How Should Automated Vehicles Communicate Critical Situations? A Comparative Analysis of Visualization Concepts

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Passengers of automated vehicles will likely engage in non-driving related activities like reading and, therefore, be disengaged from the driving task. However, especially in critical situations such as unexpected pedestrian crossings, it can be assumed that passengers request information about the vehicle's intention and an explanation. Some concepts were proposed for such communication from the automated vehicle to the passenger. However, results are not comparable due to varying information content and scenarios. We present a comparative study in Virtual Reality (*N*=20) of four visualization concepts and a baseline with Augmented Reality, a Head-Up Display, or Lightbands. We found that all concepts were rated reasonable and necessary and increased trust, perceived safety, perceived intelligence, and acceptance compared to no visualization. However, when visualizations were compared, there were hardly any significant differences between them.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; *Haptic devices*; User studies.

Additional Key Words and Phrases: Autonomous vehicles; interface design.

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

1 INTRODUCTION

Automated vehicles (AVs) are expected to change traffic [20], the interaction between driver (or, in future, passenger) and vehicle [20], and the activities the passenger engages in [79] profoundly. Expected benefits such as increased safety [20, 77] can only be achieved if the automation is trusted and, therefore, remains engaged [33]. However, people worry about the reliability of automated cars [3, 55]. Low trust in the AV can lead to decreased usage of its functionality and, ultimately, to low adoption. Therefore, prior work evaluated several transparent designs and showed their benefits [12, 58, 108]. Several visualization concepts such as a tablet- or augmented reality (AR)-based [12, 108] as well as lightband-based [58] visualizations were proposed. Displaying relevant information in critical situations seems necessary [102]. However, the question remains which information to display in which situation [102] and which visualizations are suited best to calibrate user trust in the AV. Therefore, we analyzed designs from prior work regarding how information is (spatially related to the outside

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2474-9567/2021/9-ART94 $15.00
https://doi.org/10.1145/3478111

world – called registration type and their target audience. Registration type is divided into contact analog (directly spatially related), angle analog (the visualization points in the direction of the spatial object), and unregistered (no spatial connection). Subsequently, we implemented representatives of these **three** registration types in a virtual reality (VR) simulation. Additionally, we propose a *Priority*-based concept (see Section 4). Displaying the priority an AV attributes to objects can provide transparency in the decision process and reassures the user of detecting an object (see [13]). We then compared these in a within-subjects experiment (*N*=20), including a *Baseline* with no visualization. As critical situations, we employed unexpected crossings of an older person, a child, and a dog. Generally, a visualization was found highly necessary and increased, in line with previous work, trust, perceived safety, perceived intelligence of the AV, and provided high usability. However, we found almost no significant differences between the visualizations for the dependent measures, suggesting that *how* the relevant information is displayed is of minor importance.

Contribution Statement: This work provides a literature analysis regarding communication between an AV and the passenger. In a VR study (*N*=20), we compared representatives of such visualizations and a novel *Priority*-based concept. Our results are in line with previous work suggesting individual concepts, highlighting the need for communication. However, our results of the comparison of different proposed and one newly defined visualizations indicate that the differences in visualization only play a minor part. Our work helps to safely introduce AVs, calibrate trust in them, and maximize their usage to benefit from their expected benefits.

2 RELATED WORK

Before classifying related work, we present an overview of the effects of system transparency and visualizations in manually driven and AVs.

Visualizations in the context of manual driving are used to provide additional driving-relevant information. Various technologies are used, for example, ambient light [65]. In their work, Matviienko et al. indicated different information via brightness progression. For example, in one proposed light pattern (LP6), approaching a destination was indicated by moderate pulsing, a request to be ready was accompanied by fast pulsing, and the information that the driver should turn was indicated by moderate blinking [65]. Another example of such a lightband-concept provided information on overtaking-safety [59]. Other work focused on providing relevant information at the take-over request from automated to manual driving [45, 63, 100]. Lorenz et al. [63] compared visualizing a lane. Red indicated where not to drive, green where it is safe to drive. Green led to more consistent steering behavior. Kim et al. [45] highlighted a vehicle and then let the driver indicate their fitness to overtake.

The focus of this work, however, is automated driving. An essential aspect towards the usage of an AV is trusting it. Distrusting the AV can lead to decreased usage [68] and, therefore, the anticipated advantages can not come into effect [33, 72]. However, overtrust in automated systems can lead to disengagement in the surveillance task and, ultimately, to fatal consequences [71]. The state in which the projected match with the actual capabilities is called "calibrated trust" [68]. Such trust can be established before, during, or after using such a system [34]. System transparency was shown to build and maintain trust in AVs [12, 22, 32, 48, 51]. Kraus et al. [51] showed that providing high system transparency can even prevent trust decrease after a malfunction. Frison et al. [23] showed that also the user experience influences trust in AVs.

Currently, the question arises which information should be displayed during an automated journey [12, 48, 58, 102, 109]. Wintersberger et al. interviewed 56 people about automated rides. They conclude that there is "an inverse correlation between situational trust and participants' desire for feedback" [109, p.1]. They also found six themes for information that should be provided: Predictability, impact, object characteristics, spatial properties, regulations, and visibility.

Wiegand et al. [102] identified 17 relevant situations and, for these, conducted a think-aloud study with 26 participants. For unexpected driving behavior, they found the six main concerns in emotion and evaluation, interpretation and reason, vehicle capability, interaction, future driving prediction, and explanation request times [102]. While some of their situations will become less of a problem with more advanced technology (e.g., abrupt stop at right turn, long wait at an intersection to turn left, unnecessary lane change, strong brakes and quick decisions, car is very slow), others are scenario-dependent and are only partially addressable by improving AV's capabilities: Reluctant turn right due to a pedestrian (scenario 2 [102]), another car stopping, a child crossing (scenario 9 [102]). Koo et al. [48] focused on the information content (intention and explanation) in a semi-autonomous vehicle. Providing the explanation lead to the highest trust; combining both messages lead to the safest driving behavior. The authors argue that combining both messages could lead to cognitive overload. In an AV, however, this likely is not a problem as the passenger is not involved in the driving task, which frees up cognitive resources. Löcken et al. [58] used the earlier mentioned idea of ambient light to increase user experience and trust during an automated journey. Eighteen participants experienced three scenarios: a crossing pedestrian, a crossing cyclist, and a vehicle coming out of a parking lot. The authors compared whether only showing the conflict (in red) or showing their trajectory (in grey) on a simulated LED strip increased trust and user experience. They found that trust and all subscales were significantly higher in the conflict plus intention condition than the baseline. However, they found almost no effects between the conflict only and the conflict plus intention condition. Wintersberger et al. [107] investigated visual-olfactory reliability displays showing that including this modality is a viable additional communication option.

3 CONCEPT CLASSIFICATION

To gather a clear picture of visualizations regarding AVs, we classified prior work. The dimensions we used are *Target Automation Level* and *Registration Type*. *Target Automation Level* refers to the intended audience of the visualization. This is broadly distinguished into manual and automated driving. We included manual driving as numerous concepts were proposed for manual driving and to gain a broader picture of concepts. Take-over scenarios were included in the manual driving column (e.g., [45, 63, 100]). The *Registration Type* refers to the location of information visualization. *Contact Analog* [81] (also called world-fixed [25, 96]) visual elements refer to a display directly corresponding to the relevant physical position. If there is no connection between a visual element and the physical environment, the corresponding registration type is *Unregistered* [80] (also called screen-fixed [26]). *Angle Analog* visual representations refer to pointing towards objects (that could even be outside of the driver's field of view; e.g., [92]). Often, concepts include technical prerequisites such as AR windshield [12] or lightbands [58]. *Registration Type* was, therefore, included as a technology-independent classification that incorporates information about relevant objects via placement (except for Unregistered).

