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How Should Automated Vehicles Interact with Pedestrians? A Comparative Analysis of Interaction Concepts in Virtual Reality

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Figure 1: The setup in which the display concepts were evaluated. Participants were instructed to cross the street without right of way in front of an automated vehicle, whenever it felt safe. The walkable area was about 9 x 2 m, and allowed the participant to cross the road completely. Left: what the pedestrian saw in virtual reality, here, with the F015 concept. Right: the real world.

ABSTRACT

Automated vehicles (AVs) introduce a new challenge to human-computer interaction (HCI): pedestrians are no longer able to communicate with human drivers. Hence, new HCI designs need to fill this gap. This work presents the implementation and comparison of different interaction concepts in virtual reality (VR). They were derived after an analysis of 28 works from research and industry, which were classified into five groups according to their complexity and the type of communication. We implemented one concept per group for a within-subject experiment in VR. For each concept, we varied if the AV is going to stop and how early it starts to activate its display. We observed effects on safety,

trust, and user experience. A good concept displays information on the street, uses unambiguous signals (e.g., green lights) and has high visibility. Additional feedback, such as continuously showing the recognized pedestrian's location, seem to be unnecessary and may irritate.

CCS CONCEPTS

- Human-centered computing → Empirical studies in HCI; User studies; Laboratory experiments; Virtual reality; Displays and imagers; Sound-based input / output.

KEYWORDS

vehicle-pedestrian communication, automated vehicles (AV), vulnerable road user (VRU), virtual reality (VR), external human-machine interface (eHMI), user experience, trust, acceptance

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1 MOTIVATION

In the coming age of highly and fully automated vehicles, humans will need to negotiate with machines if their paths cross. A simple everyday scenario is crossing an unregulated street, i.e., without traffic lights or crosswalks. While some research suggests that pedestrians mainly decide whether it is safe to cross based on the current distance and speed of the car (e.g., [49]), human drivers and pedestrians also interact via gestures and eye contact (e.g., [29]). Removing human drivers also removes the drivers' side of this interaction and needs to be replaced.

Several designs and prototypes for the communication with vulnerable road users (VRUs), such as pedestrians, have been developed and presented in research and by the industry to increase trust and acceptance of AVs. Throughout this paper, we use the term “interaction concept” to refer to these designs and prototypes at different fidelity levels. Some of these interaction concepts present the intention of the AV, while others give concrete advice to the other traffic participants. The information complexity ranges from merely changing the color of a display to more complex anthropomorphic elements on the AV. What is missing is an evaluation of which types of interactions have which benefits and drawbacks. Our primary research question for this work is “which aspects of the interaction concepts influence trust, user experience and the perceived safety?”

We analyzed 28 designs from research and industry and classified them into a two-dimensional matrix: four communication categories along four levels of complexity from displaying simple states like “cruising” and “yielding” up to mimicking human interaction. We focused on interactions with automated vehicles (SAE Level 4 and above) in potentially dangerous crossing situations. Based on that, we clustered similar works into five groups and selected one representative per group. Each representative has been implemented in virtual reality (VR) and tested in an informal pilot study. We then compared these representatives in a within-subjects design experiment with 20 participants.

2 RELATED WORK

This section summarizes works that are related in general. We present the analyzed interaction concepts in 3.

Various studies reveal positive effects of interacting with VRUs. For example, Boeckle [6] states that it positively influences the feelings of pedestrians. Lundgren et al. [29] reason that their system can replace human-human interaction sufficiently. Chang et al. [8] observed faster decisions of the pedestrians. Their participants also felt safer when crossing the street. De Clercq et al. [10] state that pedestrians prefer textual displays. Matthews et al. found that a simple interaction display reduced deadlock situations by 38 % [32].

Mahadevan et al. [30] compared interaction elements: a car's speed is the main signal but displaying information to VRUs is still helpful. Straightforward information about being detected is not sufficient. Pedestrians want to be informed additionally about the intentions of AVs. They recommend using multiple visual signals, which are easy to interpret. Clamann et al. [9] do not see any advantages in interaction concepts, as only 12 % of their participants said that the display influenced their decision. Speed and distance were the deciding factors. However, half of the participants thought the display was helpful. Li et al. [28] observed similar decision strategies. They recommend using additional communication methods at night. Multiple studies confirm, that position, speed, and the environment are important factors when a pedestrian decides to cross [41, 50, 58].

Overall, research has not yet reached a consensus on whether or not displays for the interaction between pedestrians and AVs are crucial or merely nice to have. However, they seem to be helpful for pedestrians. To the best of our knowledge, related experiments did only look into isolated elements of interaction concepts and did not compare concepts from various sources.

3 CONCEPT CLASSIFICATION

We included works from academia and industry but excluded works that did not meet our criteria. These criteria were:

- (1) The interaction concept needs to communicate relevant information to VRUs that try to cross the road. Some smart road concepts, like “Solar Roadways” [47], have therefore been excluded.
- (2) The concept needs to be complete. Early design ideas and prototypes that highlight certain functions without providing enough information to be completely realized, were excluded. Examples are [10, 12, 23, 28, 30, 34, 54, 56] and several patents (e.g., [20, 25, 48, 59, 64]).
- (3) We did not include works that may work for automated driving but are designed for manual driving (e.g., [39]).
- (4) Only the newest version of a concept was included. This affected “Drive.ai” [1], which was updated in 2016.
- (5) Concepts that rely on smartphones or other nomadic devices were not considered (e.g., [14, 16, 21, 22, 46]).

