Check for updates

ACM DIGITAL LIBRARY · Association for Computing Machinery · acm open

Latest updates: https://dl.acm.org/doi/10.1145/3699778

PDF Download
3699778.pdf
31 December 2025
Total Citations: 4
Total Downloads: 642

Published: 21 November 2024

Citation in BibTeX format

RESEARCH-ARTICLE

Longitudinal Effects of External Communication of Automated Vehicles in the USA and Germany: A Comparative Study in Virtual Reality and Via a Browser

MARK COLLEY, Cornell Tech, New York, NY, United States

DANIEL KORNMÜLLER, Ulm University, Ulm, Baden-Wurttemberg, Germany

DEBARGHA (DAVE) DEY, Cornell Tech, New York, NY, United States

WENDY G JU, Cornell University, Ithaca, NY, United States

ENRICO RUKZIO, Ulm University, Ulm, Baden-Wurttemberg, Germany

Open Access Support provided by:

Ulm University

Cornell University

Cornell Tech

https://doi.org/10.1145/3699778
EISSN: 2474-9567

Longitudinal Effects of External Communication of Automated Vehicles in the USA and Germany: A Comparative Study in Virtual Reality and Via a Browser

MARK COLLEY, Institute of Media Informatics, Ulm University, Germany and Cornell Tech, U.S.
DANIEL KORNMÜLLER, Institute of Media Informatics, Ulm University, Germany
DEBARGHA DEY, Cornell Tech, USA
WENDY JU, Cornell University, U.S.
ENRICO RUKZIO, Institute of Media Informatics, Ulm University, Germany

Automated vehicles are expected to communicate with vulnerable road users. In two longitudinal studies, we investigated the impact of external Human-Machine Interfaces (eHMI) on pedestrian safety and behavior when interacting with automated vehicles. Utilizing LED strips for communication, these studies probed various factors, including mixed traffic scenarios, presence of eHMIs, and being from Germany or the USA. Our experimental approaches included a Virtual Reality study with 24 participants in Germany and an online study with 28 participants from the USA and Germany. Results revealed that repeated interactions with automated vehicles featuring eHMI significantly enhance pedestrian Trust, Understanding, and perceived safety, while simultaneously diminishing mental workload. Notably, the positive effects of eHMI were consistent across the two countries. US participants exhibited a tendency for higher risk-taking in crossing situations and reported lower mental workloads, underscoring the importance of considering cultural nuances in designing eHMI systems for mixed-traffic environments.

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

Additional Key Words and Phrases: eHMI, longitudinal, culture, virtual reality

ACM Reference Format:
Mark Colley, Daniel Kornmüller, Debargha Dey, Wendy Ju, and Enrico Rukzio. 2024. Longitudinal Effects of External Communication of Automated Vehicles in the USA and Germany: A Comparative Study in Virtual Reality and Via a Browser. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 8, 4, Article 176 (December 2024), 33 pages. https://doi.org/10.1145/3699778

1 INTRODUCTION

With the introduction of automated vehicles (AVs), traffic will change [30]. For example, one advantage of AVs is expected to be increased safety [30, 89]. In urban environments, up to 73 % of pedestrian crashes examined could be prevented by AVs [91]. The use of AVs eliminates the usual modes of driver-pedestrian communication, such as hand gestures, facial expressions, or even eye contact, to solve daily ambiguous traffic situations [67, 76, 78, 80]. This could have a lasting influence on the behavior of vulnerable road users (VRUs) such as pedestrians and

Authors' Contact Information: Mark Colley, mark.colley@uni-ulm.de, Institute of Media Informatics, Ulm University, Ulm, Germany and Cornell Tech, New York, U.S.; Daniel Kornmüller, daniel.kornmueller@uni-ulm.de, Institute of Media Informatics, Ulm University, Ulm, Germany; Debargha Dey, d.dey@tue.nl, Cornell Tech, New York, USA; Wendy Ju, Cornell University, New York, U.S., wendyju@cornell.edu; Enrico Rukzio, enrico.rukzio@uni-ulm.de, Institute of Media Informatics, Ulm University, Ulm, Germany.

This work is licensed under a Creative Commons Attribution International 4.0 License.
© 2024 Copyright held by the owner/author(s).
ACM 2474-9567/2024/12-ART176
https://doi.org/10.1145/3699778

cyclists. Nevertheless, to ensure effective and pleasant communication, numerous eHMIs (external human-machine interfaces) have been designed for AVs. For example, the AVs can communicate their intentions via speakers [13], projections on the road [68], LED strips [55], or windshield displays [24]. Other factors such as the placement (e.g., on the vehicle), the information content (e.g., driving mode, intent), and the degree of scalability (e.g., single or multiple road users) of the communication modalities influence the interaction [9, 11, 21].

Previous studies evaluated communication and interaction exclusively in one-AV-on-one-pedestrian scenarios [15] in which the pedestrian has no other task [54], and environmental factors did also not vary [76]. Rasouli and Tsotsos [76] identified 38 factors that influence pedestrian crossing decisions, including pedestrian characteristics and the environment in current traffic. These can include physical context, dynamic factors, traffic characteristics, social factors, demographics, abilities, state, and characteristics [11, 76]. Although eHMIs are developed with the goal of improving safety, it must be taken into account that VRUs may also become accustomed to this interaction, resulting in a decrease in awareness of the communication. This would make eHMIs no longer needed in the future [20]. However, there are few studies that observed the interaction between AVs and VRUs over an extended period of time [7, 29, 32]. Besides, the importance of an eHMI increases when traffic consists of manually controlled vehicles as well as AVs, also called mixed traffic [62, 95]. In the interaction of VRU and AV, cultural background might also need to be taken into account — interactions with AVs and reactions from people in various, even seemingly similar cultures may be different [50].

To this end, we conducted **three** studies:

- **Study 1:** A *lab-based VR study* on vehicle-pedestrian interaction conducted in Germany with *German participants*.
- **Study 2:** An *online web-based study* on vehicle-pedestrian interaction conducted with *German participants*.
- **Study 3:** An *online web-based study* on vehicle-pedestrian interaction conducted with *US participants*.

Each study investigated how eHMIs, mixed traffic, repeated exposure, and cultural background affect pedestrian behavior and eHMI assessment in urban crossing situations. Individuals (in the role of pedestrians) participated multiple times over a week to observe learning effects. Data were collected on pedestrian position, gaze, collisions, and time spent at various locations, along with subjective questionnaire responses regarding Trust, mental workload, and perceived safety.

Using *Study 1*, we benchmark and corroborate our findings on vehicle-pedestrian interaction with related work and the state of the art. We compare the results of *Study 1 and Study 2* to evaluate the ecological validity of our online experiments by exploring the extent to which the findings hold true between VR-based and online website-based studies. Finally, we use the results from *Study 2 and Study 3* to explore the differences between German and US participants, which is our primary research question (RQ). In this case, we chose Germany and US as candidate samples to explore the aspects of cultural differences in AV-pedestrian interactions as – despite differences – German and American traffic cultures are largely similar, and we hypothesized that if significant differences were found here, they would only be magnified in other cultures representing wider contrasts in traffic interaction practices.

Contribution statement: This work contributes three studies regarding external communication of AVs. The first study reveals the longitudinal effects of eHMIs in Germany leveraging a VR approach. The second study, which employed an online approach in a virtual environment, was compared to the VR study, showing that these approaches alter the results significantly and can, contrary to previous work, not be directly compared. Third, an online-based study with US participants, compared with the online-based study in Germany, shows the contrasts in these (even relatively minor) differences in traffic cultures manifest in longitudinal exposure to eHMIs.

2 RELATED WORK

This section introduces various eHMI concepts, relevant information on road crossing factors, and presents the influence of cultural background on crossing behavior.

2.1 External Communication of Automated Vehicles

eHMIs aim to overcome the lack of communication between driverless AVs and VRUs [7, 37, 44] or manual drivers [10]. Colley and Rukzio [11] defined a design space with three dimensions and a situation part with six dimensions for modeling external communication. The three dimensions of the concept are *message type*, *modality*, and *locus*. Furthermore, *communication relationship*, *communication partner*, *number of lines*, *acoustic noise level*, *traffic autonomy* and *weather* are the six dimensions of the situation [11]. Previous work has mostly concluded that communication of *intentions* (i.e., “stopping”) should be conveyed. Regarding specific application areas, Li et al. [59] designed an eHMI to resolve misUnderstandings between AV and VRUs in mixed traffic. They applied an auditory signal as a warning and a red (visual) signal that indicated the braking of a vehicle located on the AV’s windshield. Based on the traffic situation, the eHMI displayed symbols (e.g., hand gestures) to show the intention of AV. Bazilinskyy et al. [4] collected industry approaches proposed. They investigated these approaches taking into account four characteristics: *Anthropomorphic/Nonanthropomorphic*, *Textual/Non-textual*, *Egocentric/Allocentric*, and *Color* [4]. Further design concepts by industry and research trends were collected by Dey et al. [21]. Several concepts such as abstract lightning elements [6, 60], projections on the road (e.g., pedestrian crossing) [5, 68], movement and position tracking of pedestrians [25, 79], textual and auditory representation and feedback [63, 64] were proposed.

Regarding cross-cultural studies, to the best of our knowledge, only two studies were conducted [50, 53]. Joisten et al. [50] conducted an online video-based intercultural study that revealed that the symbol-based "walking person" eHMI concept consistently influenced pedestrians’ willingness to cross and Trust in AVs across German and Chinese participants, while group size showed no significant effect, but qualitative data suggested some impact on communication processes. Lanzer et al. [53] conducted a comparative online-based video study of an automated delivery vehicle and demonstrated that a polite communication strategy increased compliance among Chinese participants and uniformly boosted Trust and acceptance across both German and Chinese samples, suggesting cultural differences in response to AV communication tactics. Importantly, none of these studies incorporated longitudinal aspects.

It is still not clear if eHMIs are "just a gimmick" or really necessary [20]. de Winter and Dodou [20] criticized the lack of standardization and consensus and that in daily traffic events, it is not necessarily directly clear to VRUs which signal is directed at them [88]. They assumed a critical attitude towards the required visual attention the VRUs needed to understand its environment [20]. Nevertheless, studies have suggested that VRU’s willingness to cross the road increased when interacting with an AV with eHMI [2, 6]. This work extends the assessment of whether eHMIs are necessary by providing a longitudinal lens to this question and additionally adding a cultural component.

2.2 Road Crossing Factors

Habibovic et al. [36] provided an overview of the factors that influence the pedestrians’ crossing behavior when the traffic consists only of manually driven vehicles. They divided the factors into three categories: the characteristics of a vehicle and its driver. These include, for example, the *vehicle kinematics*, the *type of vehicle*, the driver’s *gestures*, and *eye contact*. The second category covers the environment, which includes aspects such as *noise levels* and *visibility*. In addition, the third category deals with the attributes of a pedestrian. These include, for instance, the *speed* and *distance* of the pedestrian, as well as the *walking style* [36]. Crossing behavior and related factors can also be influenced by the gender (male and female) of the respective pedestrian [69]. Pelé et al.

[70] used agent-based models to simulate the behavior of pedestrians crossing the road. They determined that two processes are enough to model pedestrian behavior: *personal motivation* and *imitation* [70].

The identified risks and vulnerabilities of crossing the road in front of manual vehicles also apply to AVs. Rasouli and Tsotsos [76] analyzed classical crossing studies and ones in the AV context. Classical studies deal with the interaction between drivers and pedestrians. They defined two main groups: *environmental factors* and *pedestrian factors* [76].

2.3 Road Crossing Behavior in Context of Cultural Background

The cultural background influences pedestrian crossing behavior [76]. Pelé et al. [71] investigated the crossing behavior of pedestrians at four locations in Nagoya (Japan) and at three locations in Strasbourg to examine the impact of social information on the decision-making process. At each of the seven locations, they observed the crossing behavior of pedestrians at a traffic light. They recorded the people and the traffic light signal with a camera [71]. In a similar study, they already showed that French pedestrians took more risk when crossing than Japanese participants [87]. Their first finding is that the number of illegal crossings decreases the more pedestrians wait at the traffic lights. This is applicable to both countries. They also found that the first French pedestrian to cross the road at a green light stepped off the curb earlier than Japanese participants. In addition, they determined that Japanese pedestrians are more aware of the risk. They crossed the street faster when the light was red and was less influenced by social information, as the Japanese generally follow predefined rules [71]. Solmazer et al. [86] compared the behavior of pedestrians in five different European countries (Estonia, Greece, Kosovo, Russia, and Turkey). Their study investigated the measured behavior and values in each country. The data for their evaluation comes from large-scale surveys of road user behavior and traffic culture. There were 813 participants (131 pedestrians for Estonia, 249 for Greece, 112 for Kosovo, 176 for Russia, and 145 for Turkey) from the five countries mentioned. The first finding of the analysis shows that pedestrian behavior (measured via the Pedestrian Behavior Scale [35]) was consistent across the five countries. They found that Greeks and Turks were more likely to report transgressive pedestrian behavior. Another finding is that Turkish and Russian pedestrians more frequently reported missteps and aggressive behavior. In general, the authors interpret the results that context or country can influence the effect of values on pedestrian behavior [86].

Ranasinghe et al. [74] investigated the interaction between pedestrians and automated and non-AVs when crossing the road. They designed three cross-cultural studies in two countries (Germany and Sri Lanka). Germany represented western continents (USA and Europe). The choice of the two countries is based on their cultural backgrounds. Here, Germany represents a developed country with Western culture and very structured traffic based on predefined rules. Sir Lanka, on the other hand, is considered a developing country with a different cultural background and unstructured traffic. For example, a pedestrian spontaneously crosses the street at a non-existent walk. The second reason for the choice of country is the origin of the researchers involved. As part of the data collection, they filmed the behavior of pedestrians crossing the road, regardless of whether it was a manual or an AV. An AV was represented by means of a Ghost Driver (seat costume) [74].

Hell et al. [40] examined the crossing behavior of pedestrians living in Germany and Japan. The focus of the study was to investigate cultural differences in pedestrian behavior. They, therefore, measured *risk avoidance*, *compliance*, *gap acceptance*, and *walking speed* together with various environmental factors. To identify and measure the differences between cultural groups, Hofstede [42] developed a multi-dimensional approach [42]. Based on this model, two dimensions are crucial for pedestrian behavior. These are *uncertainty avoidance*, and *collectivism vs. individualism*. The concept of uncertainty avoidance can be related to risk avoidance [65]. For both uncertainty and risk avoidance, Asian (e.g., Japan or China) countries show higher values than European countries (especially Germany) [40, 65]. The second measure, collectivism, is divided into European cultures, where people see themselves as separate individuals with a set of characteristics, and Asian cultures, where harmony and togetherness play a role. The authors were able to specifically reflect the aspect of collectivism in the individual study criteria [40]. In general, crossing behavior is strongly influenced by the country where the pedestrian grew up and its social norms. In addition, the structuring of traffic and the strictness in implementing rules influence behavior.

3 METHODOLOGY

We conducted three studies to investigate the longitudinal and cultural effects of external communication.

3.1 Research Questions and Approach

Our primary focus was to investigate the cross-cultural impacts of eHMIs in longitudinal exposure scenarios, and we answered them through the following three RQs:

RQ1: What impact do the independent variables "eHMI" (not present vs present), "traffic" (mixed or automated), and "repeated exposure" (three days within one week) have on pedestrians in terms of (1) crossing behavior, (2) mental workload, (3) Trust, (4) perceived safety, and (5) communication quality?

RQ2: In which areas are results from VR comparable to an online-based study where participants interact with a mouse and keyboard?