In Table 1, we show the classification of prior work. We included work that focused on visualizing information regarding objects (or proposals, for example, [9] in manual driving) to the human user in a vehicle (excluding work for airplanes such as [64]) and presented a study or a prototype. Work focusing on, for example, design spaces [28, 103], general requirements for such communication [102], patents, or simulators to evaluate such designs (e.g., [75]) was excluded as were workshop submissions due to their non-archival state and reduced review rigor. Additionally, publications had to be in English to ensure comprehensibility both for the authors and the readers. We started with defining relevant keywords for the search in numerous databases (e.g., ACM Digital Library, ScienceDirect, Google Scholar) but quickly found that there was no uniform set of keywords (e.g., *Augmented Reality*, *Driver Assistance*, *Ambient Light*; see also [85]). Therefore, we started with a set of known publications (called "query articles" [38]) relevant to the topic and analyzed their references and work citing them (backward and forward citations [36]). These query articles were: [12, 32, 58, 60, 81, 102, 105, 108]. For the found relevant work, we repeated this process. In total, we repeated the process three times. If work included aspects that fit into multiple cells, these were populated individually. No time constraints were defined.

Table 1. Classification of prior work regarding information visualization in manual and automated driving.

Registration Type	Manual Driving	Automated Driving
Contact Analog	**29**: [2, 7, 8, 11, 14, 26, 35, 37, 45–47, 52, 54, 57, 63, 66, 69, 70, 73, 74, 78, 80–82, 87, 89, 90, 112, 113]	**6**: [12, 15, 56, 96, 108, 110]
Angle Analog	**11**: [5, 9, 17, 27, 42, 59, 61, 65, 70, 92, 104]	**3**: [58, 60, 105]
Unregistered	**19**: [1, 4, 7, 26, 30–32, 41, 43, 53, 57, 66, 67, 80, 83, 89, 100, 108, 111]	**4**: [15, 56, 96, 108]
Total	**59**	**13**

We found that most work until now focused on manual driving (59/72 or 81.94%). For each *Registration Type*, publications were found. In both manual and automated driving, most publications utilize contact analog registration. This is followed by unregistered visualization. Angle analog was used least. Additionally, three publications in automated driving include visualizations from both the contact analog and the unregistered registration type (i.e., [15, 56, 108]). Regarding the reported results, all publications claim to increase trust in some way. Comparability is, however, problematic as different scenarios and different information were employed. For example, Wintersberger et al. [108] highlighted vehicles in fog in a simulation, Löcken et al. [58] showed conflicts with bicyclists, cars, and pedestrians in clear conditions in videos, and Colley et al. [12] visualized pedestrian intention in a simulation. However, we found no comparative study. Therefore, we compared one prototype of each registration type category displaying similar information in the same scenarios.

4 IMPLEMENTATION

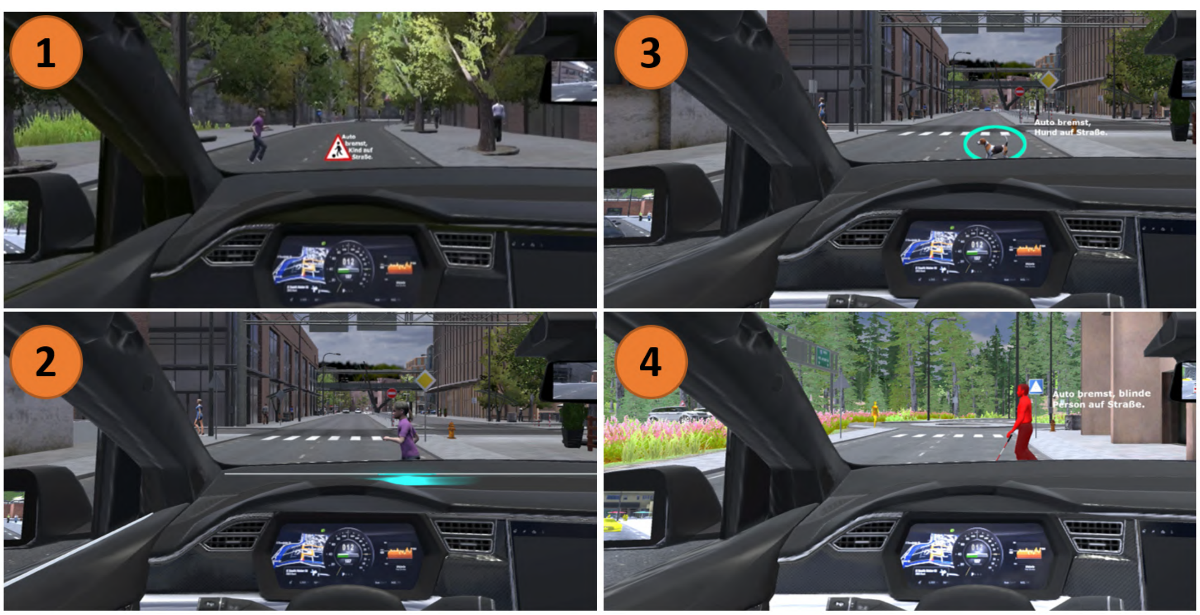


Fig. 1. The interior of the simulated Tesla X alongside the visualizations: *Head-Up Display* with the message "Vehicle brakes, child on street" (1), *AR* with the message "Vehicle brakes, dog on street" (2), *Lightband* (3), and *Priority* with the message "Vehicle brakes, blind person on street" (4).

For the comparison, we implemented a VR simulation including traffic and pedestrians using Unity [93] and the asset Windridge City [94]. Participants sat on a seat with a fan in front of them to reduce simulator sickness (see Figure 3a; [18]). In the simulated ride, the participant sits in a Tesla X model (see Figure 1). The model includes a retracted steering wheel, as it is likely that the possibility to drive manually will be present until full autonomy (SAE Level 5) is reached. To compare the visualizations, three crossing scenarios were encountered per ride: a child going for a ball, a person with a visual impairment, and a dog. These partly resemble previous scenarios in which an explanation was seen as helpful [58, 102]. While a child was mentioned by Wiegand et al. [102], a pedestrian with a visual impairment or a dog were not yet mentioned. The scenarios meet all except the visibility criteria by Wintersberger et al. [109]. The order of the encounters was fixed per but varied between conditions to minimize learning effects. All visualizations display the AV's intention and reasoning (see [48]) and had the same activation times (17m prior to the situation). The compared visualizations (see Figure 1) are based on previous work but had to, due to the differences in the concepts, be redesigned to be appropriate for the scenarios:

Head-Up Display: The vehicle is equipped with an approximately 20cm wide *Head-Up Display*, showing unregistered information in the form of a warning symbol (see attention-based specific warning visualizations [106]). Compared to the attention-specific warning by Winkler et al., we included text for the AV's intention and reasoning (see [48]).

AR: A recognized critical situation is visualized by encircling the causing object in turquoise, resembling the contact analog registration type as the circle and text move along with the object. Turquoise is a typical color proposed for AVs [101] due to its high peripheral visibility, attractivity, uniqueness, and discriminability also for people with color vision deficiency. Besides the encirclement, the AV's intention and reasoning are displayed in text. Comparability to the found related work (see Table 1) is difficult as the proposed visualizations provide either the information that an object was detected and whether it is safe to overtake [108, 110]), information on a detected crash with a warning sign [15], pedestrian intention [12], or a route indication [96].