We found 28 interaction concepts that met our criteria. We classified them into four categories, as listed in Table 1:

- A) Concepts that address vision only. For example with LEDs (e.g., [18]) or projections (e.g., [60]).
- B) Concepts that combine visual and acoustic cues (e.g., [33]).
- C) Concepts with anthropomorphic elements. For example, an AV with eyes that glance at a pedestrian: [8].
- D) Concepts that rely on the infrastructure to communicate. For example, a street as a display: [31].

Table 1: Overview of the classified works. The complexity ranges from C1 (simple on/off states) to C4 (mimicking human behavior). The communication categories are (A) visual, (B) combinations of acoustic and visual, (C) simulation of human behavior, and (D) smart infrastructure. The aggregated concepts groups (I-V) are highlighted with colors.

		Category			
		A	B	C	D
C1	I	[7], [60], [26]			
C2	II	[17], [67], [37], [5], [53], [18], [62], [35], [69], [55], [19]	[15], [65], [3], [32], [43, 44]	IV	[8], [24]
C3	III	[1], [20]	[6], [33], [42]		V
C4				[40, 57]	

We further distinguished between the way the information is expressed. We refer to this as “complexity” and defined four levels for our classification:

- C1) A simple cue giving one information. For example limited to stop & go signals (e.g., [60]).
- C2) Cues that give detailed information or constant feedback. For example, instructions (e.g., [32]) or feedback about the sensed location of VRUs (e.g., [15]). In contrast to C3, these concepts use multiple modalities redundantly and not to convey different information.
- C3) Concepts that are designed for several situations, are using multiple modes of communication (e.g. [33]), or respond to VRUs (e.g., [42]).
- C4) Concepts that mimic human behavior or use animatronics to create a “natural” interaction using, for example, eye contact and gestures for the communication. This only applies to AEVITA [57].

We continued by grouping similar concepts. Categories A and B were combined for this part because all concepts in these categories primarily rely on visual cues and only use auditory cues as a supplement. The missing works on primarily auditory designs or designs with other modalities may present a research gap that needs to be explored in the future. We chose one concept per group as representative for the experiment as listed below:

- I Concepts with simple visual cues [7, 26, 60], represented by Semcon’s “Smiling Car” [7].
- II Concepts with mainly visual cues and constant feedback or more detailed information [3, 5, 15, 17, 19, 27, 32, 35, 37, 43, 44, 53, 55, 62, 65, 67, 69], represented by IDS [37], which gives constant feedback, and AVIP [27], which shows intention and awareness. We selected the IDS as the concept for the later evaluation.
- III Complex, mainly visual concepts [1, 6, 20, 33, 42], represented by F015 [33].
- IV Concepts with anthropomorphic elements [8, 24, 57], represented by Virtual Eyes [2, 24].
- V Smart infrastructure concepts represented by its only member Smart Road [31, 61].

4 IMPLEMENTATION

The VR environment was realized with Unity3D, version 2018.2, Blender [4], Adobe Illustrator, SteamVR [63] and VRTK [13] along with several third-party assets. The scene can be seen from the pedestrian’s perspective in Figure 1. It consists of a straight road without a crosswalk or traffic lights. This way, pedestrians have to assess if it is safe to cross or not. In line with common widths on German rural roads, the width of the two lanes is 7 m.

The same car models were used for our implementations of *Smiling Car*, *IDS* and the AV yielding at the *Smart Road* to reduce the influence of the car’s model on the participant’s decision. However, *Virtual Eyes* and *F015* required different models to stay similar to the original concepts.

In our scenario, every AV initially drives at a speed of 50 km/h and starts to decelerate at a distance of 40 m to the pedestrian at a constant rate. Except for the *F015*, the interfaces are triggered at a distance of 35 m in the *early* conditions, or 10 m in the *late* conditions, simulating the recognition of the pedestrian. The characteristics of each interaction concept are described below.

Simple visual cues. The *Smiling Car* shows a straight line on the front as default. It bends the line to create the shape of a smile when it recognizes a pedestrian (see Figure 2a).

Mainly visual cues with constant feedback. *IDS* shows a text message after it recognized a pedestrian. It first displays “Stopping”. At a distance of 8 m, right before it stops completely, it displays “After You”. Additionally, a white light cue on a blue light strip displays the direction towards the recognized pedestrian (see Figure 2c).

Complex, mainly visual concepts. *F015* starts with an animation of blue lights, shaped like waves (see Figure 1). When the AV starts to yield at the early or late trigger, an animation in the front grill starts filling up the blue matrix from bottom to top and clearing it from the center to the sides afterwards. Subsequently the wave-projection changes to a red zebra-crossing. The projection changes to an animated green zebra-crossing when the AV completely came to a halt

