How to Display Vehicle Information to Users of Automated Vehicles When Conducting Non-Driving-Related Activities

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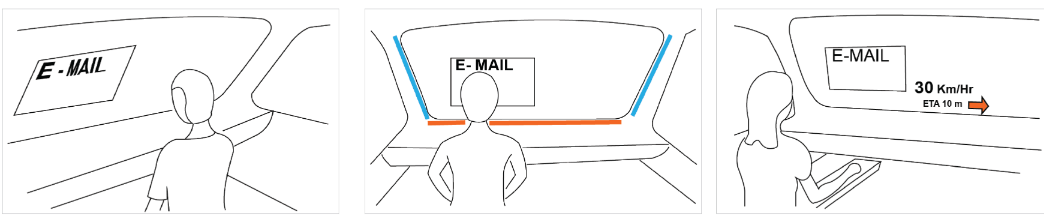

a: NDRA only (No Vehicle Information) b: NDRA + Light Bar Display c: NDRA + Windshield Display

Fig. 1. We designed two different HMI displays (b: light bar display and c: windshield display) to provide vehicle information while conducting non-driving-related activities (NDRAs) during a fully automated ride. We assessed their influence on user experience, trust, and NDRA task performance and compared them with a baseline of not showing additional vehicle information (a: NDRA-only).

Automated vehicles (AVs) are expected to enable users to engage in non-driving-related activities (NDRAs). However, users do not easily trust an automated vehicle which poses new challenges for automotive human-machine interfaces (HMIs). Over-presenting vehicle information can distract users from NDRAs, and under-presentation can impact trust and user experience (UX) negatively. To investigate how to best present vehicle information to foster users' trust and UX while performing NDRAs, we designed two in-vehicle HMI concepts: 1) A colored and animated light bar display around the windshield and 2) a windshield display interface presenting pictograms and numbers. Results from a simulator study ($N = 18$) indicate that both concepts contribute to a high trust level and UX while not affecting the NDRA performance compared to the baseline of not showing vehicle information. In addition, the light bar provides better UX than the windshield display and is also preferred by users. With our findings, we contribute to the effective design of presenting vehicle information in automated vehicles.

CCS Concepts: • **Human-centered computing** → **Interaction techniques**; Interactive systems and tools; Empirical studies in HCI; Empirical studies in visualization.

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Additional Key Words and Phrases: Automated vehicles, fully automated driving, vehicle information displays, trust in automation, non-driving-related activities, light bar displays, windshield displays

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1 INTRODUCTION

With the upcoming era of fully automated vehicles (SAE Level 5, [54]), drivers will not be required to perform any driving-related tasks [49]. This allows drivers to fully engage in non-driving-related activities (NDRAs) [47] also known as non-driving-related tasks (NDRTs) [37] such as relaxing, working, or watching movies while travelling in a car [48]. However, the likelihood of users to engage in NDRAs gets strongly influenced by the level of trust towards an AV [46, 64]. While users with a low trust level prefer to stay situational aware and thus avoid performing NDRAs, users with a high trust level lead towards misuse and over reliance [64] which affects trust calibration negatively [14].

To reduce such negative automation effects (undertrust as well as overtrust), providing information about the vehicle's status and its behavior is key [64]. Previous work shows that the presentation of vehicle information increases trust towards AVs and impacts both user experience (UX) [26, 38, 56] and usability positively [26]. However, any presented vehicle information loses its importance for users when they are engaged in a NDRA, compared to not performing a NDRA [25]. This poses a new challenge for the design of HMIs because the presentation of vehicle information, on the one hand, improves situational awareness and calibrates trust while, on the other hand, it can impede the task performance of a NDRA. Thus, there is a need for HMIs to display vehicle information in a way that the HMI interferes as little as possible with NDRAs [25].