Lightband: The *Lightband* shows the direction from the user to the detected object causing a critical situation (see [58] and Figure 2). The *Lightband* is attached at the side windows and below the windshield. The intention to yield is indicated by the *Lightband* flashing abruptly (see [58]). The illuminated part is approximately 20cm wide and was very bright in relation to the interior. The information *why* this is happening (i.e., the reasoning) is given by visualizing the critical object. This concept resembles the angle analog registration type.

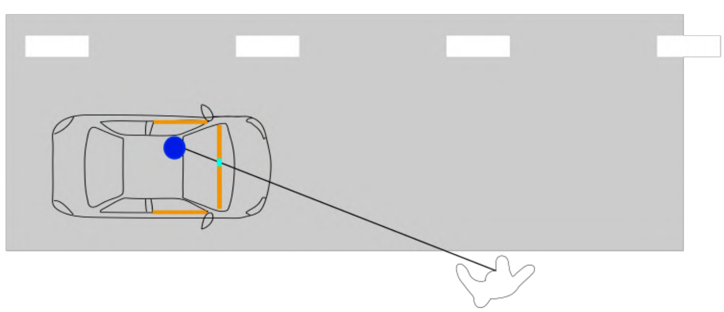


Fig. 2. Schematic top view showing the position of the user/participant (blue), the location of the *Lightband* (orange), and the, according to the pedestrian position, lit part of the *Lightband* (turquoise) depending on the position of the crossing pedestrian in a critical situation.

Priority: In this novel concept, we propose to visualize the AV's prioritization regarding the detected objects. Via such continuous feedback, the user could continuously assess the capabilities of the AV and its priority-recognition algorithms. This was implemented as follows: In an area of $r =$ 35 m, the AV detects every object. Depending on the object class (critical (older person, child, dog), vehicle, pedestrian, signposts) and the distance, the AV attributes different priorities to the road users (see Table 2). Here, we propose to give object in the vicinity (0 - 20m) a higher priority then further away as these objects are more likely to be relevant to the AV's course, thus, increasing criticality. We also pose different criticalities based on the likeliness of unforeseen actions (e.g., pedestrians change tracks more often than vehicles) and the vulnerability of the person (e.g., child and a blind person are more vulnerable than a middle-aged person). This concept is based on the work by Kim and Canny [44]. They propose to show "real-time highlighted regions of an image that causally influence the network's output (steering control)" [44, p. 1]. The authors focus on technical feasibility. Recently, Colley et al. [13] also proposed such a continuous visualization of semantic information, i.e., showing detected objects via an AR windshield and report no significant differences in trust or mental load compared to no visualization in an online video-based study. This concept varies from the other three concepts, which can be seen as prototypes for a contact analog (*AR*), angle analog (*Lightband*), or unregistered (*Head-Up Display*) visualization. These only are visible when a critical situation is encountered. In the *Priority* visualization, however, the simulated AV's attention (or priority) is constantly visible above a certain threshold. Additionally, in a critical situation, the same text is provided as in the other concepts.

Table 2. Implementation details for the *Priority* visualization showing the priorities determined by the object and the distance to the AV. Below the threshold of 5, the objects were not visualized (n.v.) to reduce visual clutter and omit cognitive overload.

Object	**0 - 20 m**	**21 - 45 m**
Critical	10 (red)	8 (orange)
Pedestrians	8	6 (yellow)
Vehicles	6	4 (light green, n.v.)
Signposts	4	2 (light blue, n.v.)

We excluded a *Head-Down Display* (i.e., a dashboard visualization) as these were already shown to be inferior compared to a *Head-Up Display* in terms of performance [25, 86] and preference [12, 13].

5 STUDY

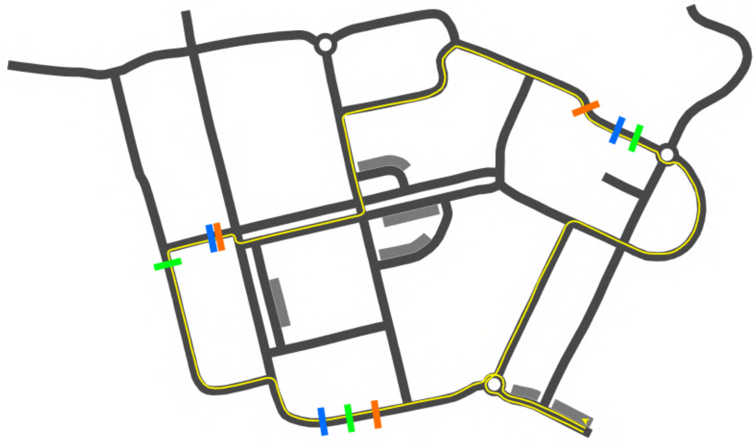
To compare the concepts, we designed and conducted a within-subject study with N=20 participants. While previous work already showed that including some visualization leads to increased trust [12, 108], we included a *Baseline* without visualization to solidify the findings of previous work further and establish these findings in the (novel: blind person, dog) scenarios. The study apparatus is shown in Figure 3a. We used a fan to reduce motion sickness. The study was guided by the research question:

> *What impact does the visualization in automated vehicles in critical situations have on (1) perceived safety, (2) mental workload, (3) usability, (4) trust, (5) perceived intelligence, (6) attributed intention of developers, and (7) capability assessment?*

5.1 Procedure

Each participant experienced **five** conditions, a *Baseline* with no visualization of the critical situation and four concepts: *Head-Up Display*, *AR*, *Lightband-*, and *Priority*-based.

(a) Study setup: (1) one of the two Vive base stations, (2) HTC Vive Pro, & (3) fan.



(b) Positions of critical situations on the route of the AV. The orange lines show the places where the children, the blue lines show where the dog, and at the green lines, the blind person crosses the road. The yellow line shows the route of the AV.

Fig. 3. The study setup and the positions of critical situations in Windridge City.

Each participant was first briefly introduced to the study, signed the consent form, and filled out a demographic questionnaire. The five conditions were then presented in counterbalanced order. The participants' task was presented as follows:

> *You will drive through a city in a Virtual Reality (VR) environment in a highly automated vehicle. The vehicle takes over the lateral and longitudinal control (braking, acceleration, steering). The vehicle tries to detect critical situations and visualize them. You will be shown different ways of visualizing in critical situations. You are supposed to follow them attentively and judge them afterwards.*

Every concept was explained using texts before experiencing them. These were:

- *Baseline*: *During this ride, there is no visualization when critical situations occur.*
- *Head-Up Display*: *While driving, the vehicle communicates on a small area of the windshield as soon as a critical situation has been detected. This is symbolized by a warning triangle. At the same time, the vehicle's intention and the reason for it are communicated.*
- *Lightband*: *A lightband is located below the windshield on the driver and passenger side. As soon as the car is in the vicinity of a critical situation, the lightband lights up in the direction of the critical situation. Braking is indicated by flashing of the lightband.*
- *AR*: *The highly automated vehicle indicates via augmented reality (i.e., directly in the scene) when a critical situation occurs. A turquoise border is placed around the critical situations and the intention of the vehicle and the reasoning behind it is stated.*
- *Priority*: *The highly automated vehicle now has an augmented reality display. Depending on the priority, critical objects (e.g., pedestrians and cars) are colored. The priority for an object is determined by how high the attention of the highly automated vehicle is for the object. There are priorities from 1 to 10 (10 being the highest), each priority is given its own color. Objects with priority 10 have the color red, objects with priority 5 have the color yellow (with intermediate levels). Objects with lower priority are not displayed. The priority of*

objects also depends on their distance from the vehicle. The intention of the vehicle and the reason for it are given.