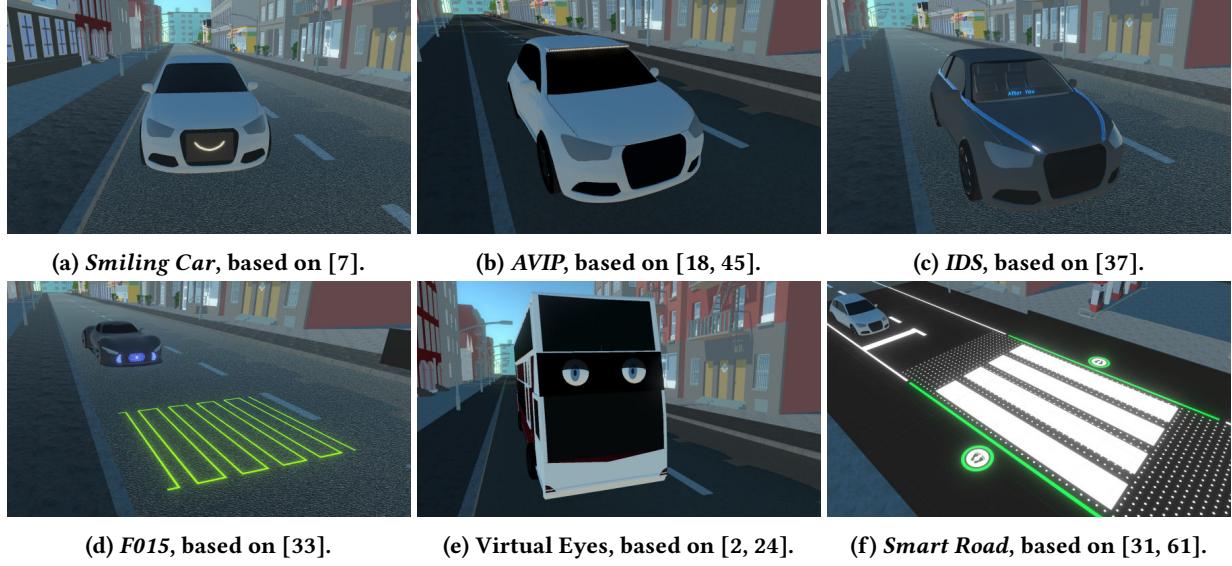


Figure 2: The six initial implementations of the interaction concepts. AVIP was not used in the VR experiment.

(see Figure 2d). Afterwards, the AV says “please go ahead”. While the AV is waiting, the animation of the projected zebra-crossing stays active and the animation in the front grill is repeatedly moving a bar of light from the left (the direction towards the pedestrian) to the right (the opposite direction).

Concepts with anthropomorphic elements. The *Virtual Eyes* open when the pedestrian is recognized. Afterwards, the eyes follow the pedestrian (see Figure 2e). The light signals from the original concept are not included to focus on the effect of the eyes.

Smart road concepts. Red signals on the *Smart Road* show when it is not safe to cross the street. Green signals and a crosswalk show when it can be considered safe (see Figure 2f). In this implementation, the crosswalk is displayed at the early (35 m) or late (10 m) triggers.

5 COMPARISON IN VR

The goal of this work is to compare concepts for the interaction between VRUs and AVs. Considering that some related works already showed that displaying information to pedestrians can be beneficial compared to not displaying anything (e.g., [6, 8, 32]), we decided not to test the implemented concepts against a situation in which the AV is not equipped with an interface to reduce the complexity of the experiment. We initially identified six groups of concepts and selected one concept per group for evaluation as seen in Figure 2. We chose VR as an environment for the evaluation because we can easily control it and thus repeat it per implemented concept. Furthermore, we did not need to implement sensors because we got all the information from the simulation and

were able to realize the interfaces quickly. The most significant benefit of VR, however, is that we did not endanger pedestrians that may have misunderstood an AV’s intention. The downside of using VR is that people may behave differently because, for example, the danger of the situation is not perceived as realistic. We argue that this is acceptable for our experiment because we are primarily interested in the relative differences between the concepts and not a ground truth for human behavior while crossing a road. Nevertheless, we measure the immersiveness of the VR experience.

We chose a scenario in which pedestrians have to cross two lanes without a crossroad. This is an interesting scenario because pedestrians do not have right of way and therefore need to assess if it is safe to cross. Also, if the negotiation between AVs and other road participants works well, there may be no need for static rules, crossroads or traffic lights in the future. Lastly, it is a common scenario in related works.

Design. We used a within-subject design to remove effects coming from individual differences. To minimize carry-over effects, we balanced the order in which the concepts were presented using a Latin Square. Our independent variables were the implemented display concepts, and the distance at which they were activated. The activation distance simulates when a pedestrian is recognized and was either 35 m or 10 m. Overall, three variations of the scenario were tried per concept in randomized order: the visualization starts early, starts late, or the AV does not stop.

Apparatus. The physical apparatus is seen on the right in Figure 1. It consists of a VR headset, i.e., an HTC Vive Pro, two SteamVR 2.0 lighthouses to track a participant’s

position, and a VR-ready PC. We prepared an area of about 9×2 m for the experiment. This size is larger than HTC's recommended maximum area, but worked for our setup.

Measures. We aim to identify the aspects of interaction concepts that influence trust, user experience, and perceived safety. We are also interested in our participants' attitudes towards automated driving and the immersiveness of our setup. We conducted an informal pilot study with two participants to test our setup and decide for the final questionnaires. Based on that, we decided to use *IDS* as a representative for the group "Mainly visual cues with constant feedback" (II). The AVIP concept seems to be too similar to *IDS* and its light strip was difficult to perceive from a distance.