RQ3: What impact do the variables "eHMI" (not present vs present), "repeated exposure" (three days within one week), and "cultural background" (German vs USA) have on pedestrians in terms of (1) crossing behavior, (2) mental workload, (3) Trust, (4) perceived safety, and (5) communication quality?

To answer these questions, we required a VR simulation, an online-based version of the same scenario, and participants from different cultural backgrounds. Therefore, we first conducted a longitudinal VR study using the Vive Pro Eye headset in Germany. We then replicated this study online with German and US participants. In the online-based version, participants downloaded an executable and interacted with the mouse and keyboard to cross the street. Using Bayesian statistics, we could deduce which parts of the VR and the online-based study are comparable. Finally, we evaluated the effects of the cultural background on the crossing decisions.

The experimental procedure followed the guidelines of our university's ethics committee and adhered to regulations regarding the handling of sensitive and private data, anonymization, compensation, and risk aversion. Compliant with our university‘s local regulations, no additional formal ethics approval was required.

3.2 Materials

3.2.1 Structure of the Crossing Scenario. As many factors affect crossing behavior [76], we describe those that were kept constant in this work. Figure 1 shows the schematic scenario structure. The pedestrian has to reach the blue X on the opposite side.

3.2.2 External Human-Machine-Interface. Figure 2 shows an AV, indicated by the cyan-colored indicator at the upper center edge of the windshield. In conditions with an eHMI, a cyan flashing LED bar on the bumper signals pedestrians that the AV is stopping (i.e., *intention*-based communication).

This Slow-Pulsing Light Band was used as a representative of the visual eHMI. We selected the light band eHMI design because it is the most widely used/proposed visual eHMI [21] due to its simplicity, ease of implementation, and abstract execution [1, 19, 25, 28, 38, 41, 72]. We adapted the light band design by incorporating insights from prior research [22, 28, 57], which indicate that a uniform pattern like a slow-pulsing animation in cyan is effective for indicating an intention to yield. For our study, we designed the SPLB to be mounted on the vehicle's bumper.

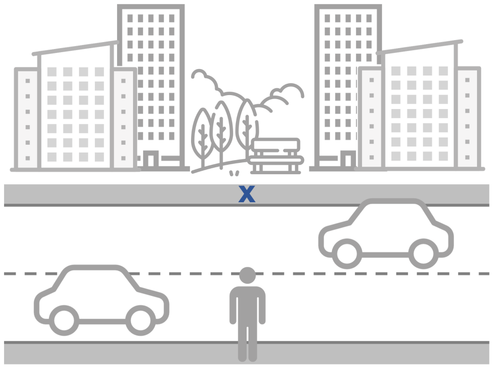


Fig. 1. Schematic structure of the crossing scenario.

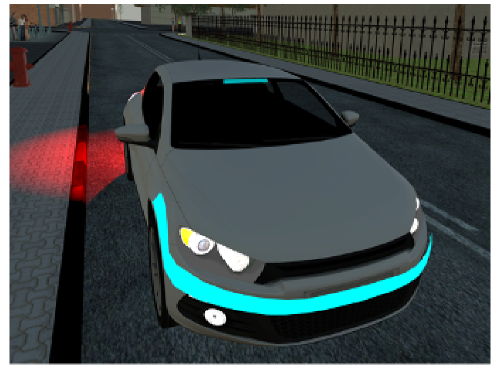


Fig. 2. eHMI on.

When the AV operates in the automated mode without the intention to yield, it does not glow. When the AV intends to yield, it pulsates in a sinusoidal pattern, with the entire light bar alternately dimming and glowing at a rate of 0.75 Hz. This pattern was chosen based on prior research that identified it as the most suitable animation to communicate a yielding intention for an AV [22]. When the AV resumes driving, the light bar returns to a steady glow, indicating the transition to "driving in automated mode." Essentially, the pulsating eHMI signals to the pedestrian, "I intend to yield," while the steady glowing eHMI indicates, "I intend to keep driving."

Other messages such as "You can cross" [12] were discarded as explicitly stating to the pedestrian that they could cross could lead to overreliance on the eHMI. Furthermore, current standardization efforts for eHMIs [46] advise refraining from instructional or advisory messages for – among other reasons – liability concerns.

3.2.3 Vehicles, Traffic, & Road. As vehicle exterior influences pedestrian crossing behavior [19], we used a compact Sedan as the study vehicle. Initially, the vehicles drive on both lanes relevant for the crossing, independently of their driving mode (automated and manual). In the actual crossing scenarios, the oncoming traffic on the far lane changes its direction to account for deviations imposed if two vehicles have to stop for the pedestrian. Figure 3 shows the schematic traffic flow during the study.

The blue dashed line in Figure 3 represents the direction of travel of the vehicles affecting the scenario. The yellow dashed line shows the flow of oncoming traffic where *(a)* represents the initial traffic flow. During the crossing, the vehicles change their direction and continue straight ahead, shown in variant *(b)*. This avoids randomness in having vehicles coming from both sides.

The vehicles drive at a velocity of *50 km/h*. There are three situations in which they brake. The first situation is when the participant waits on the sidewalk for *at least 20 seconds*. Secondly, when the test person stands directly *at the curb* of the street. The last situation is when the pedestrian is already *standing on the road* and the vehicle recognizes it. If a pedestrian enters the road rashly or uncoordinatedly, the vehicle performs a hazard braking. If this fails, the collision counter is incremented for the test person.

3.3 Data Analysis

Before each statistical test, we checked the required assumptions (normality distribution and homogeneity assumption of variance). Conditions were compared using either Friedman's (nonparametric) or repeated measures ANOVA. For non-parametric data, we used ART [96]. For post-hoc tests, the *Holm* correction was used. *R* in version 4.4.1 and *RStudio* in version 2024.04.2 was used.

Fig. 3. Traffic flow in the study. Blue represents the trajectory of vehicles relevant for the crossing decision. Yellow represents the traffic that is redirected once a situation occurs where the participant crosses.

Interpreting main effects without considering interaction effects can lead to misleading conclusions, as interactions indicate that the effect of one factor depends on another. When significant interactions are present, main effects should be interpreted in the context of these interactions, not in isolation. Thus, describing main effects alone is inadequate and potentially deceptive, necessitating an analysis that accounts for the complexity of interactions. Therefore, when there are interaction effects, we refrain from describing main effects or interaction effects with fewer factors.

4 INSIGHTS FROM VIRTUAL REALITY LAB STUDY (STUDY 1)

Study 1 was longitudinal. Participants were exposed to external communication on three separate days within a week. We also varied the presence of eHMIs attached to the AVs and whether the traffic (mixed or purely automated).

4.1 Measurements

Objective Measurements. We logged, collisions, the position with 50Hz and performed eye tracking with 20Hz. We report the duration on the sidewalk prior to crossing the street (“Duration on the sidewalk at the starting point”), the duration in the first and second lane, and the total crossing duration.

Subjective Measurements. Participants assessed their *perceived safety* using four 7-point semantic differentials. We used the version of Faas et al. [29], with the scale ranging from -3 (anxious/agitated/unsafe/timid) to +3 (relaxed/calm/safe/confident) [29]. Additionally, we used the mental workload subscale of the *raw NASA-TLX* [39]. A 20-point scale is utilized ("How much mental and perceptual activity was required? Was the task easy or demanding, simple or complex?"; 1=Very Low to 20=Very High). In addition, we use the subscales *Predictability/Comprehensibility* (from here *Understanding*) and *Trust* of the questionnaire *Trust in Automation* [52]. Understanding is measured by agreement with 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.") on a 5-point Likert scale (1=Strongly disagree to 5=Strongly agree). Trust is measured by agreement with two statements on a 5-point Likert scale ("I Trust the system." and "I can rely on the system.").

Another question examines the factors that influence the *crossing decision* [14, 76] (i.e., “On what basis did you decide to cross the road?”). These factors are speed, vehicle distance, communication (via LED), and own waiting time, which are realized with a 7-point Likert scale (1=not at all to 7=absolute). The last question evaluates the *presence of eHMI* (from here *presence*). Presence is measured via agreement on equal 7-point Likert (1=disagree at all to 7=agree at all) scales on a statement ("My behavior was influenced by the external communication of the vehicles.").

To assess the AV’s communication quality, we used the short version of the Schrepp et al. [84]’s *UEQS* in the second part. UEQ-S measures pragmatic and hedonic quality [84]. Communication was also assessed using the self-defined aspects unfriendly/friendly, impolite/polite, ambiguous/unambiguous, unnatural/natural, machine-like/human-like (as suggested by Powers and Kiesler [73]), and insufficient/adequate according to Sadeghian et al. [81].

After all three days and twelve conditions, participants completed a final questionnaire. They gave an overall assessment of the proposed communication. After evaluating the communication with the AV and the necessity and usefulness of each communication, the participants could give positive and negative open feedback.

4.2 Procedure

After giving informed consent, participants were introduced to the scenario and provided demographic data. They were then, per day, randomly distributed to the four conditions (2 eHMI × 2 traffic). This was repeated three times within one week. The study took, in total, 90 minutes (3x30 minutes). Participants crossed the road a total of twelve times. Figure 4 shows the schematic procedure.

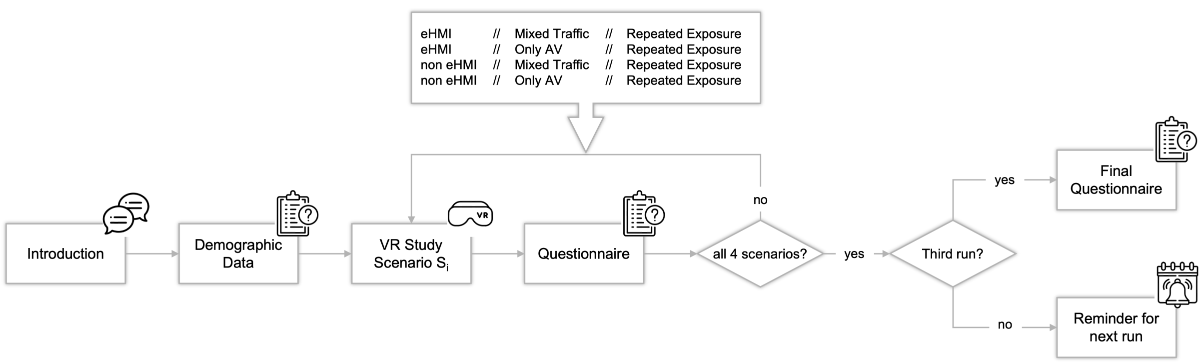


Fig. 4. Schematic procedure of the VR study.

4.3 Results VR-Study

In the following, we report the results of study 1. We refrain from reporting eye tracking metrics and findings related to the self-defined aspects of communication for conciseness. These will be made available open-source after acceptance.

4.3.1 Demographic Data. In the VR study, *N*=24 participants (14 males and 10 females) were recruited, with an average age of *M*=25.88 years (*SD*=4.16, range: 20 — 35 years). On a 5-point Likert scale *(1 = Strongly Disagree — 5 = Strongly Agree)*, participants were asked to indicate their experience with VR games and VR studies, with a medium experience for games (*M*=2.58, *SD*=1.61) and studies (*M*=2.83, *SD*=1.76). Participants also specified how much they liked playing VR games (*M*=2.25, *SD*=1.19) or whether they had never played VR games (*M*=2.67, *SD*=1.71). On another 5-point Likert scale *(1 = Strongly Disagree — 5 = Strongly Agree)*, participants showed interest in AVs (*M*=3.75, *SD*=0.90), believed AVs to ease their lives (*M*=3.96, *SD*=0.81), and were unsure whether AVs become reality by 2032 (*M*=3.46, *SD*=1.02).

4.3.2 Mental Workload, Trust & Perceived Safety. The ART found a significant main effect of *eHMI* on mental workload ($F(1,23) = 4.29$, p=0.050). The mental workload was significantly lower with (*M*=5.23, *SD*=3.74) than without an eHMI (*M*=5.78, *SD*=4.09). In addition, ART found another significant main effect of *rep. exposure* on mental workload ($F(2,46) = 4.95$, p=0.011). A post-hoc test found that *rep. exposure One* (*M*=6.17, *SD*=4.32, $padj$=0.022) and *Two* were significantly higher (*M*=5.81, *SD*=4.06) in terms of mental workload compared to *Three* (*M*=4.54, *SD*=3.14; $padj$=0.031).

The ART found a significant main effect of *eHMI* on Trust ($F(1,23) = 4.59$, p=0.043). Trust was higher with eHMI (*M*=4.27, *SD*=0.69) than without (*M*=3.98, *SD*=0.95). Furthermore, the ART found a significant main effect of *eHMI* on Understanding ($F(1,23) = 14.01$, p=0.001). Understanding was significantly higher with (*M*=4.16, *SD*=0.80) than without an eHMI (*M*=3.69, *SD*=0.99). Second, ART found a significant main effect of *rep. exposure* on Understanding ($F(2,46) = 7.77$, p=0.001). A post-hoc test found that *rep. exposure Three* was significantly higher (*M*=4.11, *SD*=0.90) in terms of Understanding compared to *One* (*M*=3.74, *SD*=0.89; $padj$=0.002).

The ART found a significant main effect of *eHMI* on perceived safety ($F(1,23) = 6.71$, p=0.016; higher with *M*=2.21, *SD*=1.05 than without an eHMI *M*=1.97, *SD*=1.23). The ART also found a significant main effect of *rep. exposure* on perceived safety ($F(2,46) = 9.95$, p<0.001, Three higher *M*=2.38, *SD*=0.93 than One *M*=1.77, *SD*=1.30; $padj$ <0.001). The ART also found a significant interaction effect (IE) of *traffic* × *rep. exposure* on perceived safety ($F(2,46) = 4.02$, p=0.025; see Figure 5).

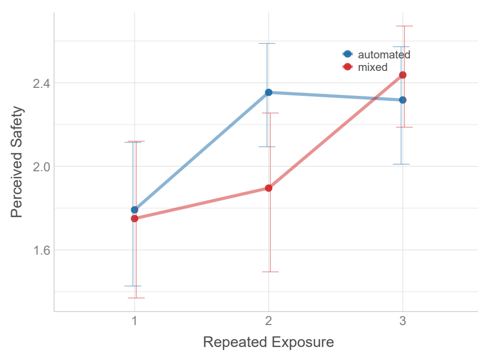


Fig. 5. IE of *traffic* × *rep. exposure* on perceived safety.

For the first *rep. exposure*, the values of automated and mixed traffic were similar. While on the second run, the perceived safety is significantly higher for automated, on the third run, the safety is higher for mixed traffic. In general, the perceived safety increases the more often the participants repeat the scenarios.

4.4 Crossing Decision

The distance (28.38 %) between vehicles has the most influence on the crossing decision. Likewise, the speed (27.56 %) of the vehicles has a substantial influence. The communication (23.93 %) of the vehicles via LED and the own waiting time (20.12 %) have less influence on the decision.

Effect of Speed on Crossing Decision. The ART found a significant three-way IE of *traffic* × *eHMI* × *rep. exposure* on the effect of *speed* on the crossing decision ($F(2,46) = 9.71$, p<0.001, see Figure 6).

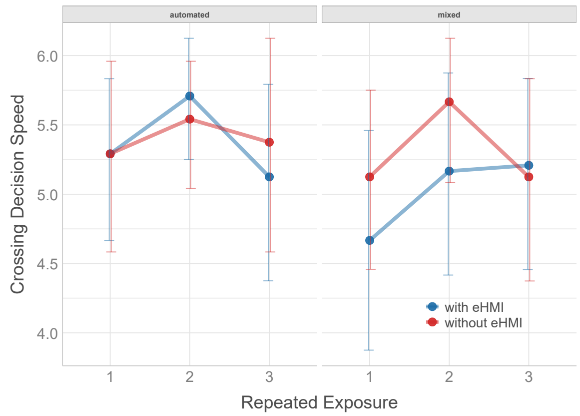


Fig. 6. Three-way IE on *Crossing Decision Speed*.