Therefore, participants were aware that the vehicle detected critical situations in all conditions and were visualized in all but the *Baseline* and were only observing the system and not supposed to take over control at any point. The situations' occurrence was altered per condition to avoid learning effects (see Figure 3b). Participants sat in the simulated vehicle for approximately 3 min per condition and then answered the questionnaires described below on a separate laptop. Finally, participants gave general feedback. On average, a session lasted 60 min. Participants were compensated with € 10. The hygiene concept regarding COVID-19 for studies (ventilation, disinfection, wearing masks) involving human subjects of our university was applied.

5.2 Measurements

Measurements regarding visualization concepts vary per publication. However, we chose measurements such as trust and cognitive load that are often used (for example, see [12, 58]).

After each condition, the following scales were administered: for cognitive load, the subscale mental workload using the raw NASA-TLX [29] on a 20-point scale was used. Other subscales were omitted due to their limited relevance, for example, *Physical Demand* as participants did not have to control the vehicle. The system usability scale (SUS) [10] was used to assess usability, for trust in automation, the German version of the Trust in Automation scale of Jian et al. [40] developed by Kraus et al. [51] was used. For acceptance, the van der Laan acceptance scale [95], for perceived safety, the four 7-point semantic differentials[19], and for perceived intelligence, the Warner and Sugerman's intellectual evaluation scale [99], a proposed measurement for robots [6], was used. The attributed intention of developers was measured with the *Intention of Developers* subscale of the Trust in Automation subscale by Körber [49]. This subscale uses two 5-point Likert scale items ("The developers are trustworthy." and "The developers take my well-being seriously.").

Additionally, participants were asked with self-developed single items on 6-point Likert scales how they subjectively assessed the longitudinal and lateral guidance of the AV. Objectively, these were exactly the same in every condition. Participants were also asked up to which distance critical situations are recognized (correct answer: 17 m) and whether the concept indicated in time that a critical situation existed (1 - *totally disagree* to 7 - *totally agree*). Furthermore, participants were asked whether the concept helped to comprehend the intention of the AV ("The concept has helped to correctly assess the intention of the vehicle"; 1 - *totally disagree* to 7 - *totally agree*) and whether they would have rather taken control or let the AV in control ("Would you rather have taken control or have the automated vehicle remain in control in these critical situations?"; 1 - *Me* to 7 - *AV*). Participants did not, however, have any control over the vehicle nor did it differ in any of the conditions. Finally, we asked participants after each trial: *In what order did the critical situations occur?* to check whether participants paid attention to the automated drive.

After all five conditions, participants rated their preferences regarding the concepts from greatest (*ranking = 1*) to lowest (*ranking = 5*). Open questions regarding feedback and improvement proposals were also administered. Participants rated their immersion using the *Immersion* subscale of the Technology Usage Inventory (TUI) [50]. The usefulness and necessity of each concept and, in general, a visualization ("I think visualization is useful/necessary) in critical situations") were measured using single-item ratings on 7-point Likert scales.

5.3 Participants

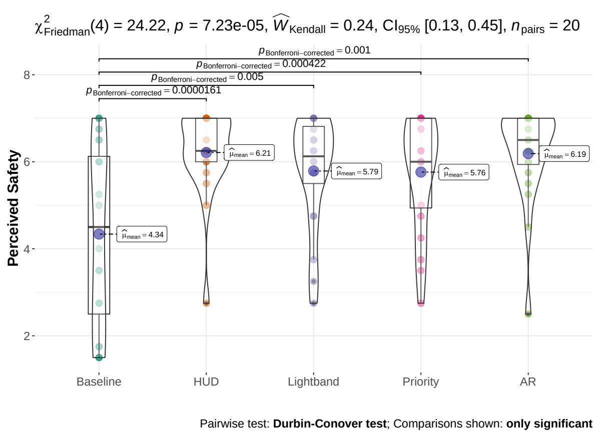
The computed required sample size via an a-priori power analysis using G*Power [21] was computed. To achieve a power of .85 with an alpha level of .05, 20 participants should result in an anticipated medium effect size (0.27 [24]) in a within-factors repeated measures ANOVA.

Therefore, *N*=20 participants (10 female, 10 male) participated in the experiment. They were on average *M*=32.05 (*SD*=13.59) years old. All participants hold a valid driving license. Ten are students, eight employees, one is self-employed, and one stated that none of the options mentioned before nor job-seeking applies. On 5-point Likert scales (*1=strongly disagree*, *5=strongly agree*), participants reported interest in AVs (*M*=3.85, *SD*=.99) and believed such an AV would ease their lives (*M*=3.75, *SD*=1.07). The participants slightly believed AVs to become reality by 2030 (10 years from today; *M*=3.75, *SD*=1.21). The *Propensity to Trust* subscale of the *Trust in Automation* questionnaire [49] was administered once before and once after all conditions. *Propensity to Trust* was relatively low (*M*=2.82, *SD*=.81) prior to the experiment. A Wilcoxon signed-rank test revealed that, after the simulation, the values for *Propensity to Trust* did not significantly change (*M*=2.82, *SD*=.70). Participants rated their Immersion in a range from 11 to 28, with a mean of *M*=19.30 (*SD*=4.62; min possible is 4, the max possible 28). We excluded no participants from the analysis since none reported very low immersion (i.e., <7).

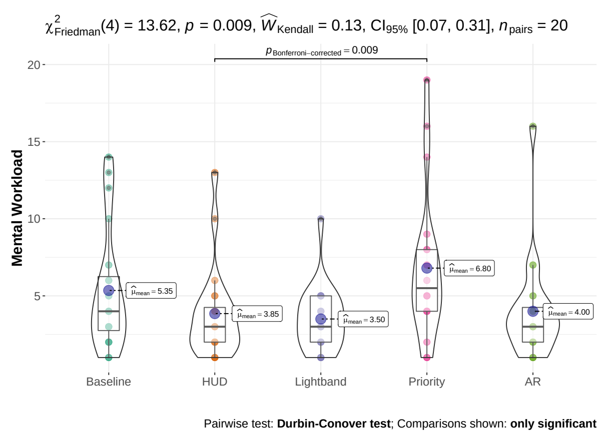
6 RESULTS

We used Friedman's or repeated measures ANOVAs to compare the four concepts and the *Baseline* depending on the data's nature [88]. For post-hoc tests, we used Bonferroni corrections. We used Version 4.0.5 of R with all packages up-to-date as of May 2021. RStudio Version 1.4.1103 was used. For the figures, we used the package *ggstatsplot* [76] which includes statistical details such as the used test and the effect size. Therefore, we refrain from rewriting these in text.

6.1 Perceived Safety and Mental Workload



(a) Results of perceived safety [19].

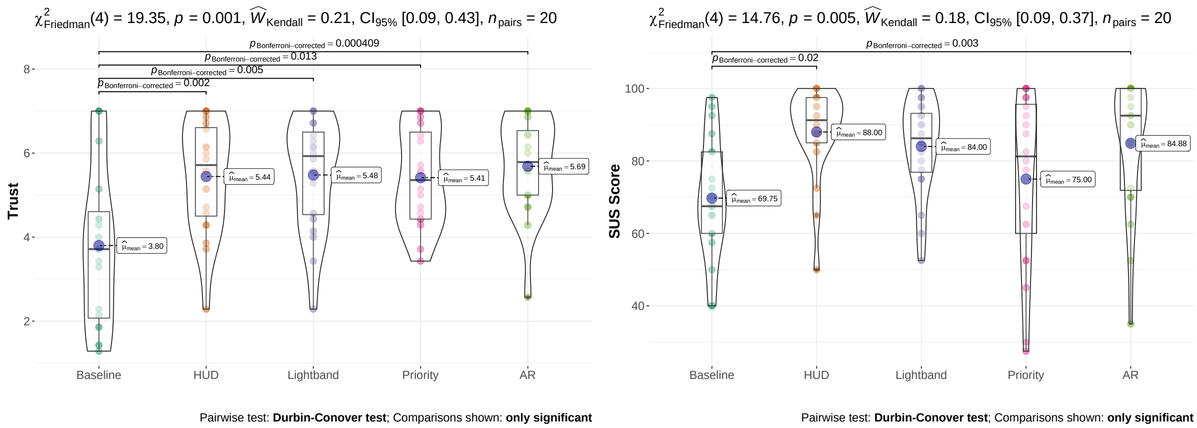


(b) Results of mental workload [29].