Previous work evaluated different HMI designs to provide vehicle status such as through light animations (e.g., [26, 38, 56]) or through pictograms on digital displays (e.g., [43, 56]) or augmented reality head-up-displays (AR-HUDs) (e.g., [6, 18]). However, these studies either focused on SAE Level 3 automation, where the driver needs to be able to take back control from the car if necessary (fallback to manual driving), whereas studies focused on Level 5 automation did not included all the required vehicle information or were tested mostly for highway driving scenarios. Apart from this, previous studies also evaluated engagement in NDRAs for different NDRA display designs (e.g., [55]), or the effect of NDRA engagement on the take-over performance for highly automated vehicles (e.g., [61, 66]). Until now, there is very little information on how to best provide vehicle information in fully automated vehicles when users may or may not want to receive the vehicle information when they are engaged in NDRAs, especially during complex tasks such as office work which requires perception, cognition, and action.

To address this research gap, we designed two HMI concepts which provide vehicle information during the engagement in NDRAs when riding in a fully automated vehicle. Figure 1 demonstrates these two concepts: 1) A light bar display around the sides and bottom of the windshield (Figure 1 b) provides vehicle information through different colors and animation patterns while 2) the windshield display (Figure 1 c) presents vehicle information at the bottom center of the windshield using pictograms and numbers. To assess the concepts' effect on trust, UX and NDRA performance and to compare them with the baseline of no vehicle information display (Figure 1 a), we conducted a simulator study with $N = 18$ participants. We report on the results gained and outline key elements for the design of future HMI for fully automated vehicles.

Contribution Statement. We contribute two HMI designs to maintain trust towards a fully automated vehicle (SAE level 5) while performing a NDRA. Based on our insights from our user study, we outline how vehicle information can be provided via HMIs in an indirect way which can outperform the traditional way of providing vehicle information without affecting NDRA performance. We additionally highlight which information should be given in an explicit and traditional way.

2 BACKGROUND

2.1 Importance of Vehicle Information

The primary purpose of the vehicle information in manually driven vehicles is to keep the driver in the loop to safely accomplish the driving tasks [44]. However, with the absence of a human driver in fully automated driving, vehicle information is no longer essential for driving safety. However, humans do not (yet) trust machines [27]. Likewise, for AVs, many humans think that they are better drivers than machines, leading to reduced trust towards AVs [14]. To confront this problem, providing feedback of the vehicle's status so that users can develop and maintain a coherent mental representation was found to be essential [65]. Experts also assume that more detailed information needs are expected during the initial interaction with the automated systems [1]. Previous studies have investigated the information needs in various levels of automation. Important information the user wants to see when riding an AV includes the vehicle status, current and planned maneuver, surrounding vehicles, and navigation information [1, 13, 17]. Further, Feierle et al. [17] report that information about the vehicle itself, navigation information, speed and speed limit should always be displayed regardless of experience and engagement in a NDRA in highly automated vehicles.

2.2 Vehicle Information Display Modalities and Design

Over the years, academia and industry proposed various concepts of vehicle information displays (e.g., [31, 39]). These concepts were found to be useful for improving UX and trust [38, 43, 57], thus supporting the results from the studies related to the importance of information needs. AVs can provide vehicle information through different modalities. For example, Johns et al. [31] created a concept of providing information through haptic feedback on the steering wheel. Other concepts include information through speech [19], head-up-displays (HUD) [4], and ambient lights [38]. From the above examples, visual feedback has the advantage over other modalities such as audio, speech, or haptic feedback, as it can provide more vehicle information simultaneously. Within the visual modality, past work highlights possible ways to provide information especially via lights, icons, numbers, or text messages (e.g., [38, 43, 56]).

Vehicle Information Display through Lights: Using lights with different color and animation pattern has a huge potential to provide vehicle information as their expressivity can be greatly exploited [21]. Light bar displays can provide information without distracting the driver while being able to get their attention when needed [39]. Industry also started emphasizing ambient light bars to provide information other than just contributing to the visual appearance. For example, the Mercedes Benz S-class 2021[1] uses sensor data to provide visual warnings through red ambient light animation for an imminent collision. Additionally, it also provides ambient light feedback while operating the climate control system or using the voice assistant system. Prior to this, light bar displays to provide information have been used for example by Pfromm et al. [50] who used LED strips with red dots to show the position of relevant objects in various traffic scenarios to make users aware of potential danger. In addition, Löcken et al. [38] used a light bar display located below the windshield to communicate intentions regarding current urban traffic situations in highly

[1] https://media.mbusa.com/releases/release-4864dc194641c85bbc82d0341802952e, last access: January 2022

automated vehicle. They found that trust and UX increase significantly when the vehicle informed the participants about the current route and identified possible conflicts in it [38]. However, the amount of vehicle information provided by these concepts is rather limited and only evaluated for a short usage period which did not include complex urban driving situations and lacked the investigation of NDRA performance.