The base speed of the decision was initially higher for eHMI in the context of purely automated traffic. The line showing without eHMI increased in the last run. In the case of mixed traffic, the speed as a basis was higher without the eHMI. Only in the last run climbed the line higher with eHMI.

Effect of Distance on Crossing Decision. The ART found no significant effects.

Effect of Communication on Crossing Decision. The ART found a significant main effect of *traffic* on the effect of *communication* on the crossing decision ($F(1, 23) = 5.03$, p=0.035; higher for automated M=4.68, SD=2.30 than for mixed traffic M=4.48, SD=2.39). The ART also found a significant main effect of *eHMI* on *crossing decision communication* ($F(1, 23) = 16.07$, p<0.001; higher with M=5.42, SD=1.97 than without eHMI M=3.74, SD=2.39). In addition, the ART found a significant IE of *traffic* × *eHMI* on *crossing decision communication* ($F(1, 23) = 4.38$, p=0.048, see Figure 7).

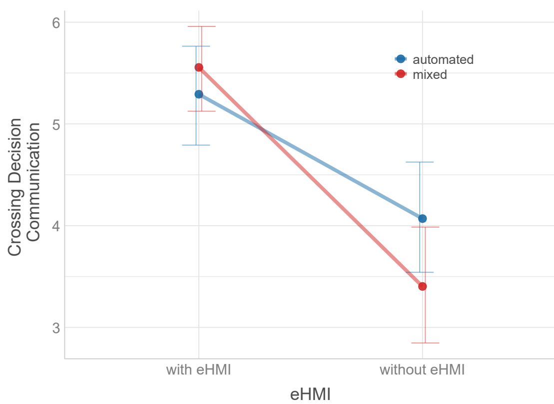


Fig. 7. IE of *traffic* × *eHMI* on *Crossing Decision Communication.*

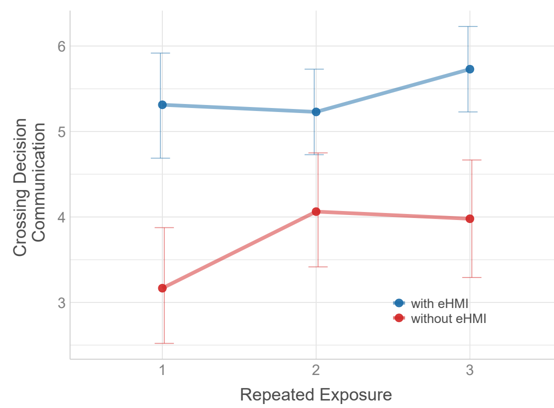


Fig. 8. IE of *eHMI* × *rep. exposure* on *Crossing Decision Communication.*

The influence of communication on the crossing decision was higher with eHMI than without. In the case of mixed traffic and without eHMI, the influence was lowest. The ART also found a significant IE of *eHMI* × *rep. exposure* on the effect of *communication* on the crossing decision ($F(2, 46) = 5.48$, p=0.007, see Figure 8).

Communication as the basis of the crossing decision is higher when an eHMI is in place. Over the days, the influence of communication on pedestrians' decisions increases.

Effect of Own Waiting Time on Crossing Decision. The ART found a significant main effect of *traffic* on the effect of *own waiting time* on the crossing decision ($F(1, 23) = 16.46$, p<0.001; lower for mixed M=3.76, SD=2.02 than for automated traffic M=3.94, SD=2.05). The ART also found a significant IE of *traffic* × *rep. exposure* on *crossing decision own waiting time* ($F(2, 46) = 3.31$, p=0.045, see Figure 9).

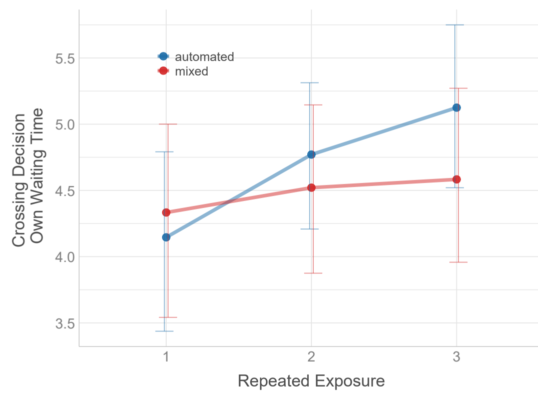


Fig. 9. IE of *eHMI* × *rep. exposure* on *Crossing Decision Own Waiting Time.*

The own waiting time as an influence on the crossing decision increases the more often the participants performed the study. The influence is highest on the third day in automated traffic.

4.5 Communication Quality

The ART found a significant main effect of *eHMI* on presence ($F(1, 23) = 12.96$, p=0.002; higher with M=5.69, SD=1.75 than without an eHMI M=4.19, SD=2.26). Furthermore, the ART found a significant IE of *traffic* × *eHMI* on presence ($F(1, 23) = 4.51$, p=0.045, see Figure 10).

Presence was significantly higher with eHMI and decreased with mixed traffic. In addition, the ART found a significant IE of *eHMI* × *rep. exposure* on the presence ($F(2, 46) = 4.84$, p=0.012, see Figure 11). Presence was permanently higher with than without eHMI. In general, it can be seen that eHMI influences the behavior of the participants.

Furthermore, the ART found a significant main effect of *eHMI* on *hedonic quality* ($F(1, 23) = 6.00$, p=0.022; higher with M=4.87, SD=1.09 than without an eHMI M=4.47, SD=1.22). The ART also found a significant IE of *traffic* × *rep. exposure* on *hedonic quality* ($F(2, 46) = 5.81$, p=0.006, see Figure 12).

Comparing the values of the first day with those of the last day, it is evident that the hedonic quality has increased. On the second day, hedonic quality is highest in the context of fully automated traffic. In contrast, on the first and last day in mixed traffic.

The ART found a significant main effect of *eHMI* on *pragmatic quality* ($F(1, 23) = 12.94$, p=0.002; higher with M=6.02, SD=0.93 than without an eHMI (M=5.36, SD=1.39). In addition, the ART found a significant main effect of *rep. exposure* on *pragmatic quality* ($F(2, 46) = 3.44$, p=0.041). A post-hoc test found no significant differences.

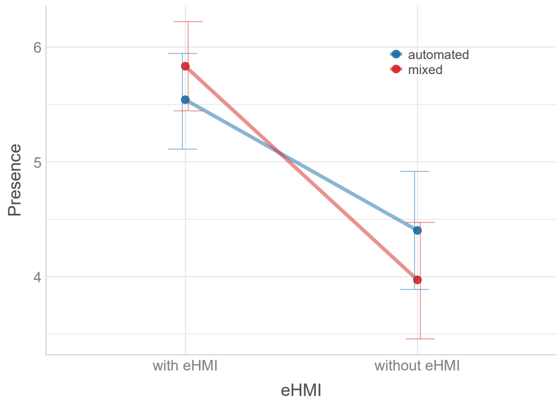


Fig. 10. IE of *traffic* × *eHMI* on *Presence*.

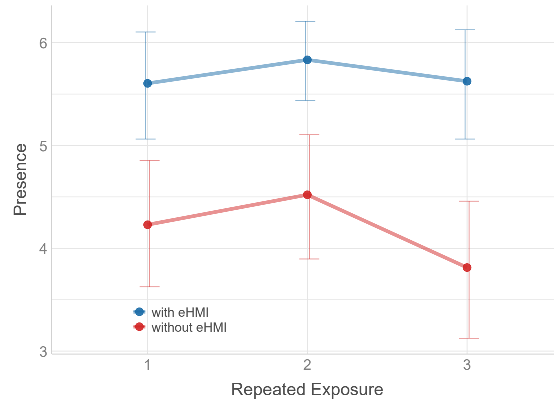


Fig. 11. IE of *eHMI* × *rep. exposure* on *Presence*.

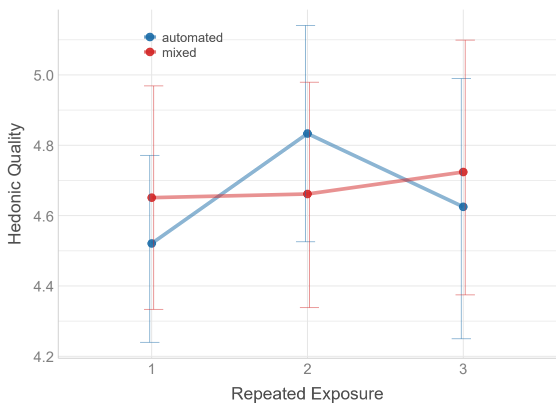


Fig. 12. IE of *traffic* × *rep. exposure* on *Hedonic Quality*.

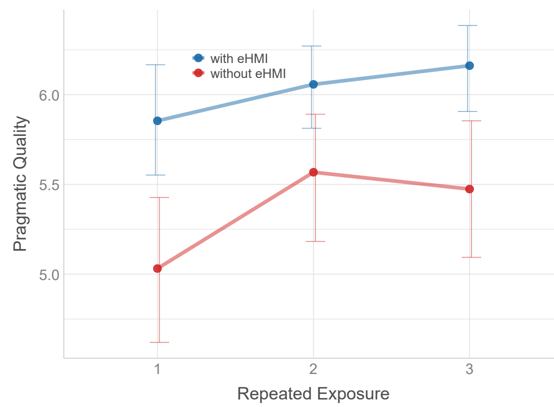


Fig. 13. IE of *eHMI* × *rep. exposure* on *Pragmatic Quality*.

The ART also found a significant IE of *eHMI* × *rep. exposure* on *pragmatic quality* ($F(2, 46) = 3.24$, p=0.048, see Figure 13). Pragmatic quality was higher with than without an eHMI.

4.6 Analysis of Crossing Behavior

In the following section, we present the results of the logging data collected during the crossings. These constitute the crossing behavior data related to the RQs.

4.6.1 Analysis Collisions between Pedestrian and Vehicles. The ART found a significant main effect of *traffic* on *collisions* ($F(1, 23) = 7.36$, p=0.012; lower with automated M=0.08, SD=0.31 than with mixed traffic M=0.15, SD=0.43). The ART found also a significant main effect of *eHMI* on *collisions* ($F(1, 23) = 71.15$, p<0.001). The number of collisions is lower with an eHMI (M=0.10, SD=0.36) than without (M=0.13, SD=0.40). Furthermore, the ART found a significant main effect of *rep. exposure* on *collisions* ($F(2, 46) = 65.22$, p<0.001). A post-hoc test found no significant differences for *collisions*.

The ART found a significant IE of *traffic* × *rep. exposure* on *collisions* ($F(2, 46) = 48.49$, $p<0.001$). The ART found a significant IE of *eHMI* × *rep. exposure* on *collisions* ($F(2, 46) = 67.18$, $p<0.001$).

The ART found a significant IE of *traffic* × *eHMI* × *rep. exposure* on *collisions* ($F(2, 46) = 47.92$, $p<0.001$, see Figure 14). What is striking about the purely automated traffic is that the number of collisions is the same on the first two runs, only varying slightly on the last day. In turn, the number of collisions varies greatly with mixed traffic. In the second run, most collisions occurred with vehicles without eHMI. On the last day, more pedestrians collided with vehicles with an eHMI.

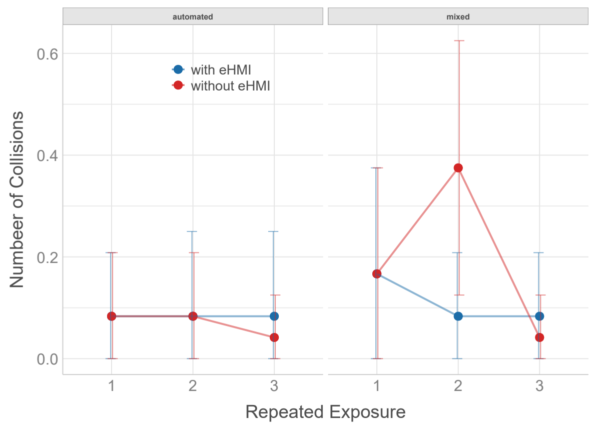
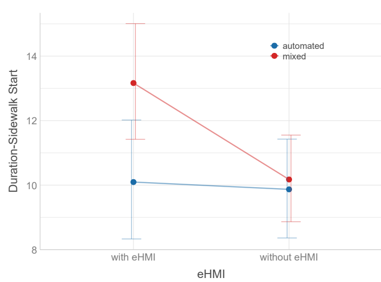
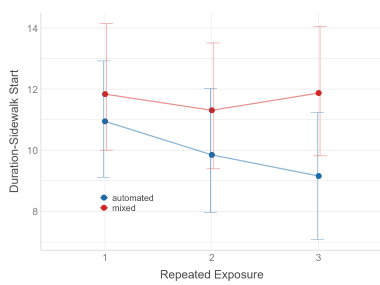


Fig. 14. Three-way IE of *traffic* × *eHMI* × *rep. exposure* on *Collisions*.

4.6.2 Analysis Crossing Duration. The ART found a significant main effect of *traffic* ($F(1, 23) = 34.91$, $p<0.001$), of *eHMI* ($F(1, 23) = 7.45$, $p=0.012$) and of *rep. exposure* on *Duration on the sidewalk at the starting point* ($F(2, 46) = 3.27$, $p=0.047$).

The ART found a significant IE of *traffic* × *eHMI* on *Duration on the sidewalk at the starting point* ($F(1, 23) = 8.25$, $p=0.009$, see Figure 15). The duration is shorter in situations without eHMI. The participants took the longest in the scenarios in which they were exposed to mixed traffic and an eHMI.





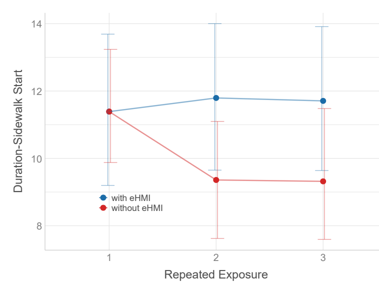


Fig. 15. IE *traffic* × *eHMI* on *Duration on the sidewalk at the starting point.*

Fig. 16. IE *traffic* × *rep. exposure* on on *Duration on the sidewalk at the starting point.*

Fig. 17. IE *eHMI* × *rep. exposure* on *Duration on the sidewalk at the starting point.*

The ART found a significant IE of *traffic* × *rep. exposure* on *Duration on the sidewalk at the starting point* ($F(2, 46) = 3.88$, $p=0.028$, see Figure 16). The duration on the sidewalk at the starting point was the longest with both manually driven vehicles and AVs. The time on the sidewalk decreased with the number of passes in purely automated traffic.

The ART also found a significant IE of *eHMI* × *rep. exposure* on *Duration on the sidewalk at the starting point* ($F(2, 46) = 5.26$, p=0.009, see Figure 17). Strikingly, the duration on the sidewalk increased with eHMI. In contrast, the duration decreased when no eHMI was present.