Fig. 4. Results for perceived safety and mental workload.

A Friedman's ANOVA with post-hoc tests revealed a significant effect of concept (see Figure 4). Participants rated the perceived safety significantly lower in the *Baseline* compared to all other concepts (see Figure 4a). Regarding the mental workload subscale of the NASA-TLX, a Friedman's ANOVA with post-hoc tests revealed that the *Head-Up Display* resulted in the lowest mental workload, significantly lower compared to the *Priority* concept (see Figure 4b).

6.2 Usability and Trust in Automation



(a) Results of trust [51].

(b) Results of the SUS [10].

Fig. 5. Results for trust and the SUS.

A Friedman's ANOVA with post-hoc tests showed a significant effect of concept on trust (see Figure 5a) and usability (see Figure 5b). Trust was significantly higher with any of the visualizations compared to the *Baseline*. Usability for the *Head-Up Display*, the *Lightband*, and the *AR* concept was categorized as excellent (above 80.3 [84]). However, usability was only significantly higher for the *Head-Up Display* and the *AR* concept compared to the *Baseline*.

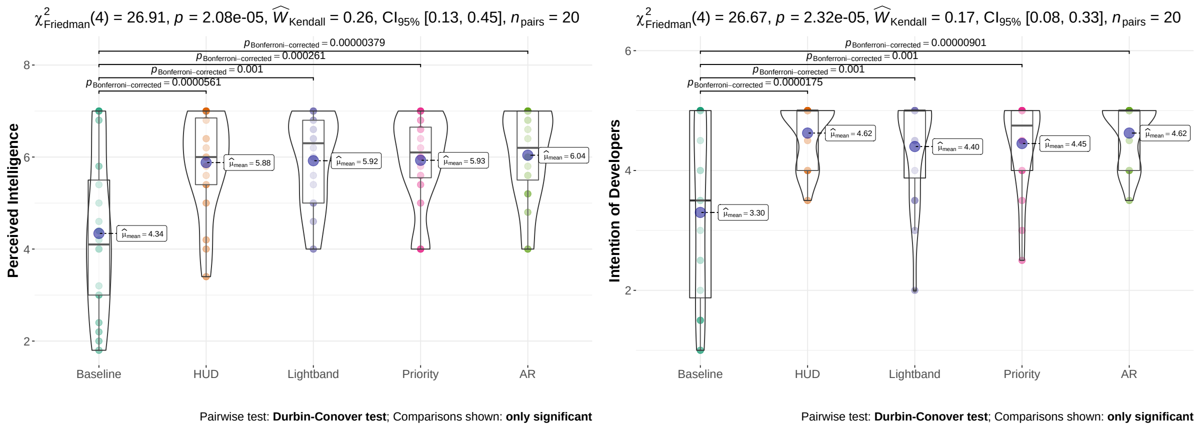
6.3 Perceived Intelligence and Intention of Developers

Friedman's ANOVAs found a significant effect concerning the concept for perceived intelligence (see Figure 6a) and intention of developers (see Figure 6b). The AV was rated significantly worse in the *Baseline* with respect to perceived intelligence and intention of developers compared to all other concepts.

6.4 Capability Assessment

Regarding lateral control, a Friedman's ANOVA with post-hoc tests showed that the *AR* concept was rated significantly higher than the *Baseline* (see Figure 7a). For longitudinal control, a Friedman's ANOVA with post-hoc tests showed that the *AR* and the *Head-Up Display* concept were rated significantly higher than the *Baseline* (see Figure 7b).

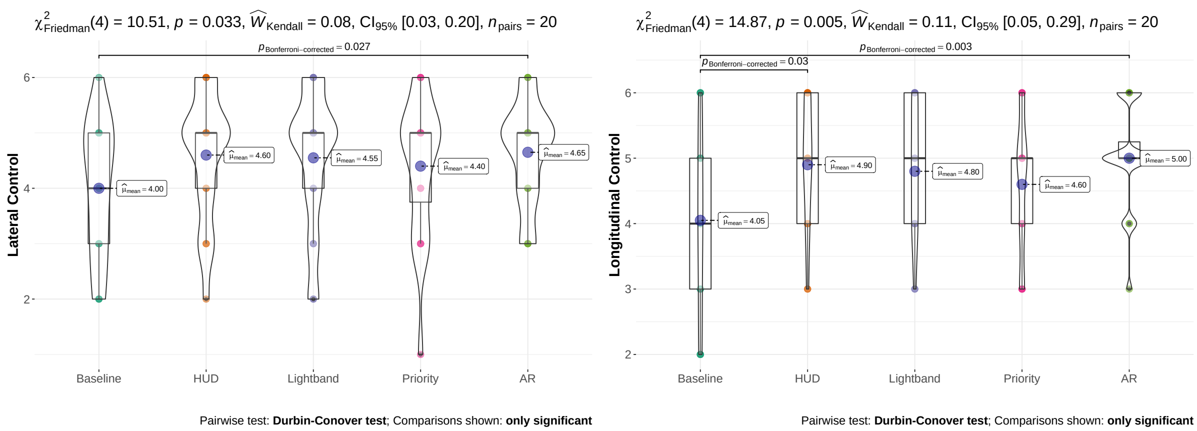
All concepts except the *Lightband* were assessed as being able to perceive critical situations significantly earlier compared to the *Baseline* (see Figure 8a). However, while the concepts were activated 17m before the actual situation (see Figure 8a dashed orange line), participants believed that the AV was less capable in perceiving these situations (mean values are below 17m). Regarding being able to understand the intention of the AV, the results showed significant differences for the concepts (see Figure 8b). This intention comprehensibility of the AV was rated significantly worse for the *Baseline*, confirming our expectations. The *Lightband* was also rated significantly worse compared to the other concepts (*AR*, *Head-Up Display*, *Priority*; see Figure 8b). No significant differences between *AR*, *Head-Up Display*, and *Priority* were found.



(a) Results of perceived intelligence [99].

(b) Results of intention of developers [49].

Fig. 6. Results for perceived intelligence and intention of developers.

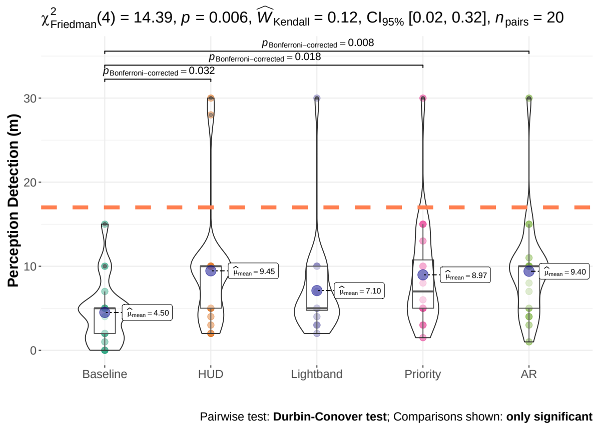


(a) Results for lateral control.