Vehicle Information Displays using Pictograms and Numbers: Providing vehicle information through pictograms and numbers has been the preferred choice of car manufactures from the starting era of automobiles. Nowadays, these types of vehicle information presentation are still present mainly on digital displays of the instrument cluster. The reason for relying on standard pictograms and numbers relates to strict traffic and safety regulations which aim to unify and ease understanding [7, 44]. Moving forward to automated vehicles, WAYMO[2] and Tesla[3] have already introduced similar information display designs, showing vehicle information on a digital screen placed either at the instrument cluster or center console area. In addition, these designs also display a pictorial representation of the road and surrounding objects of the car ("world in miniature", [23]) through the data collected from various sensors and cameras. Such displays are mainly designed for conditionally automated vehicles (SAE Level 2-3), where the driver is still required to monitor the vehicle or take-over the control when requested [54]. There are very few studies that evaluated a display design for fully automated vehicles (e.g., [6, 38, 57]). We argue that current designs of AVs of SAE level 2 and 3 may be too complex and not optimal for fully automated vehicles (SAE Level 5), where all vehicle occupants are passengers and nobody is involved in the driving task anymore, but rather in NDRAs.

2.3 Non Driving Related Activities & Interfaces for NDRAs

According to Bubb [3], manual driving tasks can be divided into primary (longitudinal and lateral control), secondary (task supporting primary tasks, e.g., use of turning indicators), and tertiary driving tasks (e.g., talking to other passengers, infotainment control). In contrast, for SAE level 5 AVs, the traditional primary and secondary tasks (also called driving-related activities, [49]) disappear and instead the vehicle occupants can dedicate their full attention to those tasks that were called tertiary task for manual driving, which we now call non-driving-related activities. As NDRAs are seen as one of the main advantages of automated driving from a user's perspective [33], various online surveys (e.g., [24, 48]), observation studies (e,g., [9, 48]), and simulator studies (e.g., [25, 60]) have been conducted to gain insights into the user needs and to understand which tasks they would like to perform during an automated ride. Commonly identified tasks are relaxing, sleeping, using the smartphone (to make calls, social media, games), watching the surroundings, watching movies, working, and many more [9, 25, 48, 60]. Out of these activities, working and well-being are seen as most potential activities which will be performed by occupants during a ride [25], as people might want to work during their commute or relax or get entertained on the way home. The study of Eost and Flytes [15] revealed substantial productivity potential for office work if the vehicle journeys are automated.

However, one of the major disadvantages of focusing on NDRAs is an increasd risk of motion sickness [12]. It has been estimated that there is a 6-12% increase in occurrence and severity of motion sickness within a conventional cabin driven automatically, due to the engagement in NDRAs [58], and this is expected to be a main challenge for acceptance of AVs [12]. To mitigate the issues of motion sickness, studies have found that the concepts should avoid incongruent self-motion cues and should allow occupants to anticipate the future motion trajectory [11]. A

[2]WAYMO: https://waymo.com/, last access: January 2022
[3]TESLA: https://www.tesla.com/, last access: January 2022

study by Kuiper et al. [35] concluded that a display located at eye level that also enables peripheral views significantly reduces the chance of motion sickness compared a display located at the glove compartment.

Overall, previous research demonstrates the importance of enabling performant NDRAs during automated rides, which includes offering possibilities to provide screen real estate for NDRAs while at the same time mitigating motion sickness and ensuring usability. However, there are other factors which could influence the task performance of the NDRA, in particular the vehicle information design [25]. Previous studies evaluated the task performance of NDRAs, e.g., [55], but they did not consider the influence of vehicle information display on NDRA performance. Therefore, there is no common understanding of the effect of vehicle information on task performance of a NDRA in fully automated vehicles yet.