Furthermore, the ART found a significant main effect of *rep. exposure* on *Duration in the first lane* ($F(2, 46) = 3.60$, p=0.035). A post-hoc test found that Three was significantly higher (M=3.19s, SD=1.54s) in terms of *Duration in the first lane* compared to One (M=2.69s, SD=1.10s; $padj$=0.031). Furthermore, the ART found no significant effects on *Duration in the second lane.*

The ART also found a significant main effect of *traffic* ($F(1, 23) = 43.07$, p<0.001; lower with only AVs M=18.50s, SD=7.56s than when mixed M=20.28s, SD=7.67s) and *eHMI* on *Total crossing time* ($F(1, 23) = 7.36$, p=0.012; longer with eHMI M=20.28s, SD=8.44s than without M=18.50s, SD=6.70s). In addition, the ART found a significant main effect of *rep. exposure* on *Total crossing time* ($F(2, 46) = 6.03$, p=0.005). A post-hoc test found that One was significantly higher (M=20.24s, SD=7.11s) in terms of *Total crossing time* compared to Three (M=18.65s, SD=7.81s; $padj$=0.005) and Two (M=19.28s, SD=8.02s; $padj$=0.033). The ART found a significant IE of *traffic* × *eHMI* on *Total crossing time* ($F(1, 23) = 8.43$, p=0.008, see Figure 18). The total time is surprisingly shorter without an eHMI. The participants took the longest when exposed to mixed traffic and an eHMI.

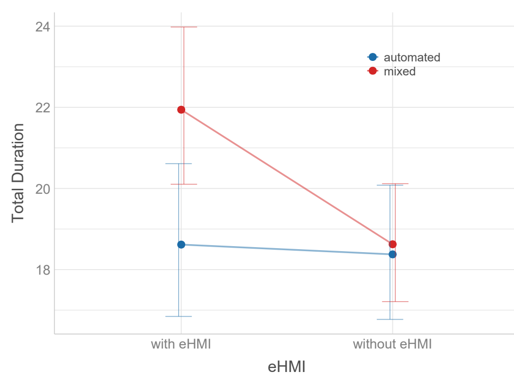


Fig. 18. IE *traffic* × *eHMI* on *Total crossing time.*

5 DEMOGRAPHICS FOR ONLINE STUDIES 2 AND 3

5.1 Procedure

The study, lasting 80 minutes, involved participants recruited via Prolific and MTurk who completed it online by crossing a road six times and answering questionnaires. Initially, participants consented to data processing, confirmed system requirements, and accessed the study materials through a provided download link. The introduction phase also included a trial run and demographic data collection. The main study phase involved road crossing via mouse and keyboard, followed by a questionnaire. The study concluded with a final questionnaire and a $15 reward for those who complied with the study rules and successfully completed attention checks.

We determined the necessary sample size via an a-priori power analysis using G*Power in version 3.1.9.7 [31]. To achieve a power of .8 with an alpha level of .05, 20 participants should result in an anticipated medium effect size (0.25 [34]) in a within-between interaction repeated-measures ANOVA with two groups and 6 measurements.

5.2 Demographic Data

United States. *N*=15 American participants (7 males, 7 females, and 1 not-binary) completed the study with an average age of *M*=34.2 years (*SD*=8.94, range: 24-59 years). The participants grew up in the following states: Arizona (1), California (3), Chicago (1), Colorado (1), Florida (1), Georgia (1), Michigan (1), New Jersey (1), New York (1), Ohio (1), Pennsylvania (1) and Utah (1). Another test person grew up in Mexico and currently lives in the USA. On a 5-point Likert scale (1 = Strongly Disagree - 5 = Strongly Agree), participants showed interest in AVs (*M*=3.73, *SD*=0.59), believed AVs to ease their lives (*M*=3.53, *SD*=0.83), and were unsure whether AVs become a reality by 2032 (*M*=3.73, *SD*=0.46). Additionally, they were asked to evaluate their pedestrian behavior using the pedestrian behavior scale [92]. They used a 6-point Likert scale (1 = never and 6 = always). The rating of pedestrian behavior in terms of intentional deviation from social rules without the intention to cause damage is below average (*M*=2.33, *SD*=1.10). Also striking is the assessment of the participants (*M*=2.67, *SD*=1.25) in relation to the insufficient knowledge of traffic rules and/or the conclusions that have an impact on the decision. In contrast, participants rated their behavior in the context of unintentional deviation due to lack of concentration as of little importance (*M*=1.48, *SD*=1.05). In addition, participants do not have the tendency to misinterpret the behavior of other road users to annoy or endanger them (*M*=1.62, *SD*=0.92). The highest rating (*M*=3.93, *SD*=0.82) was given to the participants' assessment of their behavior to avoid violations or mistakes and also ensure compliance with traffic rules. Finally, the participants were asked which means of transportation they use and their relationship to walking (*M*=2.93, *SD*=1.27) [35, 49].

Germany. *N*=13 German participants (5 males and 8 females) successfully completed the online-based study. The average age is *M*=30.62 years (*SD*=13.95, range: 21-62 years). The participants show an interest in AVs (*M*=3.69, *SD*=0.63). They also find that AVs can make their lives easier (*M*=3.46, *SD*=0.78). They also assume that AVs could be a reality in 30 years (*M*=3.84, *SD*=0.87). Participants rated their intentional deviation from social rules as above average (*M*=3.25, *SD*=1.00). In addition, the insufficient knowledge of the traffic rule and/or the conclusion of the German participants is striking (*M*=3.73, *SD*=0.90). They also indicated that the lack of concentration on the task had little effect on their pedestrian behavior (*M*=2.27, *SD*=1.12). However, the participants rated their behavior as low aggressive (*M*=1.62, *SD*=0.38). In contrast, they rated their behavior in a positive context as high (*M*=4.04, *SD*=0.75). To better classify the participants, they were additionally asked about their relationship to walking (*M*=3.82, *SD*=1.01) [35, 49].

6 ANCHORING ONLINE STUDY WITH VR STUDY: INSIGHTS FROM STUDIES 1 AND 2

We compare the results of the lab-based VR study in Germany (Study 1) and the online website-based study in Germany (Study 2) to evaluate the effects of different study modalities. We use Bayes Factors (BF), calculated with the package `BayesFactor` using *JZS priors*. We examined the factors *study (VR, online-based)*, *eHMI (with eHMI, without eHMI)*, and *repeated exposure (One, Two, Three)*. Evidence is interpreted according to Jeffreys [47]. For conciseness, we only report the effects of the study approach (VR vs. online-based), which represents the difference or equality between the two approaches.

We compare the results per dependent variable. If there was moderate evidence for equal results, we determined that this variable is comparable (✔). For anecdotal evidence, it is unclear (?).

6.1 Results

The results are shown in Table 1.

6.2 Discussion & Summary

We compared a VR study with German participants (Study 1) with an online-based study with movement via the keyboard and mouse with German participants (Study 2). Fuest et al. [33] carried out a comparative study

Dependent Variable	VR Mean	VR SD	Online-based Mean	Online-based SD	BFs	Evidence	Comparable
Mental Workload	5.35	3.85	10.14	4.28	$BF = 1.87e + 12$	Extreme	No ✗
Understanding	3.91	0.91	2.98	0.68	$BF = 2.87e + 10$	Extreme	No ✗
Trust	4.16	0.80	3.53	0.80	$BF = 2.72e + 05$	Extreme	No ✗
Perceived Safety	2.15	1.06	1.03	1.26	$BF = 3.10e + 08$	Extreme	No ✗
Effect of Speed on Decision	5.39	1.57	4.14	1.36	$BF = 7.69e + 05$	Extreme	No ✗
Effect of Distance on Decision	5.43	1.76	5.31	1.63	$BF = 1/5.79$	Moderate	Yes ✔
Effect of Communication on Decision	4.68	2.30	3.21	2.31	$BF = 1.87e + 03$	Extreme	No ✗
Own Waiting Time	3.94	2.05	3.82	1.79	$BF = 1/6.01$	Moderate	Yes ✔
Presence (eHMI)	4.97	2.09	5.64	1.72	$BF = 2.33$	Anecdotal	Unclear ?
Pragmatic Quality	5.65	1.27	4.12	1.50	$BF = 1.15e + 11$	Extreme	No ✗
Hedonic Quality	4.66	1.15	4.27	1.23	$BF = 1.99$	Anecdotal	Unclear ?
Collisions	0.11	0.38	0.18	0.42	$BF = 1/3.18$	Moderate	Yes ✔
Sidewalk Waiting Duration	10.83s	7.29s	6.55s	8.47s	$BF = 1.31e + 03$	Extreme	No ✗
First Lane Duration	3.03s	2.05s	3.01s	2.85s	$BF = 1/7.14$	Moderate	Yes ✔
Second Lane Duration	2.52s	1.19s	1.90s	3.35s	$BF = 3.32$	Moderate	Yes✔
Total Duration	19.39s	7.66s	11.76s	10.50s	$BF = 1.57e + 09$	Extreme	No ✗

Table 1. Comparison of metrics between VR and online-based studies with Bayesian Factors indicating evidence strength.

to assess the impact of AV driving behavior on pedestrians across three different settings: real life (Wizard of Oz), VR, and video. They determined that a video-based Wizard of Oz setup effectively replicates the critical pedestrian crossing rate observed in real-world scenarios, with a minimal variance of $\Delta < 1\%$ (see also Recarte et al. [77]). However, while our online and our virtual environments are equal regarding their visual appearance, the interaciton with the environment differed (keyboard and mouse vs real movement). Nonetheless, a hint as to whether the real world and virtual environments are comparable is given by Holländer et al. [43], who implemented an online game to study road-crossing behavior. They found that "real and virtual environments correlated" [43, p. 1]. This approach is the basis for the results reported by Colley et al. [8], who have implemented the closest apparatus to ours.

To the best of our knowledge, however, this study is the most comprehensive comparison of the two study methodologies, which were used extensively in prior work. We show that **the results using these methods are not directly comparable.** Nonetheless, they provide a way to compare participants in different localities efficiently and, based on the results of Holländer et al. [43], could be correlated to the real world.

7 CULTURAL DIFFERENCES BETWEEN GERMAN AND US PARTICIPANTS

In this section, we compare the data from the online, website-based study with German participants (Study 2) and US participants (Study 3) to answer RQ3. Study 3 had procedures and measurements identical to those of Study 2.

7.1 Mental Workload, Trust & Perceived Safety

The ART found a significant main effect of *rep. exposure* on mental workload ($F(2, 52) = 4.68$, p=0.014). The ART also found a significant IE of *cult. background* × *eHMI* on mental workload ($F(1, 26) = 11.97$, p=0.002).

Furthermore, the ART found a significant IE of *cult. background* × *eHMI* × *rep. exposure* on mental workload ($F(2, 52) = 3.48$, p=0.038; see Figure 19).

Participants from Germany initially have a higher mental workload with eHMI, which decreases over the second day and is almost equal to those without eHMI on the last day. For the participants from the USA, the

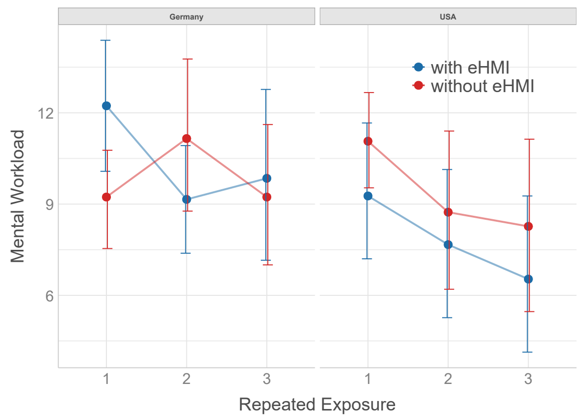


Fig. 19. Three-way IE of *cult. background* × *eHMI* × *rep. exposure* on *Mental Workload*.

mental workload decreased continuously over the three test days. In addition, the workload is lower over all three days with eHMI.

The ART found a significant main effect of *eHMI* on Understanding ($F(1, 26) = 10.15$, p=0.004). Understanding was higher with (M=2.99, SD=0.61) than without an eHMI (M=2.73, SD=0.66). In addition, the ART found a significant main effect of *eHMI* on Trust ($F(1, 26) = 11.98$, p=0.002). Trust was higher with (M=3.68, SD=0.91) than without an eHMI (M=3.35, SD=0.91).

The ART found no significant effects on perceived safety.

7.2 Crossing Decision

Using a 7-point Likert scale, participants were asked to rate the four reasons [76] that influenced the crossing decision.

In both demographics, the distance between vehicles has the greatest influence on the crossing decision (Germany: 32.22 %; USA 32.76 %). The lowest impact is represented by the communication of the vehicles via the LED in both demographics (Germany: 19.46 %; USA 19.3 %).

The individual reasons for the crossing decisions, if an effect was observed, are listed below. The ART found no significant effects on *speed* and *distance* as a decision to cross the road.

7.2.1 Effect of Communication on Crossing Decision. The ART found a significant main effect of *eHMI* on communication ($F(1, 26) = 6.34$, p=0.018). Communication had a greater impact on crossing decisions when an eHMI (M=3.75, SD=2.50) was present than without (M=2.69, SD=1.88).

7.2.2 Effect of Own Waiting Time on Crossing Decision. The ART found a significant IE of *cult. background* × *rep. exposure* on own waiting time ($F(2, 52) = 3.23$, p=0.048).

The ART also found a significant IE of *cult. background* × *eHMI* × *rep. exposure* on own waiting time ($F(2, 52) = 3.31$, p=0.044; see Figure 20).

In a general comparison, the reason for the crossing decision increases for US participants over the three trial days. In contrast, the value decreases for the German participants. For the German participants, their own waiting time had little influence on their crossing decision on the third day if the vehicle had an eHMI. In contrast, this had the highest value for US participants.

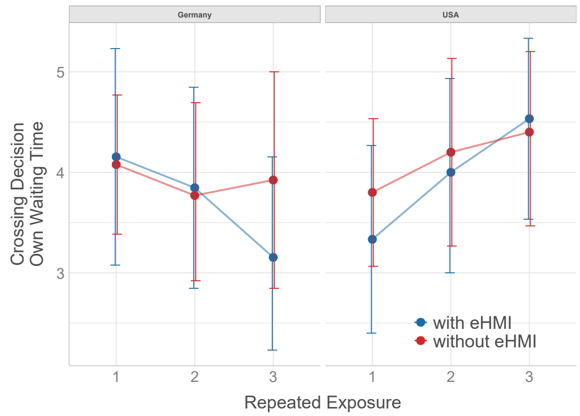


Fig. 20. Three-way IE of *cult. background* × *eHMI* × *rep. exposure* on *Own Waiting Time*

7.3 Communication Quality

The ART found no significant effects on the presence (of eHMI), which was measured by participants' agreement on a 7-point Likert scale. Furthermore, the ART found a significant main effect of *eHMI* on pragmatic quality ($F(1, 26) = 7.41$, p=0.011). Pragmatic quality was significantly higher with an eHMI (M=4.28, SD=1.79) than without an eHMI (M=3.70, SD=1.45). However, ART found no significant effects on hedonic quality.

7.4 Analysis of Logging-Data

Analysis of logging data in relation to the VR study and the cultural backgrounds of the participants.

7.4.1 Collisions between Pedestrian and Vehicles. The ART found a significant main effect of *cult. background* ($F(1, 26) = 11.74$, p=0.002), of *eHMI* ($F(1, 26) = 32.01$, p<0.001), and of *rep. exposure* on number of collisions ($F(2, 52) = 22.71$, p<0.001). The ART also found a significant IE of *cult. background* × *rep. exposure* ($F(2, 52) = 19.26$, p<0.001) and of *eHMI* × *rep. exposure* on number of collisions ($F(2, 52) = 29.86$, p<0.001).

The ART furthermore found a significant IE of *cult. background* × *eHMI* × *rep. exposure* on number of collisions ($F(2, 52) = 7.87$, p=0.001; see Figure 21).

In general, Germans have fewer collisions with vehicles than Americans. The number of collisions with vehicles with an eHMI is also higher than without, and this is independent of cultural background.

7.4.2 Analysis Crossing Duration. In this section, we investigated the participants' individual times on the two sidewalks, the road, and the total time.