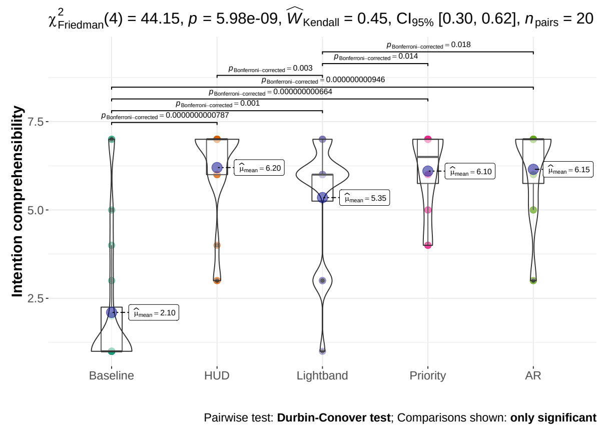
(b) Results for longitudinal control.

Fig. 7. Results for lateral and longitudinal control.

We asked participants whether they wanted to control the vehicle in critical situations themselves. A Friedman's ANOVA with post-hoc tests found that with any concept, the willingness to let the AV be in control in critical situations was significantly higher than in the *Baseline* (see Figure 9a). The timeliness of the communication was rated high (*Lightband*: *M*=5.45, *SD*=1.54; *AR*: *M*=5.80, *SD*=1.74; *Head-Up Display*: *M*=5.95, *SD*=1.57; *Priority*: *M*=6.00, *SD*=1.34; see Figure 9b). A Friedman's ANOVA with post-hoc tests found no difference between the concepts. As the question was targeted towards the concept, the significant differences compared to the *Baseline* are irrelevant.

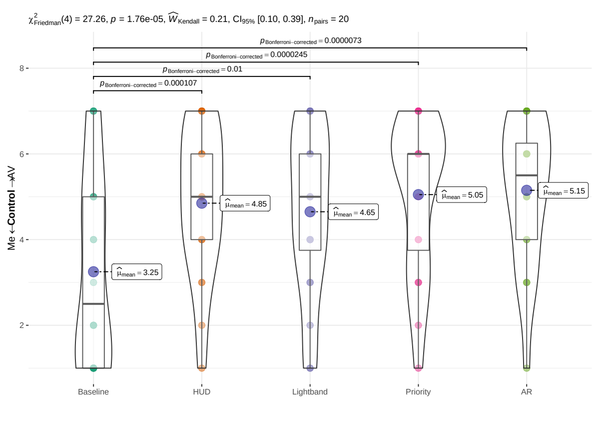


(a) Results for critical situation perception. The dashed orange line represents the actual distance for the visualization.

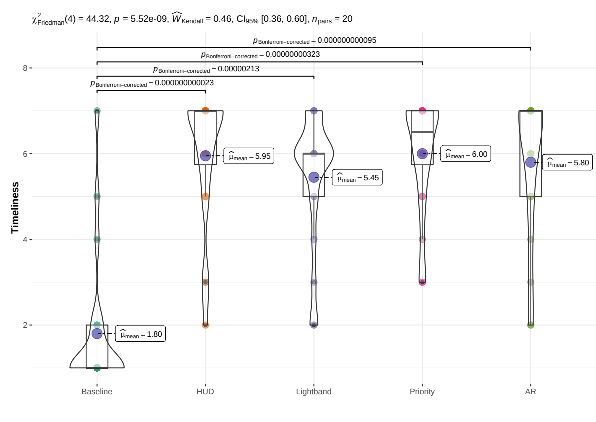


(b) Results for intention comprehensibility.

Fig. 8. Results for situation perception and intention comprehensibility.



(a) Results for control distribution.



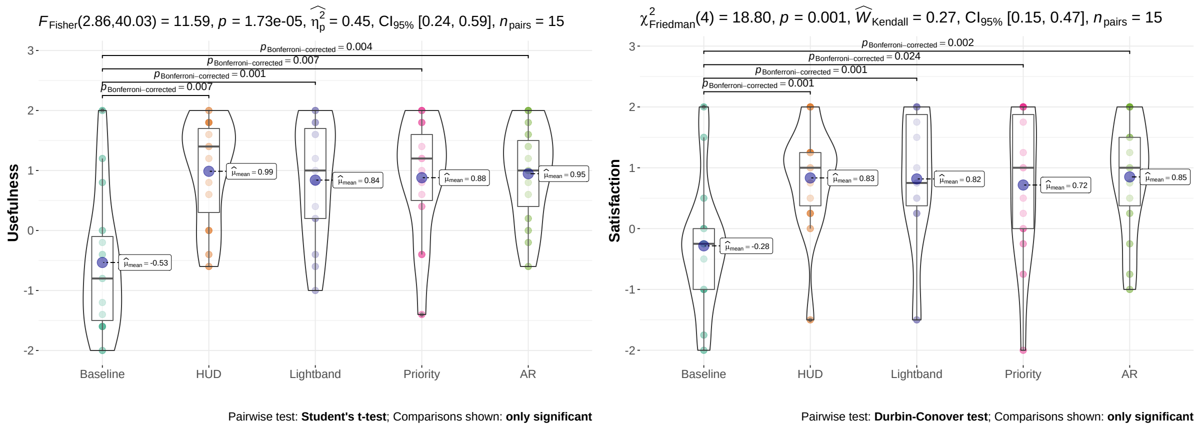
(b) Results for timeliness of visualization.

Fig. 9. Results for control distribution (oneself vs. AV) and timeliness.

6.5 Acceptance and Concept Preferences

A repeated measures ANOVA with post-hoc tests showed a significant difference in the usefulness (see Figure 10a) and a Friedman's ANOVA with post-hoc tests showed a significant difference in the satisfaction (see Figure 10b) between the *Baseline* and all other concepts.

The *Head-Up Display* concept received rankings indicating the highest preference, i.e., the lowest mean (see Figure 11). The *Baseline* was rated significantly worse than all other concepts, followed by *Priority* and *Lightband*, without significant difference between them. The *AR* concept had the second-highest preference and



(a) Results of usefulness [95]. (b) Results of satisfaction [95].

Fig. 10. Subscales of the acceptance scale [95]. 15 datasets were used as one measurement missed for the first five participants.

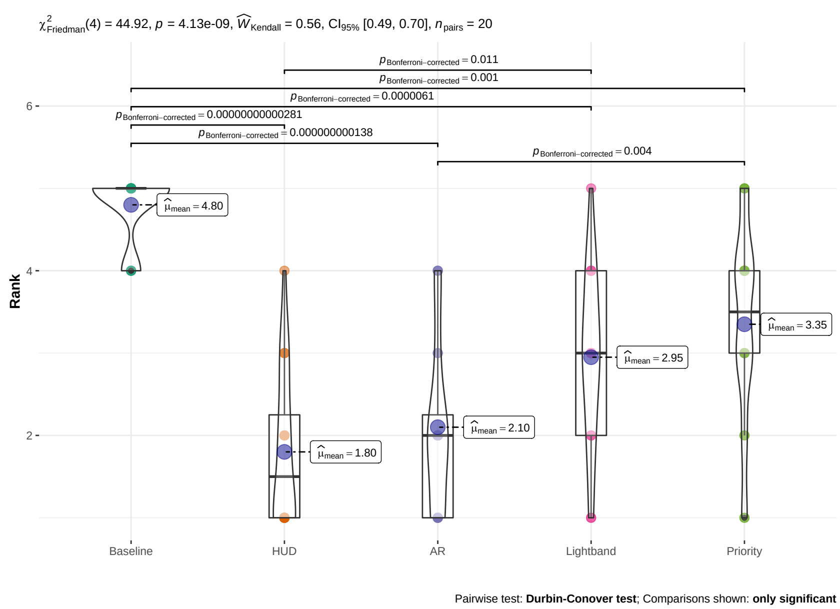


Fig. 11. Preferences for the concepts (lower is better).

was rated as significantly better than the *Priority* concept. The *Head-Up Display* had the highest preference and was rated as significantly better than all the other concepts except for the *AR*.

