showed three times more severe trust declines than those in the *status+intent eHMI/MF+* group if the AV failed to yield. Thus, the transparency provided by the additional yielding intent message led to a smaller trust reduction in the event of a malfunction, suggesting a higher transparency and a better anticipation of the behavior. As the AV's malfunction was preceded by the absence of a yielding intent signal, the behavior of the AV was still predictable by the pedestrians and, thus, their trust was less reduced by the malfunction. This is in line with previous research, which suggests that foreseeable system behavior leads to less trust reduction when system malfunctions occur (e.g. for AV-driver interaction [59] or automated aids [26, 92]).

We also confirmed that, in the event of a malfunction, the odds of pedestrians colliding with the AV was 7.3 times higher when the AV was equipped with a status eHMI (31.3% of pedestrians) than when the AV was equipped with a status+intent eHMI (5.9% of pedestrians). This suggests that if pedestrians are simply informed that a vehicle operates in automated mode via a status eHMI, roughly one-third over-relied on the AV and under-relied on vehicle cues for deciding whether to enter the street. Indeed, the results from the qualitative analysis suggest that participants in the *status eHMI/MF+* group were more likely to report negative emotions such as confusion and frustration and raised attention to the intransparency of the status eHMI. In other words, many pedestrians enter the street because of overtrust (misuse) although the AV is not yielding, thereby resulting in a collision. This is in line with the assumption of Millard-Ball [73], who forecasted that the indication of automated driving mode may cause pedestrians to cross the street in a careless manner based on their expectation that AVs must abide by traffic laws. Indeed, the results from the qualitative analysis support the assumption that non-activation of the yielding intent message provides system transparency in the event of a malfunction with the AV failing to yield to a pedestrian. Pedestrians in the *status+intent eHMI/MF+ group* report that they were able to anticipate that the AV would not yield to them (anticipation level 3 of models of situation awareness [4, 27, 62]). They could therefore adapt their crossing behavior accordingly; that is, wait for the AV to pass, resulting in safer crossing decisions.

On the contrary, a recent study by Dey et al. [22] suggests that pedestrians may be hesitant to base their street-crossing decision solely on eHMI information. The discrepancy could be due to the fact that our participants had more time to build up expectations about the AV, while in Dey et al. [22], the AV's driving profile varied between trials. The setup presented was chosen to reflect the learning processes in real life: Pedestrians will repeatedly observe AVs' consistent, law-abiding and defensive driving behavior and build up corresponding expectations and trust levels.

These summarized results for H4 entail important implications for trust calibration by means of providing transparent intention signals in eHMIs, which appear to avoid a total loss of trust after the experience of a malfunction and at the same time prevent overtrust associated with a basic status eHMI. In this regard, particularly the findings in regard to collisions and the qualitative data indicate that the presence of a yielding intent message in combination with a basic status message facilitates trust calibration through higher transparency and, eventually, more adequate and safer decision making of pedestrians crossing the street in front of AVs.

Beyond the scope of this paper, we found evidence in accordance with prior research suggesting that a status+intent eHMI may support fast crossing decisions when it is indeed safe to cross, enhancing traffic flow [32]. Further, qualitative data suggests that few pedestrians are "late crossers" who always wait for a vehicle to come to a complete stop, in accordance with prior research [34].

Taken together, from the combined evidence of H2-4, it can be concluded that the dynamic development of pedestrians' trust in AVs is to some extent analogous to the development of drivers' trust in AVs (e.g. [60, 61]). Thereby, in the same manner as drivers, pedestrians seem to build up mental models, beliefs and expectations in regard to the behavior and actions of AVs based on the sum of collected information on the trustworthiness of these vehicles (see [59]). On this basis, dynamic learned trust is built up from the expectation about the AV's behavior, which in turn essentially informs the decision to (not) cross a street in front of such vehicles. Therefore, the knowledge about the psychological foundation of the mechanisms leading to individual and situational levels of trust provides essential starting points for the dissemination and design of AVs and the associated communication and interaction concepts for coordination and cooperation with pedestrians. Such an incorporation of trust processes in the information and design measures accompanying the introduction of AVs to our roads, in this regard, might be essential for enhancing the efficacy and safety of mixed traffic of AVs and more vulnerable road users who depend on transparent and reliable communication of these vehicles to make informed decisions.