We measured the time a participant needed to cross the road to complement the subjective measures. The timer started when the AV started braking and stopped when the pedestrian reached the opposing sidewalk. We expect that people hesitate longer to cross the road if they do not trust the concept or do not feel safe. We further expect that participants need less time to cross the road in the early condition, if they trust the system, while the difference should be minor if the pedestrians do not trust the system and instead wait until the AV stops. However, due to the different display states and visualizations of each concept, this measure not very comparable across concepts.

We used seven items from the questionnaire from Nordhoff et al. [38] that were translated to German to measure a participant's attitude towards AVs. Participants used a five-point Likert scale to agree or disagree with given statements. The chosen items are listed in Figure 3. We changed A5 from "[...] take over control from the AV when I want this" to "[...] take over control from the AV at any time".

We used three custom items on a seven-point Likert-scale to measure the perceived safety for each concept: "The concept offers safety", "The AV's signals can be clearly perceived", and "I perceived crossing the street as risky". We measured trust using the "Trust Scale" with eight items on a seven-point Likert-scale from von Sawitzky [66, 68]. The user experience was measured using the short User Experience Questionnaire (UEQ-S) [51].

After the experiment, we measured the immersiveness of our VR setup using the Igroup Presence Questionnaire (IPQ) [52]. We also asked participants to rank the implemented concept by distributing 100 points across the concepts. Further, we did a semi-structured interview on their reasoning for the ranking, their thoughts on possible problems for a realization, improvements, possible combinations of designs, and if interaction concepts are necessary, or helpful at all.

Procedure. The procedure of this experiment was as follows. We first introduced the participants to the purpose of

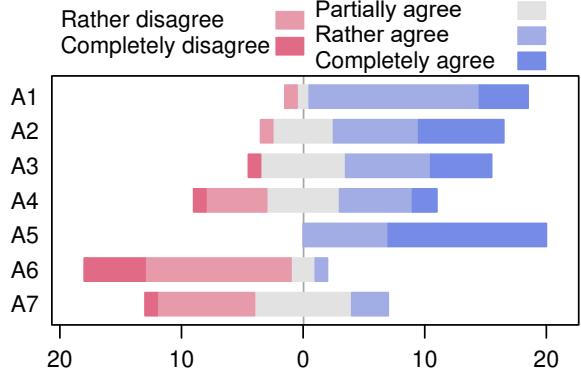


Figure 3: Answers to the attitude questionnaire. The bar widths represent the number of answers per category. A1: "I think I would enjoy taking a ride in an AV", A2: "I think that AVs would be more useful than existing travel", A3: "I trust that AVs can drive without assistance from me", A4: "I would feel uncomfortable entrusting the safety of my family to an AV", A5: "I would like to take over control from the AV at any time", A6: "I would not use an AV because technology can fail", A7: "I would trust the driving skills of AVs more than my own driving skills".

this experiment, the driverless automation level, and the scenario. After that, we asked the participants for demographic data and measured their attitude towards AVs.

In the second part, participants put on the VR headset and were asked to cross the empty street twice. This served as a training to get familiar with the system. Afterwards, the five concepts were presented and discussed in a balanced order using a Latin square. We explained the implemented interaction concept before a participant experienced it in VR. The participants were instructed to pass in front of the AV whenever it felt safe and behave as if this was a real traffic situation. Then, participants put on the VR headset and experienced three situations in randomized order: an AV that activates its interface early (35 m distance), an AV that activates its interface late (10 m distance, shortly before the AV stops), and an AV that does not stop. After the participants crossed the road, they needed to cross the now empty street again to get back to the starting position. After each concept, participants filled in the questionnaires and were interviewed about the benefits and drawbacks of the concept. This also served as a break from the VR environment to reduce the chance of experiencing kinetosis. We did not tell the participants that we were also measuring the time they needed to cross the street.

After all conditions were completed, we asked participants to assess the immersiveness using the IPQ, and to rank the implemented designs. We further conducted semi-structured interviews to gain more insights.

Table 2: Mean results per condition. Trust, safety and the qualities from the UEQ-S questionnaire range from one to seven. For the rankings, participants could distribute 100 points across the conditions, which would result in 20 points per conditions if they were equally much preferred by the participants. The standard deviations are given in brackets.

	Trust	Safety	Ranking	UEQ-S			Time to start crossing (s)		
				Hedonic	Pragm.	Overall	Early	Late	Diff.
Smart Road	6.1 (0.9)	6.5 (0.5)	36.0 (16.7)	5.6 (1.2)	6.4 (0.7)	6.0 (0.7)	8.834 (1.594)	11.612 (0.578)	2.778 (1.300)
F015	5.6 (0.9)	6.1 (0.9)	28.8 (18.6)	6.1 (0.6)	5.2 (1.4)	5.7 (0.9)	13.115 (1.568)	14.295 (2.535)	1.180 (1.826)
Smiling Car	5.2 (0.9)	5.3 (1.0)	19.3 (11.6)	4.9 (1.3)	5.7 (0.8)	5.3 (0.9)	8.957 (2.602)	9.826 (1.466)	0.869 (2.467)
IDS	4.8 (1.1)	4.7 (1.4)	11.0 (7.8)	4.9 (1.1)	4.5 (1.4)	4.7 (1.1)	11.804 (2.112)	12.159 (1.909)	0.355 (1.237)
Virtual Eyes	3.8 (1.3)	3.6 (1.2)	5.0 (5.0)	5.0 (1.2)	4.0 (1.3)	4.5 (1.0)	12.538 (2.599)	12.506 (1.986)	-0.033 (1.794)

6 RESULTS

20 people (7 female, 13 male) with a mean age of 27 years (SD: 7.2) participated in our experiment. The results of the attitude questionnaire are shown in Figure 3. The majority of the answers reveal a positive attitude towards AVs. However, the participants were undecided when it comes to entrusting the safety of a family member to an AV (A4) or trusting the AVs capabilities more than the own skills (A7). With a mean of 5.2 (SD: .5), the IPQ showed that our VR setup was rated slightly more immersive than not. Also, no participant experienced symptoms of kinetosis.