The ART found a significant main effect of *eHMI* on *Duration on the sidewalk at the starting point* ($F(1, 26) = 5.86$, p=0.023). The duration of participants on the sidewalk at the starting point was higher (M=6.01s, SD=7.50s) when the vehicle did not have an eHMI (M=9.07s, SD=10.31s) than with (M=6.01s, SD=7.50s).

The ART also found a significant main effect of *eHMI* ($F(1, 26) = 7.20$, p=0.013; higher with an eHMI: M=5.89s, SD=21.94s) and of *rep. exposure* on *Duration in the first lane* ($F(2, 52) = 7.66$, p=0.001; no sig. post-hoc test).

The ART found a significant IE of *cult. background* × *rep. exposure* ($F(2, 52) = 7.32$, p=0.002) and of *eHMI* × *rep. exposure* on *Duration in the first lane* ($F(2, 52) = 16.45$, p<0.001).

Furthermore, the ART found a significant IE of *cult. background* × *eHMI* × *rep. exposure* on *Duration in the first lane* ($F(2, 52) = 9.65$, p<0.001; see Figure 22).

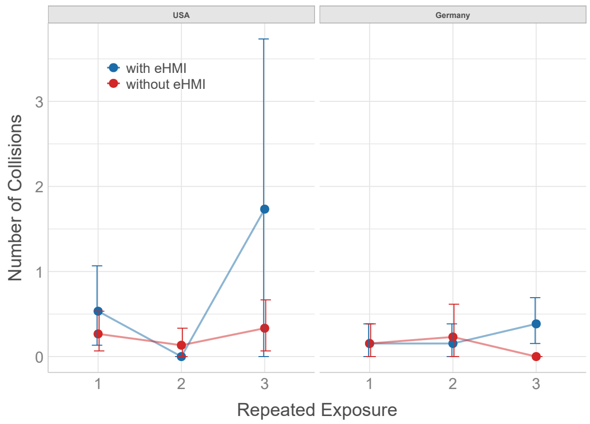


Fig. 21. Three-way IE of *cult. background* × *eHMI* × *rep. exposure* on *Number of Collisions.*

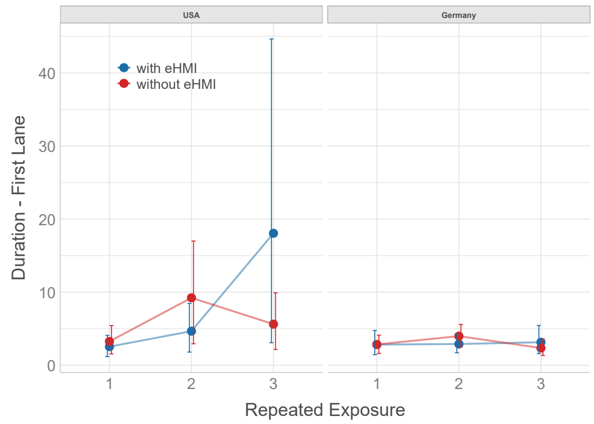


Fig. 22. Three-way IE of *cult. background* × *eHMI* × *rep. exposure* on *Duration in the first lane.*

For the German participants, the presence of an eHMI had little effect on the duration in the first lane. For the US participants, the duration in the first lane is the longest on the third day of the test with eHMI.

For *Duration in the second lane* ($F(2, 52) = 5.16$, p=0.009), the ART found a significant IE of *cult. background* × *rep. exposure* (see Figure 23).

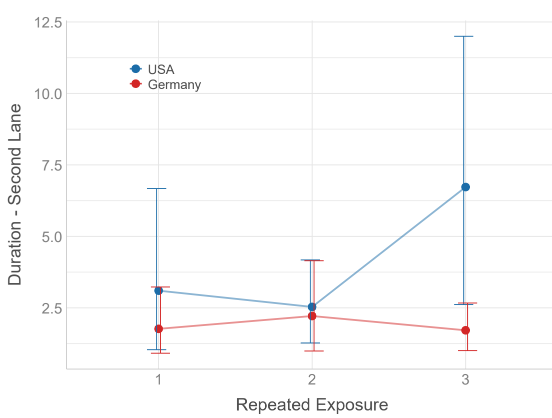


Fig. 23. IE of *cult. background* × *rep. exposure* on *Duration in the second lane.*

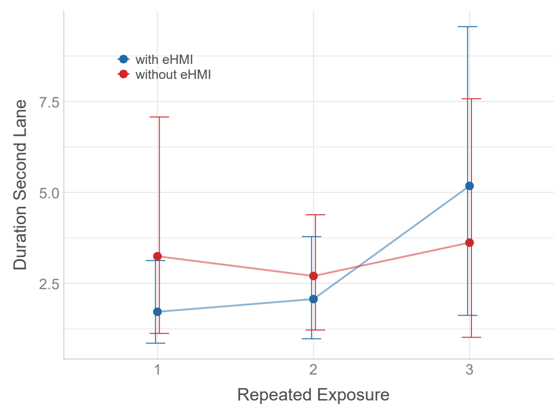


Fig. 24. IE of *eHMI* × *rep. exposure* on *Duration in the second lane.*

German participants have a shorter duration in the second lane. It is striking that the US participants spent the longest time in the second lane on the third day of the test.

The ART found a significant IE of *eHMI* × *rep. exposure* on *Duration in the second lane* ($F(2, 52) = 4.17$, p=0.021; see Figure 24). The duration of participants on the second lane on the third repeated exposure is significantly higher than the other two times.

The ART found a significant main effect of *cult. background* on *Total crossing time* ($F(1, 26) = 5.21$, p=0.031; higher for US participants with M=11.76s, SD=10.50s). The ART also found a significant IE of *eHMI* × *rep. exposure* on *Total crossing time* ($F(2, 52) = 4.42$, p=0.017). Furthermore, the ART found a significant IE of *cult. background* × *eHMI* × *rep. exposure* on *Total crossing time* ($F(2, 52) = 5.04$, p=0.010; see Figure 25). It is evident that for

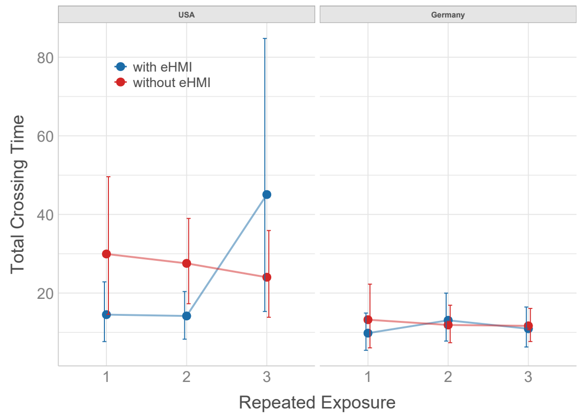


Fig. 25. Three-way IE of *cult. background* × *eHMI* × *rep. exposure* on *Total crossing time*

participants from Germany, the presence of an eHMI does not have a major impact on crossing time. In contrast, the duration increased when an eHMI was present for the participants from the US.

8 DISCUSSION

The focus of this work was three-fold. First, we evaluated the longitudinal effects of *eHMI* and *traffic* in a VR scenario in Germany. Then, we compared this to a website-based longitudinal evaluation with German participants. We found that the two methodologies do not lead to equal results; however, it is still a valid approach to gathering more diverse and international data. Finally, we compared the website-based data from Germany with website-based data from US participants. In this section, we discuss the results of the three studies in relation to the previously defined RQs and previous work.

The eHMI led to various positive outcomes, including shorter crossing times, reduced mental demand and effort, increased perceived safety and trust. These results align with earlier studies, which also observed similar positive effects [7, 19, 29, 54, 56]. The longitudinal results also aligned with previous results showing reduced traffic durations and increased trust and perceived safety [7], however, previous had evaluated these repeated exposure effects on one single day. This work confirms these effects over the duration of a week. Interestingly, most of these positive effects (i.e., mental workload, trust, and crossing decision) were perceivable both for the study with German participants in VR as well as in the online-based studies for both there German and US participants while not as pronounced when comparing the two demographics.

8.1 RQ1: Longitudinal Effects of eHMIs in Virtual Reality

The main decision for crossing found is *gap acceptance*, which depends on speed and vehicle distance [18, 27, 75]. Our participants also rate these two factors most highly as a decision reason. The IE regarding speed as a crossing decision suggests that participants trusted that AVs would stop (*"Positive effects because you Trust the vehicle more than if it was human controlled."*, *"I think AVs are less prone to failure than human drivers and therefore the risk of collisions for pedestrians can be minimized."*). Thereby, the values for with and without eHMI differ only minimally in the crossing decision (see Figure 6). For communication as a reason for crossing, the perceived presence of an eHMI is higher rated than without (meaning that participants **did** notice the eHMI). In addition, the data suggest that communication via the LED strips is more necessary in mixed traffic than when the traffic consists of only AVs (see Figure 7). This observation is consistent with previous research that found clear communication of AVs in mixed traffic to be necessary [36, 66, 83]. Participants spent less on the sidewalk in terms of time in relation to traffic over the course of the study. This also suggests increasing Trust and perceived safety in the AVs and their functioning. Another interaction occurs in the duration of the participants' stay on the sidewalk at the starting point in relation to eHMI and traffic type. For example, in mixed traffic, participants waited longer for feedback from the AV so that it was clear that they could cross the street. In addition, an interaction between eHMI and repeated exposure occurs the more times they have experienced the situation. This observation is consistent with the improved learning ability measured by Faas et al. [29] with regard to a more frequent interaction between pedestrians and AVs [29]. The data also suggest that the more Trust the participants had in the AVs, the shorter they waited on the sidewalk at the starting point. This can be seen in the figures of the waiting behavior and the walking profiles. This aligns with the observations of M. Faas et al. [61] in their video-based study [61]. The IE in the context of the number of collisions suggests that participants rely on and are more likely to wait for the AVs and their eHMI than, in contrast, participants without eHMI. More collisions occurred in mixed traffic because participants did not know whether the vehicle understood their intention to cross. This observation is also reflected in the IE of total crossing time, as participants in mixed traffic and with eHMI took the longest.

Furthermore, our data recommend that an eHMI helps increase Trust, Understanding, and perceived safety and reduces mental workload. This aligns with previous work and further highlights the potential benefits of eHMIs. Furthermore, the data indicate that as the number of repetitions increases, especially in the relation between the first and third runs, comprehension and perceived safety increase and mental workload decreases. This is in accordance with the longitudinal video study of Faas et al. [29] and the VR study of Colley et al. [7]. In addition, we found a significant IE between traffic and repeated exposure in terms of perceived safety. Thus, safety increases when participants cross the street more often, although the type of traffic has no influence.

The eHMI also had a significant influence on the quality of communication, namely on the presence (of an eHMI), hedonic quality, and pragmatic quality. The ratings of the eHMI align with the color and animation preferences for eHMI of Dey et al. [23]. An important longitudinal result is that it seems that participants no longer paid attention to the eHMI later in the study (*"At the beginning of the study, I still paid attention to the LED lights, but in the course of the study, the LED lights were no longer decisive"*, *"I would already no longer need the communication"*, *"I think it will go relatively quickly that this communication will no longer be necessary. People will Trust the system."*). This is in line with results by Colley et al. [7]. Similar behavior can be observed for appropriateness in the context of repeated exposure, with/without eHMI and automated traffic. Only in the case of mixed traffic is appropriateness with eHMI required since, here, a direct comparison can be drawn between the manually driven vehicles and AVs.

8.2 RQ2: Comparison Germany VR & Online-based Study

For most dependent variables, we found moderate to extreme evidence for differences (see Table 1). For example, the participants in the online-based study spent less time on the sidewalk. This may be due to the limited perception of pedestrians to the crossing situation [33, 55, 72]. The data also suggest that the participants were quicker to complete the crossing scenarios successfully. However, an increased number of collisions implied that the participants were riskier (see Section Table 1). This may be because online participants are more inaccurate in their execution [17]. Furthermore, in the case of mental workload, the VR and the online-based study are not comparable, potentially because the immersion in the crossing situation is reduced, and the control of the pedestrian in combination with the head rotation requires more concentration. The data suggest that mental workload was the lowest for the scenarios in VR. The reason for this may be the participants' lack of spatial awareness in the online-based study; they are not aware of where they are currently positioned in the study.

In conclusion, the choice of the study approach directly impacts the results. This is in line with the results of the empirical study by Voit et al. [93] but also contradicts previous research on comparability [33]. Therefore, this paper also acts as a call to determine possibilities to incorporate the findings of many studies on eHMIs into a coherent picture. It can also be summarized that the participants in the VR study were more completely immersed and that this had a significant influence on the behavior [16, 33].

8.3 RQ3: Comparison German and US Participants in Online-based Study

While the study samples for studies 2 and 3 were only moderate, we discuss some key findings.

For both backgrounds, the main reason for crossing is the distance between vehicles (see Section 7.2). For the German sample, similar to the VR study, the data also suggest speed as a determinant for crossing decisions. For the US sample, however, it is their own waiting time. The data suggest that the rating increases the more often they interact with a vehicle. Whereas for Germans, the score drops. The Germans waited longer for the vehicle to stop and/or the eHMI to communicate. As US participants crossed earlier, an eHMI could not reduce the crossing risk, leading to more collisions than the German participants. It is striking that the number of collisions increases significantly for US participants during the course of the study. The reason for this may be the earlier entry into the first lane. The crossing duration being longer for US participants can be explained by the three outliers who chose a longer path when crossing, which is evident in the walking profiles (see Appendix A).

The IE between eHMI, cultural background, and repeated exposure (see Figure 19) shows that US participants reported a generally lower mental workload with an eHMI and that this also decreased quickly over the three days.

In so-called Dignity cultures [58], found mainly in Western Europe and North America, self-worth comes from within and is not influenced by others' opinions or values. These cultures prioritize individualism, have low power distance, and operate within an egalitarian context focusing on individual goals. Legal systems here enforce contracts and rights, fostering an environment where people treat each other as equals and engage in reciprocal exchanges to build integrity and trust. Consequently, there is a prevailing belief in "swift trust," where people are trusted unless proven otherwise. These traits suggest that individuals from dignity cultures may quickly trust in automation. As the US and the German participants both belong to the so-called Dignity cultures [58], it is not surprising that we found no significant differences between the two study populations in Trust. Nonetheless, our data suggest that an eHMI increases both Trust and Understanding. However, no main effects were recorded for perceived safety.

Although the traffic cultures in the US and Germany share many similarities, our research identified significant differences in how individuals from these demographics interact with AVs. This finding underscores the presence of notable distinctions between even culturally similar but geographically distinct regions, particularly in the context of traffic behavior. These disparities are likely to be even more pronounced in other countries and contexts where cultural differences are expected to be greater, such as in various European countries, Asia, and the Global South. Consequently, it is imperative to carefully consider the influence of cultural factors when designing interactions with AVs.

Despite the overarching similarities in traffic regulations, vehicle technology, and road infrastructure between the US and Germany, our study highlights that cultural nuances significantly affect human-AV interactions. This suggests that cultural attitudes towards technology, risk, and authority are crucial in shaping these interactions. As AV technology continues to evolve and become more prevalent globally, the impact of cultural differences will become increasingly critical. In countries with vastly different traffic cultures and societal norms, such as Asia or the Global South, the interaction dynamics with AVs may differ even more starkly. Therefore, it is essential for designers and engineers to integrate a deep understanding of these cultural factors into the development process to ensure the safe and efficient deployment of AVs. We highlight here that a one-size-fits-all approach to AV interaction design is inadequate. Instead, a culturally sensitive framework is necessary, one that takes into account the specific behaviors, expectations, and attitudes of users from diverse backgrounds. This approach will not only enhance the usability and acceptance of AVs but also contribute to their overall safety and effectiveness on a global scale.