3 CONCEPT

Fully automated vehicles should allow users to easily engage in NDRAs through a display while also providing vehicle information due to the aspects mentioned before. Since there is very little information on how to combine and present these two aspects, we took design inspiration from various fields and results from previous studies [5, 26, 39]. First, to show the NDRA content, we used the windshield to display the content at the foveal region of the passenger (driver), where the visual acuity is highest, and where users pay the most attention to objects of interest in this area [40]. The positions of the NDRA display is at eye level for minimizing the motion sickness [35] caused by engagement in a NDRA [12]. Furthermore, users prefer this location for work-related activities [52]. The selected location and size enable the passengers to perceive natural motion cues as the display does not completely cover the windshield.

To provide vehicle information, we looked into various areas, where implicit information through simple lights has already proven its ability both for internal HMIs (e.g., [26, 38, 56]) and external HMIs (e.g., [10, 42]) to enhance UX and trust. As an alternative, pictograms and numbers are common for decades already to explicitly communicate information in cars. Thus, we build upon these two methods and propose two initial, non-conclusive concepts of showing vehicle information through implicit and explicit ways. Our goal was to create concepts that include all the required vehicle information in an intuitive and subtle way for a fully automated vehicle in order to not distract user from the NDRA while maintaining trust and providing a high UX. Additionally, we focused on developing concepts that can easily show the information to other passengers and not just a single user. However, in the study, we only focused on testing the concepts for a single user.

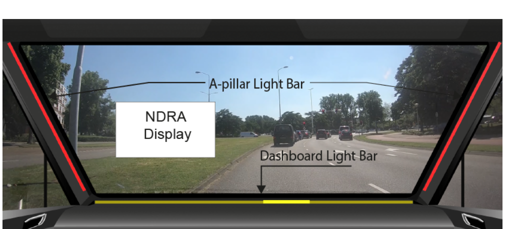


Fig. 2. Light Bar Display (LBD): Vehicle information through lights located at two A-pillars and the dashboard.

Fig. 3. Windshield Display (WSD): Vehicle information through pictograms and numbers displayed at bottom center of the windshield.

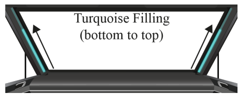
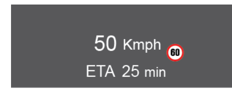
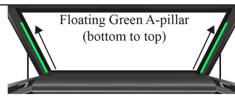
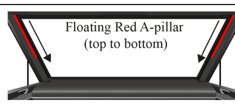
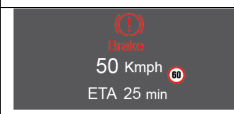
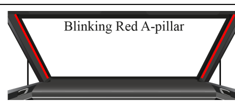
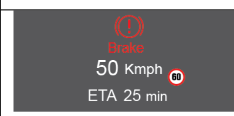
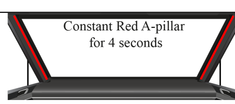
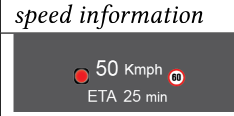
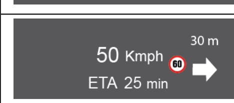
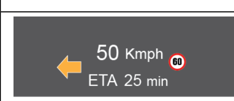
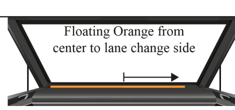
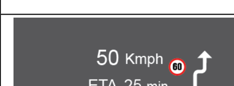
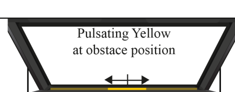
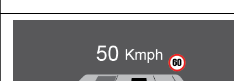
Vehicle Information	Light Bar Display & Description		Windshield Display & Description	
Default Information		Provides trip progress during constant speed		Provides Speed, speed limit and ETA in numbers
Acceleration		Animation frequency decreases as vehicle approaches constant speed	*Implicit through speed information*	
Braking		Gradually decreasing animation frequency		Shows brake symbol over default information
Emergency Braking		2 Hz blinking frequency		Brake symbol blinks to distinguish from normal braking
Stopped			*Implicit through speed information*	
Traffic Signal	*Not conveyed*			Only during crossing a traffic signal
Upcoming Turn		The turning side A-pillar turns orange with no animation		Constant turn signal in white color with distance to turn on top
Turn		The orange A-pillar starts blinking		The white symbol turns orange and starts blinking
Lane Change		Right lane change here and other part stays constant		Blinking lane change symbol
Obstacle		40% yellow color at Other areas		Road view and obstacle illustration at ETA location