The descriptive statistics per measurement are given in Table 2. In the following, we summarize the results. We used IBM SPSS version 25 for the analysis. One-way repeated measures ANOVAs with Greenhouse-Geisser corrections were conducted if not stated differently. We used the Bonferroni corrections for post-hoc comparisons. We consider an effect to be significant if $p < .05$.

Needed Time to Cross the Road

On average, participants needed 11.6 s (SD: 2.6 s) to reach the opposite sidewalk after the AV started to brake. The mean time with early activated displays is 11 s (SD: 2.8s). The mean time with late activation is 12.1 s (SD: 2.3 s). Participants needed the most time to cross the road with *F015*, followed by *Virtual Eyes* and *IDS*. Participants were fastest with *Smart Road* when the display is activated early, and with *Smiling Car* when the display is activated late. The time to cross the road depends on two independent variables, thus we used a two-way repeated measures ANOVA and found significant effects for concept ($F(4, 76) = 61.67, \eta_p^2 = 0.764$), activation distance ($F(1, 19) = 39.35, \eta_p^2 = 0.674$), and their interaction ($F(4, 76) = 7.12, \eta_p^2 = 0.272$). The post-hoc tests showed that an earlier activation led to shorter times. Looking into the interactions, several displays had shorter times with early activation, compared to other displays with later activation. However, only the *Smart Road* led to significantly shorter times with the early activation, compared to the later

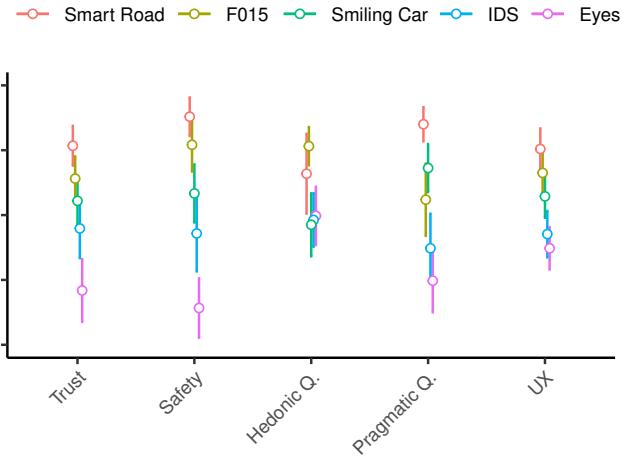


Figure 4: Mean values with 95 % confidence intervals for the questionnaire results per condition and aspect.

activation, which is in line with the mean differences shown in Table 2. *F015* led clearly to the longest crossing times. They are significantly slower than for all other conditions. The times for *Virtual Eyes* and *IDS* were slower than the ones for *Smiling Car* and *Smart Road*.

Questionnaires

Participants answered questions regarding trust, safety and user experience after each condition and ranked the interaction concepts after the experiment. The results are summarized in Figure 4 and are discussed below.

Trust. The *Smart Road* received the highest trust. On a scale from 1 (no trust) to 7 (complete trust), only *Virtual Eyes* received an average of less than four, indicating that participants were unsure if they can trust the system. The ANOVA revealed significant differences between the implemented concepts ($F(4, 76) = 19.91, \eta_p^2 = .51$). Post-hoc tests showed that *Smart Road* received significantly better ratings than *Smiling Car*, *IDS*, and *Virtual Eyes*. Participants also trusted *F015* and *Smiling Car* significantly more than *Virtual Eyes*.

Perceived Safety. The *Smart Road* was rated as safest. The ANOVA showed significant effects between the conditions ($F(4, 76) = 28.08, \eta_p^2 = .60$). The post-hoc tests showed that *Smart Road* received significantly better scores than *Smiling Car*, *IDS*, and *Virtual Eyes*. Participants also perceived *F015* as significantly safer than *IDS* and *Virtual Eyes*. *Smiling Car* was also rated significantly safer than *Virtual Eyes*.

User Experience. The UEQ-S can be discussed with three scores: the hedonic qualities, the pragmatic qualities, and the overall score (UX). While the order of concepts from best UX to lowest UX is the same as for trust and safety, it differs for the pragmatic and hedonic qualities. The ANOVA showed significant effects ($F(4, 76) = 14.78, \eta_p^2 = .44$) for the overall UEQ-S scores. Post-hoc tests showed that the *Smart Road* has a higher UX than *Smiling Car*, *IDS*, and *Virtual Eyes*. Also, *F015* and *Smiling Car* have a better UX than *Virtual Eyes*.