6.6 Reasonability and Necessity

Participants were asked about their agreement towards the reasonability and necessity for each concept, a visualization in general, and the communication of the AV's intention and the explanation on 7-point Likert scales (1=*Totally disagree* to 7=*Totally agree*; see Table 3).

Table 3. Assessments of necessity and reasonability for concepts and general visualization. Additionally, the visualization of intention and explanation were rated.

Variable	Min	q_1	$\tilde{x}$	$\bar{x}$	q_3	Max	sd	IQR
Lightband reasonable	1	2.75	5	4.70	6.25	7	2.03	3.50
Lightband necessary	1	2.00	5	4.25	6.00	7	1.94	4.00
Head-Up Display reasonable	3	6.00	7	6.25	7.00	7	1.16	1.00
Head-Up Display necessary	2	5.00	6	5.65	7.00	7	1.50	2.00
AR reasonable	2	5.00	6	5.90	7.00	7	1.29	2.00
AR necessary	1	5.00	6	5.70	7.00	7	1.53	2.00
Priority reasonable	1	2.00	4.50	4.05	6.00	7	2.09	4.00
Priority necessary	1	2.00	4.00	3.95	5.00	7	1.90	3.00
visualization reasonable	4	7.00	7	6.70	7.00	7	0.80	0.00
visualization necessary	3	5.75	6	6.05	7.00	7	1.15	1.25
intention reasonable	1	4.75	6	5.40	7.00	7	2.06	2.25
intention necessary	1	3.75	6	5.00	7.00	7	2.32	3.25
explanation reasonable	1	3.00	5	4.85	7.00	7	2.16	4.00
explanation necessary	1	2.00	5	4.25	5.25	7	2.05	3.25

Participants rated the *Head-Up Display* as most reasonable (*M*=6.25, *SD*=1.16). The *AR* (*M*=5.70, *SD*=1.53) and the *Head-Up Display* (*M*=5.65, *SD*=1.50) were the concepts that were rated most necessary. The *Priority* was rated both the least reasonable (*M*=4.05, *SD*=2.09) and the least necessary (*M*=3.95, *SD*=1.90). Friedman's ANOVAs showed significant differences in the reasonability scores (χ^2 (3)=15.18, p=.0017) and the necessity scores (χ^2 (3)=19.58, p<.001). Post-hoc tests showed that the *Lightband* and the *Priority* were rated significantly less reasonable than the *Head-Up Display*. The *Lightband* was also rated significantly less necessary than the *Head-Up Display*. Overall, a visualization was rated as highly reasonable (*M*=6.70, *SD*=.80) and necessary (*M*=6.05, *SD*=1.15; see Table 3).

6.7 Situation Relevance

After the study, we asked participants how critical they perceived the situations. Participants also ranked the situations according to the perceived criticality (1 = highest criticality). While participants rated all situations as highly critical (dog: *M*=6.60, child: *M*=6.80, blind person: *M*=6.85), a Friedman's ANOVA found a significant difference in the ranking (χ^2 (2)=16.90, p<.001) there was a clear ranking of the criticality: children (*M*=1.35), then blind person (*M*=2.00), and least critical, the dog (*M*=2.65). Post-hoc tests showed all these differences to be significant.

6.8 Open Feedback

No participant stated that such a communication/visualization is unnecessary, on the contrary, for example [P3] stated that "actually I just found the system without visualization bad because you can't get any information from the car. I expect this from a car that drives itself!" [P7] stated that "without visualization important / necessary information is missing" despite not actually being involved in the driving task. Regarding improvement proposals, three participants wanted an acoustic signal accompanying the visualization. Some participants wanted to combine two systems. [P3] and [P8] wanted to combine *Head-Up Display* and *Lightband*, [P13] *AR* and *Head-Up*

Display. [P20] stated that "Several systems should be offered as an option that everyone can individually adjust according to their trust in the system. For example, the system may initially be able to take away the skepticism of drivers, but once the skepticism has been taken away and one trusts the vehicle completely, the option can be set down to the lightband. This means that after building up trust, the system may become annoying and should be able to be adjusted down in intensity." This is interesting as not the information content but the intensity is the relevant factor for this participant claiming that the information is still relevant but visualization should be less intense in later stages of using the AV. Some participants also suggested to visualize more situations and objects such as objects affecting the trajectory ([P5]), all pedestrians crossing the road ([P2] and [P12]), or braking and turning ([P7]).

7 DISCUSSION

Overall, all concepts (except the *Baseline*) had high trust, acceptance, perceived intelligence, and perceived safety ratings. This confirms previous work that showed that transparent systems [16, 48] and AR systems [12, 32, 108] lead to increased trust, acceptance, and perceived safety. Usability was only assessed as significantly higher in the *Head-Up Display* and the *AR* concept compared to the *Baseline* (see Figure 5b). The *Lightband* concept evoked higher mental workload than the *Head-Up Display* (significantly) and the *Baseline* as well as led as the only concept not to earlier critical situation perception compared to the *Baseline*. Participants rated the visualization of critical situations as highly necessary and reasonable. However, participants did not show great variety in their assessments between the four concepts (*Head-Up Display*, *AR*, *Priority*, *Lightband*). Therefore, we reflect on the general necessity and the relevance of the visualization. Finally, we discuss practical implications for future AVs.

7.1 Necessity of Critical Situation Visualization

The data shows that a visualization, in general, was rated as highly reasonable (see Table 3), and all visualizations were preferred over no visualization. Additionally, almost all measurements indicate the superiority of having communication in critical situations (except mental workload, which was higher for *Priority* but low for all other concepts; see Figure 4b). Regarding explainable automation requirements in the context of AVs, our critical situations cover some of the themes presented by Wintersberger et al. [109]. As the pedestrians and the dog impact the trajectory, visualizing these enhances predictability of AV's actions. These road users are moving (see *object characteristics* [109]) across the street (see *spatial properties* [109]) and belong to very vulnerable groups (see *regulations* [109]). Their visibility, however, is rather high. Nevertheless, our experiment supports the findings of Wintersberger et al. [109] in that these properties are relevant for explainable automation. Therefore, in line with previous work[12, 16, 32, 48, 108], we conclude that visualizations of the detection and the intention plus explanation in critical situations are necessary.

In line with work by Wiegand et al. [102], participants indicated that they did not want to take over control of the vehicle in the presence of an explaining visualization (see Figure 9a). Therefore, presenting such information helps to avoid post-automation effects (see also [97, 98]).

7.2 Relevance of Visualization Type

As shown in Table 1, numerous works used different types of visualizations to aid drivers (e.g., [46, 69, 78, 80]) and to increase trust in AVs (e.g., [58]). While we categorized these by the technology-independent registration type, different technologies were also used or simulated. Löcken et al. [58, 60] used ambient light via LED strips while others used AR windshields [12, 56, 108]. Today, *Head-Up Display* become prevalent in vehicles. These could also be used in an autonomous context to provide relevant information. Therefore, we compared this plethora of visualization concepts for critical situations (child, a person with a visual impairment, or dog crossing). While all concepts (besides the *Lightband* concept) performed consistently better than the *Baseline*, there were only very few significant differences between the concepts.