8.4 Limitations and Future Work

The number of participants (VR: N=24; online-based: N=15 (USA) & N=13 (Germany)) was rather low. In the two other intercultural studies on eHMIs, Lanzer et al. [53] recruited 90 participants and Joisten et al. [51] recruited 205 participants in total. While some studies used as few as 28 participants for a comparison between China, USA, and Germany [82], generally, for other cultural comparisons, numbers can even be much higher (e.g., 856 for comparing general pedestrian crossing between Beijing, China and Munich, Germany [48]). However, these works used online-based video studies compared to our interactive simulation. Additionally, the two cultural backgrounds of our study are usually grouped together in research because they are both considered Western [53, 58, 74, 94]. Nonetheless, there are crucial differences between the two (e.g., how ready AVs are perceived [90]), so such a comparison is often made in previous work [82]. Therefore, it is difficult to make a globally valid statement about culture because many countries have left-hand traffic, and we had right-hand traffic in the study [3]. The collisions also suggest that participants would have behaved more cautiously in the real world (see Sections 4.6.1, Table 1, and 7.4.1). In addition, three experimental days can only provide an indication of the extent to which participants can become accustomed to an AV with/without eHMI.
Transferability to a real-world scenario is difficult to assess. However, we can provide initial evidence of how pedestrians behave in scenarios with eHMIs, with repeated exposure in relation to their cultural background.

The online-based study should be conducted in a country with a different cultural background, such as China or Japan, as the form of politeness is different from that in Western countries [45, 53].
Another RQ could examine the behavior of pedestrians when other people are around them or also want to cross the street [7]. In countries such as China or Japan, harmony and togetherness within the population influence behavior and predefined social rules [40, 71]. In addition, investigations into the behavior of test persons in combination with left and right-hand traffic would be interesting. In many cases, pedestrians look at their cell phones while crossing the street and thus have a secondary task [54]. An investigation could find out whether a cultural tendency is also emerging in this environment.

One inherent limitation of this study might be its reliance on a VR and screen-based methodology. While this provides a straightforward and safe way for proof-of-concept validations, it may lead participants to engage in riskier behaviors than they would in a more hazardous real-world setting. Nonetheless, previous research, such as that by Recarte et al. [77], indicates that time-to-arrival estimates are consistent between video simulations and real-life situations. Similar methodologies have been effectively employed in past research to examine interactions between AVs and pedestrians [26]. Furthermore, the literature supports that the impact of vehicles on pedestrians, when viewed through videos, aligns closely with actual experiences. Shen et al. [85] created a video-based tool to assess the safety of young pedestrians' street-crossing behavior and found these video-based assessments to be both valid and reliable. Fuest et al. [33] compared the effects of AV driving behaviors on pedestrians in real-life scenarios, VR, and video settings. They determined that a video-based Wizard of Oz setup, similar to the one used in this study, closely replicates real-world pedestrian crossing rates with a negligible difference of less than 1% [33]. Therefore, we believe our findings are ecologically valid.

Finally, the comparability between the VR and screen-based methodologies, despite using the same graphical fidelity, is unclear. VR offers not only greater immersion but also reduced participant control. This increased interactivity can lead to different levels of engagement and potentially affect participant responses and behaviors, contrasting with the more static nature of screen-based environments.

9 CONCLUSION

We explored how pedestrian behavior is influenced when crossing streets in an urban setting, with particular attention given to eHMIs, the number of repetitions with an AV, the type of traffic (manual or automated), and the pedestrian's cultural background. Three distinct studies were conducted. First, in a VR study with N=24 participants executed at the University of Ulm, participants physically moved and interacted within a virtual environment. The second and third were online-based studies, which utilized keyboard and mouse inputs to simulate pedestrian behavior. These studies were international, with 13 participants from Germany (Study 2) and 15 participants from the USA (Study 3). The VR study results showed that as participants interacted more with the AV, their Understanding, Trust, and perceived safety increased. Furthermore, the mental workload decreased over time. Additionally, participants reported finding communication via eHMI to be more pleasant and easier to understand. The online-based studies yielded some contrasting results, particularly concerning cultural differences. US participants showed lower levels of mental workloads. However, this lower mental workload was associated with more collisions as the study progressed. The VR study results aligned with existing research, confirming the beneficial role of eHMI in increasing pedestrian safety and reducing mental workload. However, the online and VR study outcomes were not directly comparable, potentially due to the differences in the level of immersion and the limitations in the perception of the online-based study participants. This work helps assess different study approaches regarding the effects of eHMIs and provides initial evidence regarding cultural differences.

OPEN SCIENCE

The scenarios, anonymized data, and evaluation scripts are available to interested researchers (see https://github.com/M-Colley/longitudinal_usa_germany_eHMI_comparison).

ACKNOWLEDGMENTS

We thank all study participants. This work was supported by a fellowship of the German Academic Exchange Service (DAAD).

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. https://doi.org/10.1016/j.apergo.2018.11.002

[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*. ACM, Honolulu HI USA, 1–14. https://doi.org/10.1145/3313831.3376197

[3] ADAC. 2022. Linksverkehr - Tipps für Autofahrer. https://www.adac.de/reise-freizeit/ratgeber/reisetipps/linksverkehr/

[4] Pavlo Bazilinskyy, Dimitra Dodou, and Joost De Winter. 2019. Survey on eHMI concepts: The effect of text, color, and perspective. *Transportation research part F: traffic psychology and behaviour* 67 (2019), 175–194. Publisher: Elsevier.

[5] Mercedes Benz. 2022. The Mercedes-Benz F 015 Luxury in Motion. https://www.mercedes-benz.com/en/innovation/autonomous/research-vehicle-f-015-luxury-in-motion/

[6] Marc-Philipp Böckle, Anna Pernestål Brenden, Maria Klingegård, Azra Habibovic, and Martijn Bout. 2017. SAV2P: Exploring the Impact of an Interface for Shared Automated Vehicles on Pedestrians' Experience. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct*. ACM, Oldenburg Germany, 136–140. https://doi.org/10.1145/3131726.3131765

[7] Mark Colley, Elvedin Bajrovic, and Enrico Rukzio. 2022. Effects of Pedestrian Behavior, Time Pressure, and Repeated Exposure on Crossing Decisions in Front of Automated Vehicles Equipped with External Communication. In *CHI Conference on Human Factors in Computing Systems*. ACM, New Orleans LA USA, 1–11. https://doi.org/10.1145/3491102.3517571

[8] Mark Colley, Julian Britten, and Enrico Rukzio. 2023. Scalability in External Communication of Automated Vehicles: Evaluation and Recommendations. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 2, Article 51 (jun 2023), 26 pages. https://doi.org/10.1145/3596248

[9] Mark Colley, Julian Czymmeck, Mustafa Kücükkocak, Pascal Jansen, and Enrico Rukzio. 2024. PedSUMO: Simulacra of Automated Vehicle-Pedestrian Interaction Using SUMO To Study Large-Scale Effects. In *Proceedings of the 2024 ACM/IEEE International Conference on Human-Robot Interaction* (Boulder, CO, USA) *(HRI '24)*. ACM, New York, NY, USA, 890–895. https://doi.org/10.1145/3610977.3637478

[10] Mark Colley, Tim Fabian, and Enrico Rukzio. 2022. Investigating the Effects of External Communication and Automation Behavior on Manual Drivers at Intersections. *Proceedings of the ACM on Human-Computer Interaction* 6, MHCI (Sept. 2022), 1–16. https://doi.org/10.1145/3546711

[11] Mark Colley and Enrico Rukzio. 2020. A Design Space for External Communication of Autonomous Vehicles. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, Virtual Event DC USA, 212–222. https://doi.org/10.1145/3409120.3410646

[12] Mark Colley and Enrico 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*. ACM, Honolulu HI USA, 1–8. https://doi.org/10.1145/3334480.3382844

[13] 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*. ACM, Honolulu HI USA, 1–14. https://doi.org/10.1145/3313831.3376472

[14] 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*. ACM, Utrecht Netherlands, 442–449. https://doi.org/10.1145/3349263.3351523

[15] Mark Colley, Marcel Walch, and Enrico 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*. ACM, Honolulu HI USA, 1–9. https://doi.org/10.1145/3334480.3382865

[16] Cassandra L. Crone and Rachel W. Kallen. 2022. Interview with an avatar: Comparing online and virtual reality perspective taking for gender bias in STEM hiring decisions. *PLOS ONE* 17, 6 (June 2022), e0269430. https://doi.org/10.1371/journal.pone.0269430

[17] Frédéric Dandurand, Thomas R. Shultz, and Kristine H. Onishi. 2008. Comparing online and lab methods in a problem-solving experiment. *Behavior Research Methods* 40, 2 (May 2008), 428–434. https://doi.org/10.3758/BRM.40.2.428

[18] Sanghamitra Das, Charles F. Manski, and Mark D. Manuszak. 2005. Walk or wait? An empirical analysis of street crossing decisions. *Journal of Applied Econometrics* 20, 4 (May 2005), 529–548. https://doi.org/10.1002/jae.791

[19] Koen de Clercq, Andre Dietrich, Juan Pablo Núñez Velasco, Joost de Winter, and Riender Happee. 2019. External Human-Machine Interfaces on Automated Vehicles: Effects on Pedestrian Crossing Decisions. *Human Factors* 61, 8 (2019), 1353–1370. https://doi.org/10.1177/0018720819836343

[20] Joost de Winter and Dimitra Dodou. 2022. External human–machine interfaces: Gimmick or necessity? *Transportation Research Interdisciplinary Perspectives* 15 (2022), 100643. https://doi.org/10.1016/j.trip.2022.100643

[21] 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 (Sept. 2020), 100174. https://doi.org/10.1016/j.trip.2020.100174

[22] 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. In *CHI Conference on Human Factors in Computing Systems*. ACM, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376325

[23] 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. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–13. https://doi.org/10.1145/3313831.3376325

[24] 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*. ACM, Virtual Event DC USA, 192–204. https://doi.org/10.1145/3409120.3410642

[25] 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*. ACM, Toronto ON Canada, 82–86. https://doi.org/10.1145/3239092.3265946

[26] Debargha Dey, Toros Ufuk Senan, Bart Hengeveld, Mark Colley, Azra Habibovic, and Wendy Ju. 2024. Multi-Modal eHMIs: The Relative Impact of Light and Sound in AV-Pedestrian Interaction. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*

(Honolulu, HI, USA) *(CHI '24)*. ACM, New York, NY, USA, Article 91, 16 pages. https://doi.org/10.1145/3613904.3642031

[27] Eliza Yingzi Du, Kai Yang, Feng Jiang, Pingge Jiang, Renran Tian, Michele Luzetski, Yaobin Chen, Rini Sherony, and Hiroyuki Takahashi. 2013. Pedestrian behavior analysis using 110-car naturalistic driving data in USA. , 27–30 pages.

[28] Stefanie M. Faas and Martin Baumann. 2019. Yielding Light Signal Evaluation for Self-driving Vehicle and Pedestrian Interaction. In *In: Ahram T., Karwowski W., Pickl S., Taiar R. (eds) Human Systems Engineering and Design II. IHSED 2019. Advances in Intelligent Systems and Computing*, Vol. 1026. Springer International Publishing, Cham, 189–194. https://doi.org/10.1007/978-3-030-27928-8_29

[29] 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)*. ACM, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376484

[30] 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. Publisher: Elsevier.

[31] 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.

[32] Nicholas N. Ferenchak. 2023. Longitudinal bicyclist, driver, and pedestrian perceptions of autonomous vehicle communication strategies. *Journal of Traffic and Transportation Engineering* 10, 1 (Jan. 2023), S2095756423000107. https://doi.org/10.1016/j.jtte.2022.07.005

[33] Tanja Fuest, Elisabeth Schmidt, and Klaus Bengler. 2020. Comparison of methods to evaluate the influence of an automated vehicle's driving behavior on pedestrians: Wizard of Oz, virtual reality, and video. *Information (Switzerland)* 11, 6 (jun 2020), 22 pages. https://doi.org/10.3390/INFO11060291

[34] 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

[35] Marie-Axelle Granié, Marjorie Pannetier, and Ludivine Guého. 2013. Developing a self-reporting method to measure pedestrian behaviors at all ages. *Accident Analysis & Prevention* 50 (2013), 830–839. https://doi.org/10.1016/j.aap.2012.07.009

[36] Azra Habibovic, Victor Malmsten Lundgren, Jonas Andersson, Maria Klingegård, Tobias Lagström, Anna Sirkka, Johan Fagerlönn, Claes Edgren, Rikard Fredriksson, Stas Krupenia, Dennis Saluäär, and Pontus Larsson. 2018. Communicating Intent of Automated Vehicles to Pedestrians. *Frontiers in Psychology* 9 (Aug. 2018), 1336. https://doi.org/10.3389/fpsyg.2018.01336

[37] Mathias Haimerl, Mark Colley, and Andreas Riener. 2022. Evaluation of Common External Communication Concepts of Automated Vehicles for People With Intellectual Disabilities. *Proc. ACM Hum.-Comput. Interact.* 6, MHCI, Article 182 (Sept. 2022), 19 pages. https://doi.org/10.1145/3546717

[38] Michael Hamm, Wolfgang Huhn, and Johannes Reschke. 2018. Ideas for Next Lighting Generations in Digitalization and Autonomous Driving - Technocal Paper 2018-01-1038. *SAE Technical Papers* 2018-April (2018), 1–8. https://doi.org/10.4271/2018-01-1038

[39] 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. https://doi.org/10.1016/S0166-4115(08)62386-9

[40] Lorena Hell, Janis Sprenger, Matthias Klusch, Yoshiyuki Kobayashi, and Christian Muller. 2021. Pedestrian Behavior in Japan and Germany: A Review. In *2021 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, Nagoya, Japan, 1529–1536. https://doi.org/10.1109/IV48863.2021.9575809

[41] Ann-Christin Hensch, Isabel Neumann, Matthias Beggiato, Josephine Halama, and Josef F. Krems. 2019. How Should Automated Vehicles Communicate? – Effects of a Light-Based Communication Approach in a Wizard-of-Oz Study. In *AHFE 2019. Advances in Intelligent Systems and Computing, vol 964*, Vol. 964. Springer International Publishing, Cham, 79–91. https://doi.org/10.1007/978-3-030-20503-4_8

[42] Geert Hofstede. 2011. Dimensionalizing Cultures: The Hofstede Model in Context. *Online Readings in Psychology and Culture* 2, 1 (Dec. 2011). https://doi.org/10.9707/2307-0919.1014

[43] Kai Holländer, Luca Schellenberg, Changkun Ou, and Andreas Butz. 2020. All Fun and Games: Obtaining Critical Pedestrian Behavior Data from an Online Simulation. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. ACM, New York, NY, USA, 1–9. https://doi.org/10.1145/3334480.3382797

[44] 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*. ACM, Yokohama Japan, 1–13. https://doi.org/10.1145/3411764.3445480

[45] Yongliang Huang. 2008. Politeness Principle in Cross-Culture Communication. *English Language Teaching* 1, 1 (2008), 96–101. Publisher: ERIC.

[46] International Organization for Standardization (ISO)/TR 23049. 2018. *TECHNICAL REPORT ISO: Road Vehicles — Ergonomic aspects of external visual communication from automated vehicles to other road users*. Technical Report. ISO. https://www.iso.org/obp/ui/{#}iso:std:iso:tr:23049:ed-1:v1:en

[47] Harold Jeffreys. 1961. *Theory of Probability* (3 ed.). Oxford University Press, Oxford.

[48] Xiaobei Jiang, Wuhong Wang, Klaus Bengler, and Weiwei Guo. 2015. Analyses of pedestrian behavior on mid-block unsignalized crosswalk comparing Chinese and German cases. *Advances in mechanical engineering* 7, 11 (2015), 1687814015610468.