Table 1. Implemented light bar display and windshield display concepts to communicate vehicle information

3.1 Light Bar Display (LBD)

In fully automated vehicles, vehicle information does not need to be presented in front of the driver as they are not involved in any driving tasks [54]. Additionally, humans are quite sensible in detecting changes in their peripheral field of view given that the patches are large [53] and are also capable of detecting motion [16]. Thus, we placed the light bar around the windshield (see Figure 2), allowing peripheral interaction [38]. This way, it will provide the vehicle information without losing much attention from NDRA. The color of the light bar and its animation patterns were curated based on the general meaning of color usage and animation according to Western European automotive norms. For example, red color in traffic is associated with braking while orange is associated with turning. We decided to use three light bars (between windshield and dashboard and at the two A-pillars) to display vehicle information as this corresponds with vehicle actions or environmental information. For example, the turning indicator information is placed at the corresponding A-pillar while obstacle information is located underneath the windshield. Accordingly, most of the information to be displayed occurs at the ground level. Therefore, we did not use the top side of the windshield to place a light bar. As the light bars do not allow to display exact speed values, we divided the speed information into three categories: acceleration, constant/fluctuating speed, and braking.

3.2 Windshield Display (WSD)

The windshield display concept provides vehicle information through pictograms and numbers. We used a windshield display (which spans the whole windshield) as this is an upcoming promising technology to utilize the unused area in AVs [29] while also keeping the interior layout clean. All information is placed at the bottom center of the windshield as shown in Figure 3, instead of using a narrow HUD in front of the driver (passenger) as we want to easily convey information to other passengers, too. We used standardized symbols and pictograms for various maneuvers that are already in use in instrument clusters or navigation systems to ease understanding. For the environment and obstacle information, instead of showing the information continuously, such as in the HMI concepts of Tesla or WAYMO, the concept will show obstacle and environment information only when the vehicle needs to maneuver due to an obstacle with an illustration of road and the obstacle.

3.3 Additional aspects and information

Previous studies suggest that vehicle status (speed), current and planned maneuver (turn and upcoming turn), vehicles ahead and navigation information (ETA) are the most important information for building trust towards an AV and enhancing in-car UX [1, 13, 17]. We built upon these insights and created a list (see Table 1) of events and information to show through the two concepts explained above. In Table 1, we demonstrate the design of providing individual information through the *LBD* and *WSD* along with a description. Additionally, as our concepts are for a fully automated vehicle (SAE Level 5), the concept should be able to provide multiple information, such as during urban driving. Thus, the individual information of the two concepts was designed to also provide information of complex scenarios. For example, Figures 2 to 3 show the scenario of braking due to a stopped vehicle in front.

4 RESEARCH QUESTIONS

We used the proposed concepts to evaluate their effect on UX and trust towards AVs, and to understand their effect on NDRA task performance. Additionally, we included "no information" as a baseline condition, in particular to compare our concepts with a condition when no vehicle information is provided. With our study we intend to answer the following research questions:

- **RQ1:** Which effects do vehicle information displays (No Information, LBD and WSD) have on trust and User Experience towards automated vehicles?
- **RQ2:** How do LBD and WSD affect the task performance of an NDRA compared to not showing any information?

5 METHOD

5.1 Setup and Apparatus

We conducted the study in a lab with a 49" TV screen of mounted on a stand. We used a car seat mounted on a wooden platform, positioned in front of the TV screen with an offset to the left to give the participant the perspective of a driver's position (left-hand drive). The seat was placed such that the participant's eyes will be approximately 0.60m away from the TV screen, which will give a field of view (FOV) of 84° horizontally and 54° vertically. Through this setup, the *WSD* center location had an offset of 24.7° horizontally and 10.7° vertically from the center point of the NDRA display, while the bottom light bar had an offset of 14.2° (leftmost point) to 41.65° (rightmost point) horizontally and 16.2° vertically. The left side horizontal light bar was at 22.1° horizontally and the right side light bar was at 46.1° horizontally from the center point of the NDRA display (see Figure 4). Although this FOV is smaller than the visual field of human eyes (200° diameter horizontally and 125° vertically), the central vision only extends up to a radius of 5° around fixation [40]. Thus, the *LBD* was in the user's peripheral field of view as intended. A remote eye tracker was mounted below the television screen and was calibrated for every participant. In addition, a table was placed next to the seat to place the interaction device (mouse) for the NDRA. The overall study setup is shown in Figure 5. The experiment was approved by the local ethics board and we followed local COVID-19 protocols.