Intention comprehensibility (see Figure 8b) was significantly worse for the *Lightband* concept compared to the other visualizations. *AR* also lead to perceived higher perceived lateral and longitudinal control compared to the *Baseline*, which the other visualizations did not (see Figure 7). Also, the SUS showed that only *Head-Up Display* and *AR* (see Figure 5b) were rated significantly better than the*Baseline* in terms of usability. We also found significant differences for mental workload (*AR* significantly lower compared to *Priority*; see Figure 4b) and for intention comprehensibility (*Lightband* lower than all other concepts; see Figure 8b). Preferences, however, showed that participants favored the *Head-Up Display* or the *AR* concept. The discrepancy between dependent measurements and preference indicates that the employed performance metrics are not that relevant for personal preference. As only a few differences were found, we conclude that all concepts provide clear benefits to a user, with the *Lightband* concept being the most complicated to understand but also, from a technical standpoint, the easiest implementable.

While lateral and longitudinal control for the AV were the same in all conditions, we found that the *Baseline* was rated significantly worse than the *AR* concept for lateral (see Figure 7a) and significantly worse than the *Head-Up Display* and the *AR* (see Figure 7b) for longitudinal control. A visualization also led to a significantly higher acceptance of letting the AV in control (see Figure 9a). Together with a significantly better attributed critical situation perception (see Figure 8a) and significantly higher perceived intelligence and intention of developers (see Figure 8), we constitute that the Halo effect is at work here. The Halo effect is a cognitive bias that leads to positive impressions of system attributes based on other (unrelated) positive impressions. Our work contrasts with the work presented by Colley et al. [12]. In their work, different concepts visualizing pedestrians' intentions lead to no significant differences for lateral and longitudinal control.

7.3 Relevance of Scenario

With the study design, we measured the dependent variables after all three scenarios were encountered per visualization. Therefore, the study design did not allow us to explore differences between the scenarios. The child scenario resembles scenario 9 in the work of Wiegand et al. [102]. However, the other scenarios were not accounted for and provide two additional scenarios in which an explanation seems necessary. Wiegand et al. [102] proposed other scenarios in which an explanation could be necessary or wanted. Most of these include unexpected behavior by the AV, only scenarios 2, 8, and 9 include a pedestrian. In some of our scenarios, more pedestrians were present than the one performing the critical behavior. We found that *Head-Up Display* and *AR* were rated almost equally regarding their preference. However, in scenarios with even more pedestrians, a contact analog, i.e., the *AR* concept, could be beneficial as the relevant object for the AV's behavior is clearly highlighted.

7.4 On the Need of Comparative Studies and Baseline Selection

This work presents a comparative study regarding visualization concepts for the communication of AVs with passengers. These were derived from the literature (*Lightband*, *AR*, *Head-Up Display*) and included one novel concept (*Priority*). The results show that in several often used dependent variables (trust, control, perceived intelligence, usability, mental workload), there is little difference between the conditions but significant differences to the *Baseline*. Therefore, the question arises whether the right dependent variables are currently used in research on the visualization in critical systems or whether the measurements are sensitive enough to assess the differences between the concepts as participants showed a strong preference towards *Head-Up Display* and *AR* concepts. The reasons for this could be manifold, including personal preference or familiarity (with *Head-Up Display*, for example). As most studies only compared the developed concept (and variations of it) with a baseline **without** any visualization, and as we showed that **all** concepts were mostly rated higher compared to the *Baseline*, we strongly argue that future work must include other proposed concepts more in their studies. It is obvious that this increases the number of conditions, however, we propose to at least choose a baseline that is not **without any visualization** but is actually the best-rated concept in literature. We conclude that more comparative studies are necessary to account for the numerous visualization concepts proposed.

7.5 Practical Implications and Design Recommendations

Previous work in social psychology showed that people prefer simple [62], general [62], and coherent (with prior knowledge) [91] explanations. In the domain of automated driving, Koo et al. [48] demonstrated that providing *why* information led to highest trust. While the authors mentioned that additionally presenting *how* information could lead to cognitive overload [48], we included this information to increase system transparency. We argue that in the context of AVs, cognitive overload is only a problem with higher mental workload as the AV completely takes over the primary driving task. Our results indicate that providing the intention of the vehicle (*how* information) was assessed as even more reasonable (M=5.40, SD=2.06) than providing the explanation (*why* information; M=4.85, SD=2.16; see Table 3).

Previous work discussed AR windshield displays' feasibility, especially highlighting the areas depth perception, tracking, registration, lighting, background, and color blending [25]. While the *AR* approach is more technologically advanced, already today, the *Head-Up Display* or *Lightband* approaches are feasible or even already present. Therefore, we argue that for automated rides that could be feasible in some scenarios, this technology should be used. In the future, with fully AVs (SAE Level 5), our data suggests that visualizing the intent and an explanation in a critical situation is reasonable and necessary, at least in the introductory phase. With our data, we highlight that no technologically advanced visualization (e.g., *AR*) is necessary for this visualization. As it is unclear when such *AR* technology is available, the already available *Head-Up Display* seems to be an appropriate visualization technique. Open feedback also indicated that information needs of AV users will likely change over time. Therefore, the design of such information visualization should not be static over the course of usage by an individual but should incorporate knowledge about the user's experience with AVs. One possible combination already feasible would be *Head-Up Display* and afterward *Lightband*.

While some work suggests that it should be configurable which situations are highlighted [60], we believe that a standardized approach is beneficial as rides with multiple passengers should not lead to confusion for some of them.

8 LIMITATIONS

Regarding the classification of prior work, we employed a semi-systematic approach due to the vastness of relevant keywords. Therefore, some relevant literature could be missing in the classification. Nevertheless, we included all relevant work which other current work (e.g., [58, 102, 109]) base their publications on. As a VR simulation was used, transferability to the real world is limited. While we provided an immersive scenario, the vection of the vehicle could not be simulated with our setup. Also, participants potentially did not perceive risks in the critical situations due to the VR. Lastly, the *AR* and *Priority* portrayed futuristic technology which could not be available at the entry phase of AVs. Regarding attendance, a limited number of participants took part (N=20). Only visual concepts for critical situation communication were used. While this modality is unobtrusive and, therefore, potentially highly acceptable, from our study, it is unclear whether other modalities (e.g., audition, tactition, olfaction [107], thermoception) would perform better. Also, only three situations were used. A multitude of situations is possible (see [58, 102]) and it is unclear whether our findings hold for these other situations. However, we chose situations which can not be overcome by technology alone, therefore, provide evidence for a set of situations imaginable even in the distant future. The AV detected critical situations 17 m before the stopping point (see Figure 8a). While this was necessary to ensure comparability, this is likely not possible in a real-world scenario. While Waymo claims to "identify [...] stop signs greater than 500 meters away" [39], detecting critical situations is more difficult as these can occur instantaneously and often moving objects are involved. The findings are also limited as for dependent measurements, only subjective ratings were used.

9 CONCLUSION AND FUTURE WORK

In conclusion, we classified prior work in manual and automated driving regarding the proposed registration type of information via a backward and forward search. A representative for each of the three registration type contact analog, angle analog, and unregistered was implemented, and we additionally proposed a novel priority-based concept. These were compared in a controlled experiment in VR (N=20) together with a *Baseline*. The results showed that the ratings between concepts were close together and only few significant differences were found. However, almost all concepts were rated significantly better in most dependent measures compared to the *Baseline*. We conclude that more comparative studies are necessary and reflect on the chosen dependent variables. Future work must, therefore, deeply consider their choice of baseline and compare their solutions to existing ones. Additionally, the potential difference in needs of novice and experienced users of AVs should be explored.

ACKNOWLEDGMENTS

The authors thank all study participants. This work was conducted within the project 'Interaction between automated vehicles and vulnerable road users' (Intuitiver) funded by the Ministry of Science, Research and Arts of the State of Baden-Württemberg.

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