[49] Philip Joisten, Lukas Bier, and Bettina Abendroth. 2022. Validierung der deutschen Fassung der "Pedestrian Behavior Scale": Ein Fragebogen zur Erfassung des Verhaltens von Fußgänger:innen bei der Straßenquerung. https://doi.org/10.26083/TUPRINTS-00021676
[50] Philip Joisten, Ziyu Liu, Nina Theobald, Andreas Webler, and Bettina Abendroth. 2021. Communication of Automated Vehicles and Pedestrian Groups: An Intercultural Study on Pedestrians' Street Crossing Decisions. In *Mensch und Computer 2021*. ACM, Ingolstadt Germany, 49–53. https://doi.org/10.1145/3473856.3474004
[51] Philip Joisten, Ziyu Liu, Nina Theobald, Andreas Webler, and Bettina Abendroth. 2021. Communication of Automated Vehicles and Pedestrian Groups: An Intercultural Study on Pedestrians' Street Crossing Decisions. In *Proceedings of Mensch Und Computer 2021* (Ingolstadt, Germany) *(MuC '21)*. ACM, New York, NY, USA, 49–53. https://doi.org/10.1145/3473856.3474004
[52] 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) Volume VI: Transport Ergonomics and Human Factors (TEHF), Aerospace Human Factors and Ergonomics 20*. Springer, 13–30.
[53] Mirjam Lanzer, Franziska Babel, Fei Yan, Bihan Zhang, Fang You, Jianmin Wang, and Martin Baumann. 2020. Designing CommunicationStrategies of AutonomousVehicles with Pedestrians: An Intercultural Study. In *12th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, Virtual Event DC USA, 122–131. https://doi.org/10.1145/3409120.3410653
[54] Mirjam Lanzer, Ina Koniakowsky, Mark Colley, and Martin Baumann. 2023. Interaction Effects of Pedestrian Behavior, Smartphone Distraction and External Communication of Automated Vehicles on Crossing and Gaze Behavior. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. ACM, New York, NY, USA, Article 768, 18 pages. https://doi.org/10.1145/3544548.3581303
[55] Merle Lau, Meike Jipp, and Michael Oehl. 2022. Towards a Holistic Communication Approach to an Automated Vehicle's Communication with Pedestrians: Combining Vehicle Kinematics with External Human-Machine Interfaces for Differently Sized Automated Vehicles. *Frontiers in Psychology* (July 2022), 4128. https://doi.org/10.3389/fpsyg.2022.882394
[56] Merle Lau, Duc Hai Le, and Michael Oehl. 2021. Design of External Human-Machine Interfaces for Different Automated Vehicle Types for the Interaction with Pedestrians on a Shared Space. In *Proceedings of the 21st Congress of the International Ergonomics Association (IEA 2021)*, Nancy L. Black, W. Patrick Neumann, and Ian Noy (Eds.). Springer International Publishing, Cham, 710–717. https://doi.org/10.1007/978-3-030-74608-7_87
[57] Yee Mun Lee, Ruth Madigan, Chinebuli Uzondu, Jorge Garcia, Richard Romano, Gustav Markkula, and Natasha Merat. 2022. Learning to interpret novel eHMI: The effect of vehicle kinematics and eHMI familiarity on pedestrian' crossing behavior. *Journal of Safety Research* 80, December (2022), 270–280. https://doi.org/10.1016/j.jsr.2021.12.010
[58] Angela K-Y Leung and Dov Cohen. 2011. Within-and between-culture variation: individual differences and the cultural logics of honor, face, and dignity cultures. *Journal of personality and social psychology* 100, 3 (2011), 507.
[59] Yang Li, Hao Cheng, Zhe Zeng, Hailong Liu, and Monika Sester. 2021. Autonomous Vehicles Drive into Shared Spaces: eHMI Design Concept Focusing on Vulnerable Road Users. In *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)*. IEEE, Indianapolis, IN, USA, 1729–1736. https://doi.org/10.1109/ITSC48978.2021.9564515
[60] Yeti Li, Murat Dikmen, Thana G. Hussein, Yahui Wang, and Catherine Burns. 2018. To Cross or Not to Cross: Urgency-Based External Warning Displays on Autonomous Vehicles to Improve Pedestrian Crossing Safety. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*. ACM, Toronto ON Canada, 188–197. https://doi.org/10.1145/3239060.3239082
[61] Stefanie M. Faas, Johannes Kraus, Alexander Schoenhals, and Martin Baumann. 2021. Calibrating Pedestrians' Trust in Automated Vehicles: Does an Intent Display in an External HMI Support Trust Calibration and Safe Crossing Behavior?. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. ACM, Yokohama Japan, 1–17. https://doi.org/10.1145/3411764.3445738
[62] Karthik Mahadevan, Elaheh Sanoubari, Sowmya Somanath, James E. Young, and Ehud Sharlin. 2019. AV-Pedestrian Interaction Design Using a Pedestrian Mixed Traffic Simulator. In *Proceedings of the 2019 on Designing Interactive Systems Conference*. ACM, San Diego CA USA, 475–486. https://doi.org/10.1145/3322276.3322328
[63] 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*. ACM, Montreal QC Canada, 1–12. https://doi.org/10.1145/3173574.3174003
[64] Milecia Matthews, Girish Chowdhary, and Emily Kieson. 2017. Intent communication between autonomous vehicles and pedestrians.
[65] R.Bruce Money and John C Crotts. 2003. The effect of uncertainty avoidance on information search, planning, and purchases of international travel vacations. *Tourism Management* 24, 2 (April 2003), 191–202. https://doi.org/10.1016/S0261-5177(02)00057-2
[66] Merlin Monzel, Kristof Keidel, Wolfgang Schubert, and Rainer Banse. 2021. A field study investigating road safety effects of a front brake light. *IET Intelligent Transport Systems* 15, 8 (Aug. 2021), 1043–1052. https://doi.org/10.1049/itr2.12080
[67] Dimitris Nathanael, Evangelia Portouli, Vassilis Papakostopoulos, Kostas Gkikas, and Angelos Amditis. 2019. Naturalistic Observation of Interactions Between Car Drivers and Pedestrians in High Density Urban Settings. 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.). Vol. 823. Springer International Publishing, Cham, 389–397. https://doi.org/10.1007/978-3-319-96074-6_42 Series Title: Advances in

Intelligent Systems and Computing.
[68] 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*. ACM, Utrecht Netherlands, 284–294. https://doi.org/10.1145/3342197.3344543
[69] Eryn O'Dowd and Thomas V Pollet. 2018. Gender Differences in Use of a Pedestrian Crossing: An Observational Study in Newcastle upon Tyne. *Letters on Evolutionary Behavioral Science* 9, 1 (May 2018), 1–4. https://doi.org/10.5178/lebs.2018.65
[70] Pelé, Deneubourg, and Sueur. 2019. Decision-Making Processes Underlying Pedestrian Behaviors at Signalized Crossings: Part 2. Do Pedestrians Show Cultural Herding Behavior? *Safety* 5, 4 (Nov. 2019), 82. https://doi.org/10.3390/safety5040082
[71] Marie Pelé, Caroline Bellut, Elise Debergue, Charlotte Gauvin, Anne Jeanneret, Thibault Leclere, Lucie Nicolas, Florence Pontier, Diorne Zausa, and Cédric Sueur. 2017. Cultural influence of social information use in pedestrian road-crossing behaviours. *Royal Society Open Science* 4, 2 (Feb. 2017), 160739. https://doi.org/10.1098/rsos.160739
[72] Tibor Petzoldt, Katja Schleinitz, and Rainer Banse. 2018. Potential safety effects of a frontal brake light for motor vehicles. In *IET Intelligent Transport Systems*, Vol. 12. Wiley Online Library, Hoboken, New Jersey, USA, 449–453. https://doi.org/10.1049/iet-its.2017.0321
[73] 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*. ACM, New York, NY, USA, 218–225. https://doi.org/10.1145/1121241.1121280
[74] Champika Ranasinghe, Kai Holländer, Rebecca Currano, David Sirkin, Dylan Moore, Stefan Schneegass, and Wendy Ju. 2020. Autonomous Vehicle-Pedestrian Interaction Across Cultures: Towards Designing Better External Human Machine Interfaces (eHMIs). In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems*. ACM, Honolulu HI USA, 1–8. https://doi.org/10.1145/3334480.3382957
[75] Amir Rasouli, Iuliia Kotseruba, and John K. Tsotsos. 2017. Agreeing to cross: How drivers and pedestrians communicate. In *2017 IEEE Intelligent Vehicles Symposium (IV)*. IEEE, Los Angeles, CA, USA, 264–269. https://doi.org/10.1109/IVS.2017.7995730
[76] Amir Rasouli and John K. Tsotsos. 2020. Autonomous Vehicles That Interact With Pedestrians: A Survey of Theory and Practice. *IEEE Transactions on Intelligent Transportation Systems* 21, 3 (March 2020), 900–918. https://doi.org/10.1109/TITS.2019.2901817
[77] Miguel Ángel Recarte, Ángela Conchillo, and Luis Miguel Nunes. 2005. Estimation of arrival time in vehicle and video. *Psicothema* 17, 1 (2005), 112–117. http://www.redalyc.org/articulo.oa?id=72717118
[78] Zeheng Ren, Xiaobei Jiang, and Wuhong Wang. 2016. Analysis of the Influence of Pedestrians' eye Contact on Drivers' Comfort Boundary During the Crossing Conflict. *Procedia Engineering* 137 (2016), 399–406. https://doi.org/10.1016/j.proeng.2016.01.274
[79] Markus Rothmüller, Pernille Holm Rasmussen, and Signe Alexandra Vendelbo-Larsen. 2018. Designing for Interactions with Automated Vehicles: Ethnography at the Boundary of Quantitative-Data-Driven Disciplines. *Ethnographic Praxis in Industry Conference Proceedings* 2018, 1 (Oct. 2018), 482–517. https://doi.org/10.1111/1559-8918.2018.01219
[80] Alexandros Rouchitsas and Håkan Alm. 2019. External Human–Machine Interfaces for Autonomous Vehicle-to-Pedestrian Communication: A Review of Empirical Work. *Frontiers in Psychology* 10 (Dec. 2019), 2757. https://doi.org/10.3389/fpsyg.2019.02757
[81] 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*. ACM, Virtual Event DC USA, 205–211. https://doi.org/10.1145/3409120.3410657
[82] Vanessa Sauer, Alexander Mertens, Stefan Groß, Jens Heitland, and Verena Nitsch. 2022. Designing automated vehicle interiors for different cultures: Evidence from China, Germany, and the United States. *Ergonomics in Design* 30, 3 (2022), 16–22.
[83] Anna Schieben, Marc Wilbrink, Carmen Kettwich, Ruth Madigan, Tyron Louw, and Natasha Merat. 2019. Designing the interaction of automated vehicles with other traffic participants: design considerations based on human needs and expectations. *Cognition, Technology & Work* 21, 1 (Feb. 2019), 69–85. https://doi.org/10.1007/s10111-018-0521-z
[84] 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. https://doi.org/10.9781/ijimai.2017.09.001
[85] Zhuo Shen, Jinfei Ma, and Ning Wang. 2023. Development and validation of a video-based assessment tool for children's street-crossing safety. *Journal of Transport & Health* 33 (2023), 101716. https://doi.org/10.1016/j.jth.2023.101716
[86] Gaye Solmazer, Derya Azık, Gizem Fındık, Yeşim Üzümcüoğlu, Özlem Ersan, Bilgesu Kaçan, Türker Özkan, Timo Lajunen, Bahar Öz, Anton Pashkevich, Maria Pashkevich, Vassiliki Danelli-Mylona, Dimitra Georgogianni, Ema Berisha Krasniqi, Muhamed Krasniqi, Evangelos Makris, Ksenia Shubenkova, and Gentianë Xheladini. 2020. Cross-cultural differences in pedestrian behaviors in relation to values: A comparison of five countries. *Accident Analysis & Prevention* 138 (April 2020), 105459. https://doi.org/10.1016/j.aap.2020.105459
[87] Cédric Sueur, Barbara Class, Charlène Hamm, Xavier Meyer, and Marie Pelé. 2013. Different risk thresholds in pedestrian road crossing behaviour: A comparison of French and Japanese approaches. *Accident Analysis & Prevention* 58 (Sept. 2013), 59–63. https://doi.org/10.1016/j.aap.2013.04.027
[88] Wilbert Tabone, Joost de Winter, Claudia Ackermann, Jonas Bärgman, Martin Baumann, Shuchisnigdha Deb, Colleen Emmenegger, Azra Habibovic, Marjan Hagenzieker, P.A. Hancock, Riender Happee, Josef Krems, John D. Lee, Marieke Martens, Natasha Merat, Don

Norman, Thomas B. Sheridan, and Neville A. Stanton. 2021. Vulnerable road users and the coming wave of automated vehicles: Expert perspectives. *Transportation Research Interdisciplinary Perspectives* 9 (March 2021), 100293. https://doi.org/10.1016/j.trip.2020.100293
[89] Pavlos Tafidis, Haneen Farah, Tom Brijs, and Ali Pirdavani. 2022. Safety implications of higher levels of automated vehicles: a scoping review. *Transport Reviews* 42, 2 (March 2022), 245–267. https://doi.org/10.1080/01441647.2021.1971794
[90] Richard Threlfall. 2018. Autonomous vehicles readiness index.
[91] R. Utriainen. 2021. The potential impacts of automated vehicles on pedestrian safety in a four-season country. *Journal of Intelligent Transportation Systems* 25, 2 (March 2021), 188–196. https://doi.org/10.1080/15472450.2020.1845671
[92] Romane Vandroux, Marie-Axelle Granié, Mathilde Jay, Cédric Sueur, and Marie Pelé. 2022. The pedestrian behaviour scale: A systematic review of its validation around the world. *Accident Analysis & Prevention* 165 (2022), 106509.
[93] Alexandra Voit, Sven Mayer, Valentin Schwind, and Niels Henze. 2019. Online, VR, AR, Lab, and In-Situ: Comparison of Research Methods to Evaluate Smart Artifacts. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM, Glasgow Scotland Uk, 1–12. https://doi.org/10.1145/3290605.3300737
[94] Florian Weber, Ronee Chadowitz, Kathrin Schmidt, Julia Messerschmidt, and Tanja Fuest. 2019. Crossing the Street Across the Globe: A Study on the Effects of eHMI on Pedestrians in the US, Germany and China. In *HCI in Mobility, Transport, and Automotive Systems*, Heidi Krömker (Ed.). Vol. 11596. Springer International Publishing, Cham, 515–530. https://doi.org/10.1007/978-3-030-22666-4_37 Series Title: Lecture Notes in Computer Science.
[95] Marc Wilbrink, Merle Lau, Johannes Illgner, Anna Schieben, and Michael Oehl. 2021. Impact of External Human–Machine Interface Communication Strategies of Automated Vehicles on Pedestrians' Crossing Decisions and Behaviors in an Urban Environment. *Sustainability* 13, 15 (July 2021), 8396. https://doi.org/10.3390/su13158396
[96] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. 2011. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, Vancouver BC Canada, 143–146. https://doi.org/10.1145/1978942.1978963

A ANALYSIS OF POSITION TRACKING

This section shows the positional data of the online-based study in the form of the participants' waiting behavior and the individual walking path for each participant. The data were partitioned by cultural background and repeated exposure.