The hedonic qualities are the only measure in which *Smart Road* did not receive the best scores. Instead, *F015* received the highest mean value. The ANOVA showed significant differences ($F(4, 76) = 7.3, \eta_p^2 = .28$). The post-hoc tests showed that *F015* has a significantly higher hedonic quality than *Smiling Car*, *IDS*, and *Virtual Eyes*.

Smart Road received the highest pragmatic quality. The ANOVA revealed significant effects ($F(4, 76) = 17.92, \eta_p^2 = .49$). Post-hoc tests showed that *Smart Road* has a significantly better score than all other concepts, except for *Smiling Car*. *Smiling Car* received better ratings than *IDS* and *Virtual Eyes*. Also, *F015* received a higher score than *Virtual Eyes*.

Ranking. At the end of the experiment, we asked participants to rank the concepts. The order from most points to fewest points is similar to most other measures, with *Smart Road* receiving the most points and *Virtual Eyes* receiving the fewest. The ANOVA test showed significant differences ($F(2.27, 43.03) = 14.99, \eta_p^2 = .90$). The post-hoc tests showed that *Smart Road* received significantly higher scores than *Smiling Car*, *IDS*, and *Virtual Eyes*. Furthermore, *F015* received more points than *IDS* and *Virtual Eyes*. *Smiling Car* was ranked significantly higher than *Virtual Eyes*.

Interviews and Observations

We interviewed participants after each condition and at the end of the experiment. Also, we observed the participants' behavior during the experiment. In the following, we summarize the results of the interviews and observations.

Smart Road. This concept was mentioned to be intuitive, unambiguous, and simple. It does not need much attention and gives a high level of felt safety. Also, participants liked the red and green signals but missed a yellow signal to complete the traffic light metaphor. 16 participant mentioned that it would be hard to realize, mainly arguing that it would

be too expensive or might not work while manually driven cars are still part of the traffic.

F015. Five participants already knew this concept. We observed that several participants wanted to cross before the animation terminated. Also, they often heard the acoustic signal after they already entered the street. Participants liked the additional acoustic signal. They also appreciated the animation for the braking process. Other positive aspects are the high visibility and clear signals. While some participants preferred the combination of multiple signals, others were concerned about the number of signals that a pedestrian has to perceive at once. Also, it may be dangerous to only display information for the lane ahead and not the other lanes that a pedestrian needs to cross. Three participants felt that a realization of this concept may be too expensive.

Smiling Car. Participants liked the simple, unambiguous, plain, and intuitive symbol. They argued that it provides safety. However, they were concerned that this concept may not work in bad weather conditions. Furthermore, it was difficult to perceive the signal and it needed too much attention. Also, the participants missed a green or red color.

IDS. Participants mentioned that the moving light cue is a good idea. However, some participant also argued that it is not necessary. The display was too small and not easy to read. Some participants also mentioned that another display with a clearer signal would be needed. Another downside for the German participants was the use of English language.

Virtual Eyes. A few participants liked the human element of *Virtual Eyes*. However, most participants perceived it as not trustworthy, not safe to use, or experienced an uncanny-valley effect. This effect is known in robotics and describes how the affinity towards a system drops, or enters a valley, in between a very human-like system (e.g., a healthy person) and an apparently artificial entity (e.g., toy robot) [36]. According to Mori [36], this valley contains, for example, corpses, prosthetic limbs, and, based on our results, eyes on a bus. The participants mainly relied on the AV's speed and reported that the eyes were not visible enough. Some participants also argued that the dangers of traffic situations may be trivialized with this concept. In addition, we observed that participants seemed to be more hesitant to start crossing the street, which is in line with the other measures.

Further Observations and Feedback. Overall, we observed that participants often only crossed when the AV has nearly stopped instead of starting to cross as early as possible.

The final interviews revealed that the most essential factor for a good interface is the clarity of its signals. Also, visibility, high level of safety, intuitiveness and efficiency were stressed several times. Some participants mentioned the importance

of keeping the needed attention low. The attractiveness is of minor importance. Overall, two interviewees (10%) would find it helpful to display information to road users around the AV. The remaining 17 (85%) think it would be crucial. They reason that the interaction increases trust into AVs and prevents accidents because it is easier to anticipate if an AV has recognized a pedestrian or stops for another reason.

When asked for the optimal concept, several participants answered that they would combine *Smart Road* and *F015*. For example, *F015* could be simplified to project a zebra-crossing for both lanes, similar to *Smart Road*, while removing the additional signals on the grill. Another proposed concept is the combination of *Smart Road* and *Smiling Car*: the *Smart Road* could stay as it is, while AVs should still communicate their status. This way, the two concepts complement each other and would also work for AVs without a display or for equipped AVs at regular road sections.

7 DISCUSSION

This VR experiment explored the differences between five concepts to identify characteristics that are beneficial for the interaction between AVs and pedestrians. The setup was the same across conditions and the balanced design ensured that the results are not biased from carry-over effects. The IPQ showed that our setup was immersive, which gives evidence that these results may be relatively valid to the real world. Most measures point to the same order of preferred concepts as shown in Table 2 or Figure 4: *Smart Road*, followed by *F015*, *Smiling Car*, *IDS*, and *Virtual Eyes*.