6.2 Practical Implications

Trust development and misuse (i.e. entering the street) in face of an AV malfunction are highly influenced by the information displayed by the eHMI. Via a status eHMI, pedestrians show overtrust in the AV and a high probability of misuse (31.3% of pedestrians). In this regard, it is essential to not misinterpret our findings: They do not contradict the incorporation of a status message, but rather advocate a combination of status and intent messages in eHMIs. We emphasize that the study does not advise against the application of a status eHMI. However, we advise for an additional yielding intent message in eHMI displays to support pedestrians in the anticipation of future developments (level 3 of situation awareness models [4, 27, 62]). Taken together, as human-centered in-car HMIs are a key point for safe driver-AV interaction, human-centered eHMIs promote safe pedestrian-AV cooperation. Based on the results of this study, we suggest the following two key recommendations for manufacturers and policymakers to promote AV transparency:

Communication of automated driving mode and yielding intent via eHMI. In addition to the status message, the yielding intent message offers an essential safety margin through increased system transparency associated with a reduction of overtrust and safer crossing behavior. As in practice it is a realistic scenario that such malfunctions occur from time to time, meaningful communication of the AV's intention to stop (such as the yielding intent message signals investigated) can help to provide an efficient and at the same time safe design approach to enable a pleasant and safe coexistence and cooperation between pedestrians and AVs. In this regard, we propose to equip AVs not simply with a status eHMI displaying automated driving mode as recommended by the SAE [86], but also with a status+intent eHMI displaying a yielding intent message. Taken together, the requirements of eHMIs for facilitating safe cooperation between AVs and pedestrians (and other vulnerable road users) are comparable to the requirements of cooperative driver-vehicle interfaces in automated driving mode and entail e.g. a means to enhance mutual predictability and calibrated trust.

Education on AV capabilities and eHMI meaning. Furthermore, it seems very practical to systematically educate pedestrians on the capabilities, functionality and limitations of AVs. Trust formation is a dynamic psychological process — including among pedestrians. Study findings indicate that they learn about the capabilities and the behavior of an AV in different situations from which they build up knowledge from which they derive conclusions about the trustworthiness of AVs. Therefore, this learning process must be addressed on different levels of the introduction of the familiarization process of AVs. For example, pedestrians might be taught that AVs may misjudge a traffic situation or may misclassify a pedestrian at times. Further, pedestrians might be taught how they can detect a malfunction of the AV through eHMI. Thereby, the education of pedestrians about AV functioning and eHMI meaning (e.g. via public campaigns) cannot start early enough before pedestrians actually have to deal with such situations in real traffic.

6.3 Limitations

We recognize some limitations in the reported study that require consideration and should be addressed in future research. First, the study had to be conducted as a simulation to reduce participants' actual probability to be harmed in case of collisions. While this might have led to a somewhat inflated risk in pedestrians' behavior, in light of the safety risks of conducting studies with non-yielding vehicles in real traffic, a simulation-based study was an ethical trade-off. Second, as highlighted before, due to the Covid-19 pandemic, only Daimler AG employees could be recruited, who constitute a specific pool of participants. However, the participants were subjected to a number of manipulation checks to ensure that they move in traffic as a pedestrian and that they believe that the vehicle had moved in automated mode. Third, the implemented eHMI design solutions are only a few of many possibilities. It is fair to assume that the timing and design of the information provided by an eHMI have differential effects on trust development (e.g. activation timing of the yielding intent message, see [15, 52]). Future research should explore the effect of further design specifications seeking to maximize the saliency and positive effect of the yielding intent message. Fourth, our study is limited to the use of an ambiguous German crossing environment with single interactions between one vehicle and one pedestrian. It is recommended that future studies examine the long-term trust development in diverse traffic scenarios with a higher density of vehicles and pedestrians. Apart from this, future research might use eye-tracking to further enhance the understanding of pedestrians' crossing decisions.

7 CONCLUSION

We conducted an experimental lab study to understand pedestrians' trust development and crossing behavior during repeat encounters with an AV that may malfunction in a single trial (i.e. not giving way when it must). We explored pedestrians' reactions for two eHMI concepts: Either the AV is equipped with a status eHMI indicating automated driving mode (as recommended by the SAE [86]) or with a status+intent eHMI additionally indicating the AV's intent to yield. Our results suggest that pedestrians' trust and COT are negatively associated; that is, the more trust pedestrians have in the AV, the earlier they enter the street. In addition, our results suggest that during the early phase of flawless interaction, pedestrians' trust increases and COT decreases. After a single high-risk malfunction with the AV not giving way, pedestrians' trust declined but recovered immediately after further flawless interactions. A first essential conclusion is that pedestrians' trust in AVs is formed and calibrated in patterns that are similar to drivers' trust in AVs and that trust is an important psychological antecedent for crossing behavior.

The main conclusion in terms of designing safe and cooperative AVs is that a basic status eHMI causes pedestrians to overtrust in AVs compared to a status+intent eHMI. Pedestrians are prone to engage in dangerous crossing behavior in front of an AV after repeated exposure to the status eHMI. Unlike this, a status+intent eHMI seems to be associated with better trust calibration in AVs as it allows for the detection of a malfunction. We conclude that a basic status eHMI may lead to unintended safety issues in the presence of a malfunction due to pedestrians' overtrust in the AV. We advocate an additional yielding intent message for the standardization of eHMI design to facilitate the safe and efficient cooperation between AVs and pedestrians.

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