Waiting behavior of the pedestrians. In this section, we examine participants' waiting behavior for each repeated exposure divided into cultural backgrounds. The wider the bubble, the longer the participants waited at this position. Figure 26 shows the waiting behavior of the German participants. The participants waited for a long

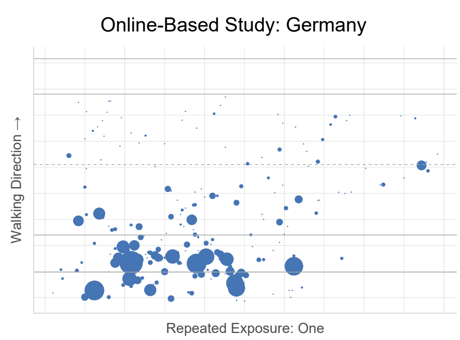


Fig. 26. Waiting behavior for German participants for repeated exposure One.

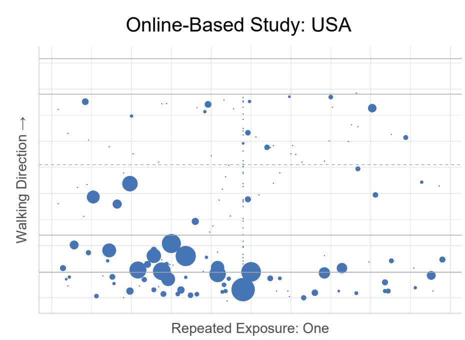


Fig. 27. Waiting behavior for US participants for repeated exposure One.

time at the curb away from the roads on the test day. This behavior can also be seen in the US participants in Figure 27.

The participants' waiting behavior on the second repeated exposure changed from the first day. The Germans, shown in Figure 28, spent less time below the sidewalk but oriented more toward the curb, which led the AVs

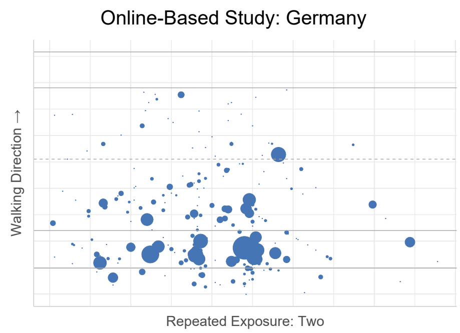


Fig. 28. Waiting behavior for German participants for repeated exposure Two.

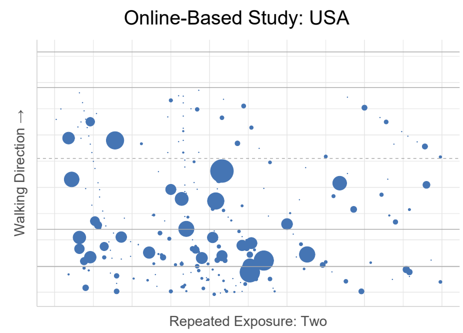


Fig. 29. Waiting behavior for US participants for repeated exposure Two.

to recognize the intention to cross. A more active behavior of the US participants can be observed in Figure 29. Their waiting behavior increased in the first lane compared to the first day of the experiment.

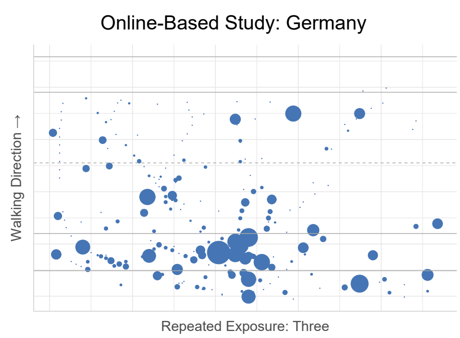


Fig. 30. Waiting behavior for German participants for repeated exposure Three.

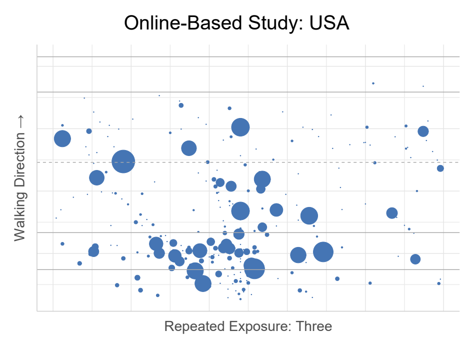


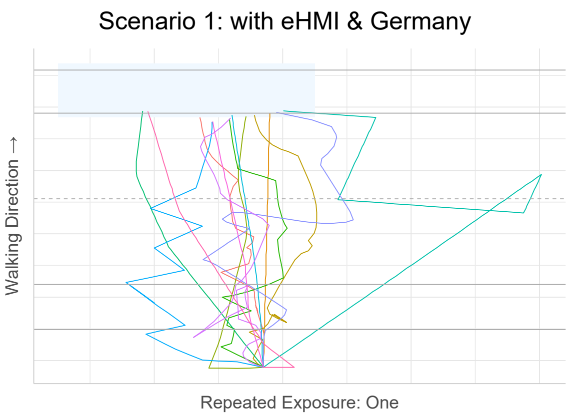
Fig. 31. Waiting behavior for US participants for repeated exposure Three.

On the third day of the experiment, the waiting time of the German citizens on the two lanes also increased, as shown in Figure 30. Similar behavior can be seen in Figure 31 for the US participants.

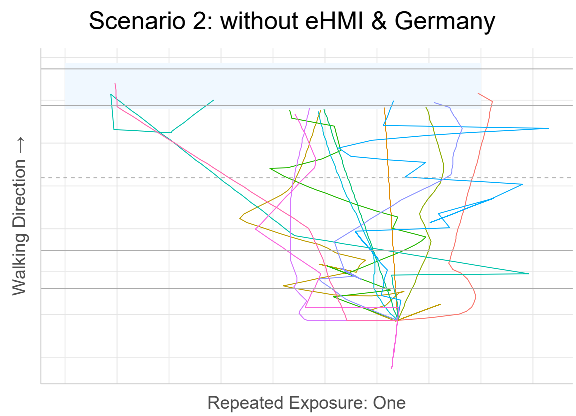
Walking path of the pedestrians. In this section, we present the movement profiles of each participant as they moved for each scenario on that particular day. The light blue rectangle at the top sidewalk shows a cross-section of the checkpoint. The wider the checkpoints shown in the figures, the more fine-grained the differences between the individual tracked position data.

The walking profiles, shown in the four illustrations within Figure 32, are very similar in both cultural backgrounds. The only noticeable differences are the three US test participants, who oriented one far to the right and crossed the street.

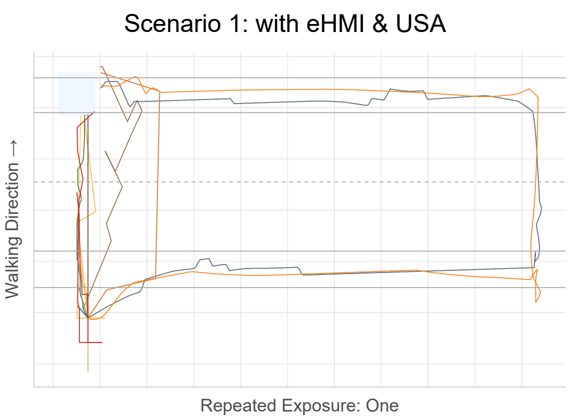
The four walking profiles shown in Figure 33 indicate that the profiles of the German participants with the eHMI are similar. It is noticeable that the participants from the USA chose a longer path in the scenario without eHMI than with eHMI.



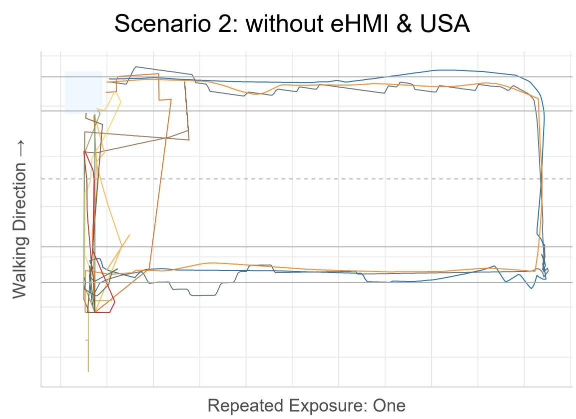
(a) Germany: Scenario 1 & Repeated Exposure One.



(b) Germany: Scenario 2 & Repeated Exposure One.



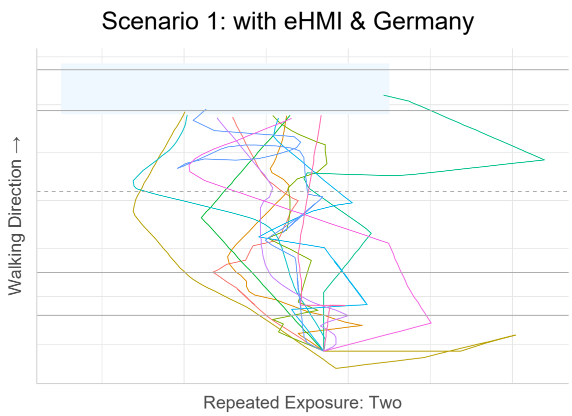
(c) USA: Scenario 1 & Repeated Exposure One.



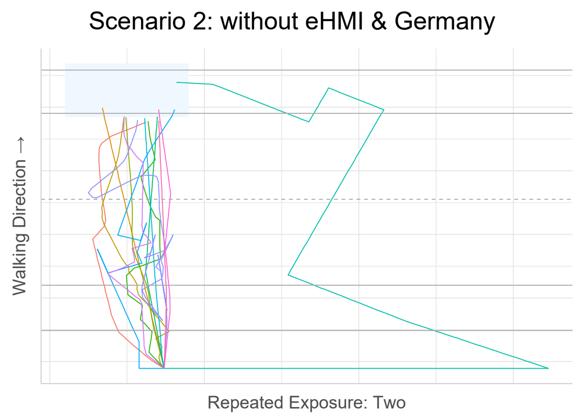
(d) USA: Scenario 2 & Repeated Exposure One

Fig. 32. Walking path of the pedestrians on the first day.

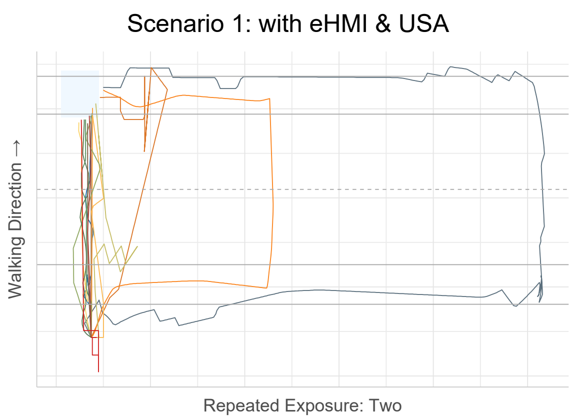
In the walking profiles on the third day of the experiment, see Figure 34, no change in walking behavior is observable for the US participants. The behavior of the Germans also shows no significant change over the course of the study.



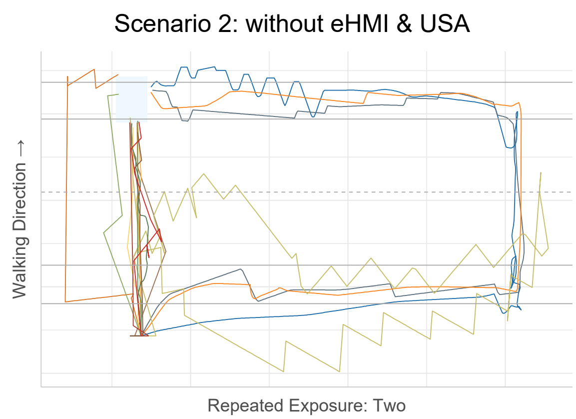
(a) Germany: Scenario 1 & Repeated Exposure Two.



(b) Germany: Scenario 2 & Repeated Exposure Two.

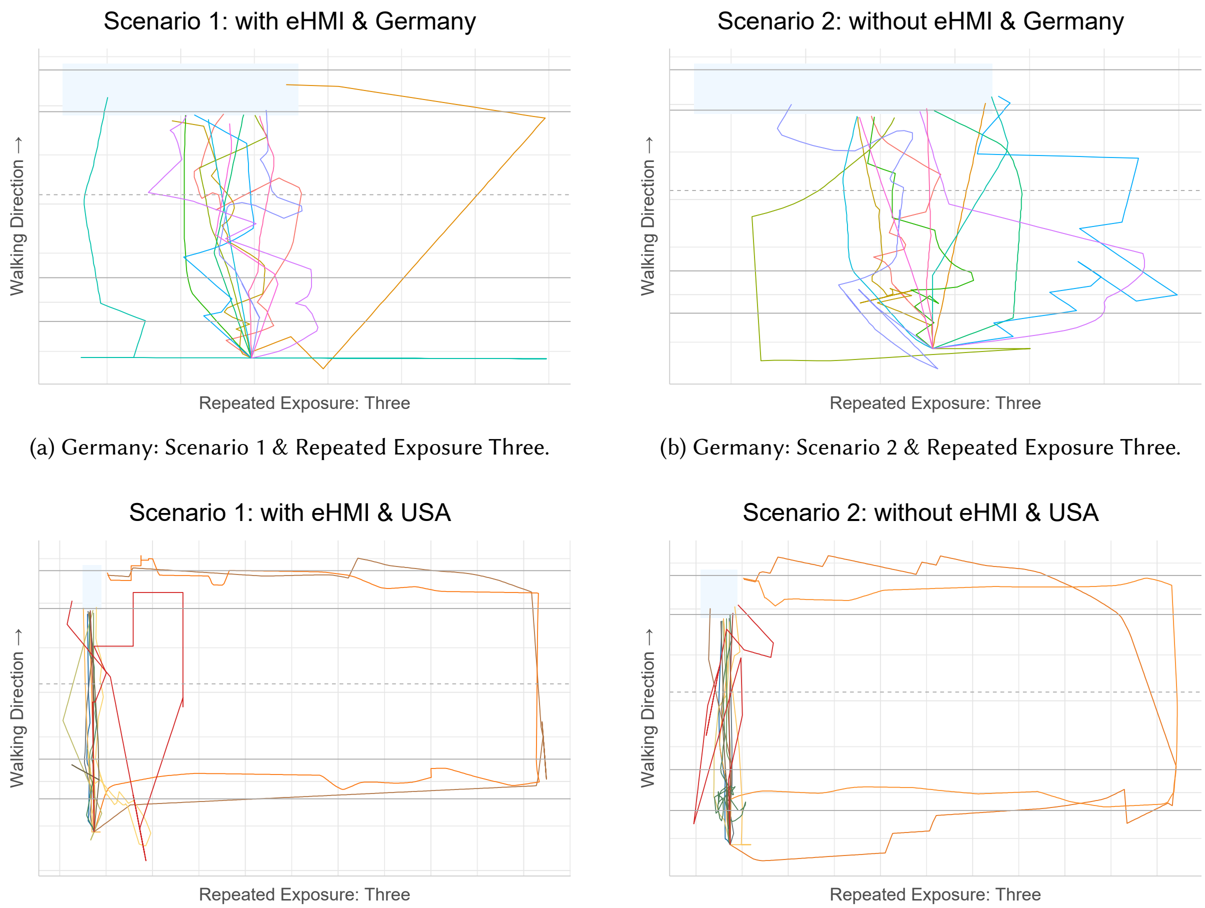


(c) USA: Scenario 1 & Repeated Exposure Two.



(d) USA: Scenario 2 & Repeated Exposure Two.

Fig. 33. Walking path of the pedestrians on the second repeated exposure.



(a) Germany: Scenario 1 & Repeated Exposure Three.

(b) Germany: Scenario 2 & Repeated Exposure Three.

(c) USA: Scenario 1 & Repeated Exposure Three.

(d) USA: Scenario 2 & Repeated Exposure Three.

Fig. 34. Walking path of the pedestrians on the third study day.