Concept Groups

Rather Simple Visual Cues: Smiling Car and IDS. The representatives of the first two concept groups are in between the best and worst concepts. Both concepts were liked for their simple, unambiguous design with only two states. However, providing information via text was not the most preferred option, contradicting the recommendation by de Clercq et al. [10]. Still, our textual display was much smaller and therefore not as visible. Thus, the results will probably depend on how familiar pedestrians are with the language that is presented and how easy the text can be perceived.

Visual displays (categories A & B) seem to work well if the information is unambiguously presented early. As the increased complexity for the additional continuous information with *IDS* (C2) seems not to provide benefits to the pedestrians, we suggest to keep the display simple (C1).

Complex, Mainly Visual Cues: F015. This concept most often received the second highest ratings without having significantly different rankings from *Smart Road*. Especially the hedonic qualities were rated high, indicating that the interaction design appealed to the participants. However, this

measure may also have been affected by the futuristic look of the vehicle (cf. [11]). While the ratings and the crossing time seem to correlate, *F015* is the exception, having high ratings but the longest times. The reason for this is likely that the projected zebra-crossing only turns green when the AV came to a full stop, while other concepts changed to their final state earlier. Considering the novelty of this display and that our participants were in no rush, they may have been willing to wait to see the full animation. This behavior may be different in a real setting.

Most participants argued that the main benefit is the clear communication of the situation using the zebra-crossing projection. This indicates that the additional information in the grill may be unnecessary, similar to the results for *IDS*. The main reason for the better results with *F015* may be explained with the higher visibility of the information in front of the pedestrian and the additional auditory cue. With regard to the classification, we can argue that additional information is not needed but that the increased visibility and the use of a second modality (audio) were beneficial for the pedestrians. However, although this would not be in line with the interview results, the better results may also be caused by the additional information in the grill. Thus, further research is needed to evaluate this effect.

Concepts with Anthropomorphic Elements: Virtual Eyes. This concept received the lowest ratings except for its hedonic qualities. Also, people needed the second most time to cross the road in this condition. This indicates that while adding eyes to the car appealed to some pedestrians, they did not trust this interaction. Furthermore, the display in this concept was the only one attached to a heavy vehicle instead of a passenger car. Considering the results of Dey et al. in [11], this difference may have influenced the perception of the participants. On the other hand, the participants mentioned several problems with using eyes, such as an reduced affinity due to an uncanny-valley effect (cf. [36]).

With regard to the classification, we argue that adding anthropomorphic elements to the AV may not make pedestrians trust it more. In fact, our implementation of *Virtual Eyes* was the only of the five concepts in which participants tended more towards not trusting the system and feeling unsafe on average. Thus, our results seem to contradict the ones from Chang et al. [8]. However, we did not test the concepts against AVs that did not communicate. Therefore, we argue that *Virtual Eyes* may be better than providing no information while still not being the best choice.

To increase the trust, concepts in this group may have to add unambiguous signals about when to cross the road. However, this may lead to the same results as for *IDS* because the additional signal may be enough to render the anthropomorphic element unnecessary. Another solution could be to

use the anthropomorphic element to give the unambiguous signal. Future research needs to design and evaluate such a concept to explore this assumption.

Smart Infrastructure. *Smart Road* is trusted most, perceived as safest, had the best user experience, and made the participants cross the street the earliest (in the early condition). The participants liked this concept for its simplicity and clarity, which in turn created a high amount of trust. They did not wait for the AV to communicate with them and instead started walking as soon as the street turned green. Also, the participants were already familiar with zebra-crossings and traffic lights using red and green colors. Thus, it is not surprising that they trust a system that combines both concepts.

Considering the results for *Smart Road*, a smart infrastructure (category D) may have the biggest potential for a good communication. The interview results indicate that pedestrians would prefer if the communication was done by the infrastructure and the AVs simultaneously. The AV interface would then be reassuring but also needed in places where the infrastructure cannot be equipped with an interface. This is also in line with Mahadevan et al. [30]: a combination of multiple visual, highly visible signals is beneficial for clearly communicating with pedestrians.

The benefits of displays in the infrastructure should apply to most concepts in this category, even though we only analyzed one example: (i) the information is clearly visible because it is close to the pedestrian and not attached to a moving car, and (ii) displaying the information does not depend on the capabilities of the AV. The primary downside for all concepts in this category is that existing infrastructure needs to be changed, which may be costly.

Classification Criteria

In the following, we reflect on our criteria for selecting and classifying the analyzed concepts.

The communication categories (A-D) are based on the analyzed works. For the evaluation, we combined the categories A (visual displays) and B (combinations of visual and other modalities). However, other modalities were not considered and need to be added in future research. A dedicated criterion for the addressed senses may show which modalities have not been investigated much yet. For example, most concepts primarily rely on vision which shows a research gap for auditory or tactile displays. Participants seem to appreciate a redundant information channel, such as the auditory signal in *F015*. It was also stressed that addressing different senses is important when designing for visually impaired traffic participants. We may also distinguish between projected symbols (e.g., *F015*) and displayed text (e.g., *IDS*) within the visual category in the future. Thus, a future classification

should also include how many modalities were combined and how they complement each other.

Comparing the complexity classes did not provide much information. Participants seem to rely primarily on the information “you can cross now” which needs to be communicated clearly and as early as possible. Additional information was either ignored or not deemed necessary. These observations indicate that interfaces need to be designed with minimal complexity (C1).

We further considered “communication types” as a third criterion for the classification because the type of communicated information differs between different concepts. For example, an AV may communicate its current state, like “yielding” (see *Smiling Car*), an advice, e.g., “go ahead” (see *F015*), or other types of information. However, these communication types are often combined or not clearly described in the analyzed works.

Other criteria, like “placement on the AV” or “scalability” should also be considered to further explore the design space. Also, the criteria for excluding works may be changed. For example, works about manual driving or concepts that rely on nomadic devices may be included in the future. However, this detailed classification was outside the scope of this work.

Limitations

The goal of this work was to identify characteristics of an excellent AV-VRU interaction. However, it is impossible to implement and test all analyzed works against each other with a reasonable amount of resources. Thus, the biggest limitation of this work is the limited number of compared concepts. We selected concepts that represent a wide range of designs. However, the results can often not be generalized to the groups of concepts that our implementations represent.

Further, our data collection has several limitations that need to be taken into account when interpreting the results. We did only use a subset of the attitude questionnaire from [38] and did not further validate them. We argue that this is acceptable for our research because this measure only served for giving an overview on the participants’ attitudes towards automated driving and was not further analyzed. Similarly, we did not take measures against anchor effects in our questionnaires. The order of concepts was counterbalanced. Hence, the relative differences should not change due to this. Only the ranking after the experiment was always in the same order and may have been affected. Related to this are the individual biases from the participants. We used a within-subjects design with a counter-balanced order of conditions, thus, the relative differences between the concepts should be similar if this experiment is replicated. However, we did not analyze if previous experiences with VR or AVs may have changed the participants’ overall assessment of the concepts. For example, a novelty effect may have biased

them towards being more enthusiastic about the technology overall. Also, most of our participants were recruited from the same culture and age group.

We did not have access to the original code or models. Therefore, the comparison of our implementation to the original works is limited by our interpretation of the concepts. The generalizability of this work is also limited by the realism of virtual reality. Furthermore, we only covered one scenario and effects may be different in different scenarios (e.g., when many cars are equipped with the display). Also, *Virtual Eyes* and *F015* used different car models as a basis, which may have influenced the results.

Overall, this work can give several directions for a good VRU-AV interaction design but much more research needs to be done to address the limitations and get a complete overview on the effect of different designs.

Design Recommendations

Besides the discussed benefits and drawbacks per concept group, we can give these general recommendations considering the limitations discussed above:

- Provide a clear and simple signal about whether it is safe to cross the road (see *Smart Road*).
- Use green color to signal “please start to cross” (see *F015* and *Smart Road*).
- Use a familiar traffic light or a crossroad metaphor (see *F015* and *Smart Road*).
- Include all lanes for the recommendation (see *Smart Road* and interview results for *F015*).
- Communicate additional information only if needed as this may add confusion (see *IDS*, *F015*).
- Combine smart infrastructure with simple information on the AV. This reassures that the AV behaves as signalled by the infrastructure and adds a fallback communication channel for situations without smart infrastructure (see interview results).
- Consider using complementing modalities to signal the intention of the AV to people with different kinds of disabilities (see interview results).

8 CONCLUSION

This work aimed at identifying characteristics that make an interaction design perceived as trustworthy and safe with a positive user experience. We analyzed 28 concepts from industry and academia that communicate an automated vehicle's status or intention to vulnerable road users. We classified these works into a two-dimensional matrix with one dimension being the complexity of the communication and the other the category of the used communication modalities. We selected five concepts that represent different places on the matrix and studied their differences in a virtual reality

experiment with 20 participants. We measured the participants' trust into the AV, how safe they felt when crossing the road, how good the user experience was, how much time they needed to cross the road, and how they would rank the concepts. Further, we conducted semi-structured interviews to learn about the benefits and drawbacks of the concepts as well as additional thoughts on the interaction between humans and automated vehicles.

We learned that the best interaction concept is the one that participants are already familiar with: projecting a zebra-crossing on the street to indicate that they may cross and turning it green as a traffic light metaphor to stress the invitation to cross the road, as seen in the *Smart Road* and *F015* concepts. Apart from that, our participants preferred systems that provided a simple and highly visible cue about whether it is safe to cross. Additional information, such as a continuous feedback about the current perceived position of the pedestrian (e.g., used in *IDS* and *Virtual Eyes* concepts) or the current state of the car (e.g., used in *F015*), were sometimes appreciated, but often perceived as too much and did not benefit the performance of the concepts. Adding eyes to the car to simulate eye contact did not provide a clear signal to cross the road and made some participants experience an uncanny-valley effect.

Future research needs to address the limitations of this work. For example, by refining the classification and looking into concepts that are not primarily addressing vision. Also, the concepts need to be compared to a baseline condition without a display. Future researchers should also investigate different environmental conditions, such as bright sunlight or snow and dirt because these may affect the displays differently. In addition, the effect of occasional display failures and how to ensure that pedestrians do not misinterpret them is open to future research. It is unclear if the systems are effective for other vulnerable road users, such as cyclists, groups of people with different trajectories, distracted people, or people with disabilities. In addition, the presented interaction concepts can be further improved, e.g., by optimizing the activation time or distance of a signal, or its design.

Overall, 95 % of our participants believed that interaction concepts are helpful or even needed to realize automated driving that is accepted by society. This work contributes to a better understanding of the characteristics of a good interaction between humans and automated vehicles.

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