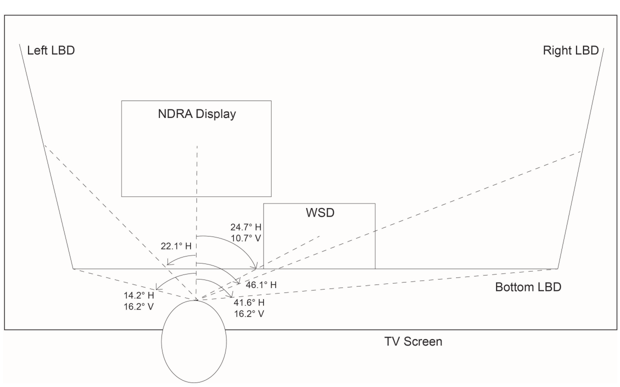


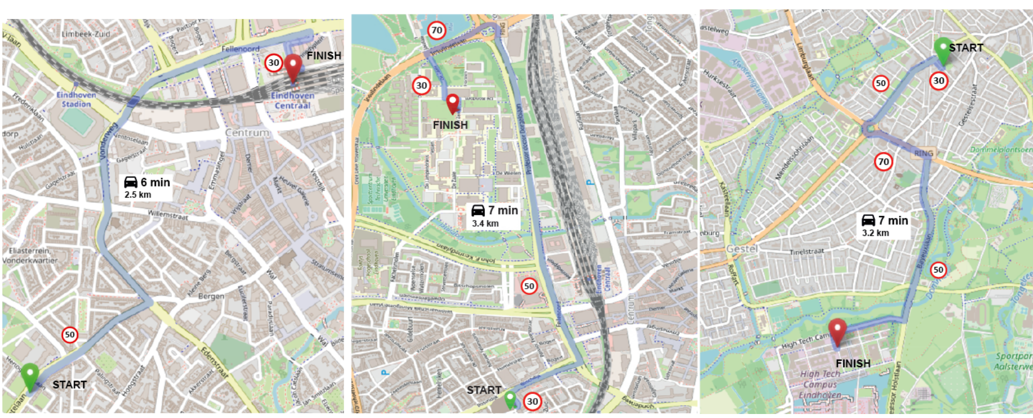
Fig. 4. Viewing angles for the 3 light bars and and the *WSD* from the center point of NDRA display.

Fig. 5. Study setup showing TV screen and car seat

5.1.1 ***Automated Driving Scenario: Urban Drive***

To test the concepts during simulated driving, we decided to record real-world driving videos in an urban environment instead of relying on a driving simulation as real-world driving videos provide a visually more realistic experience and, which has already been used for testing user interfaces and applications for AVs in previous studies (e.g., [23, 38]). For the recording, we attached a GoPro Hero 6 (1080p and wide angle) to the windshield of a *Volkswagen Golf*, near to the inside rear view mirror, so that the videos were recorded from the car center point and at a height of driver or passenger eye level. To get information of the speed of the vehicle, we placed a mobile camera between the two front seats which aimed towards the instrument cluster of the vehicle. This information was required to show the speed in windshield display concept and to see the exact timing of braking, complete stop and acceleration for both the concepts.

We selected three routes for our study (one for each condition). The selection of the routes was based upon fixing the destination to a well known location in Eindhoven, Netherlands. Each route was pre-selected so that the duration of the ride was approximately the same (6-8 minutes), included multiple speed limit sections, traffic signals, and right and left turns (see Figure 6). The three resulting videos were 6:44, 7:57 and 7:14 minutes long. We strove for consistency by recording the three videos continuously on the same day and during non-rush hours. Before starting the drive to record the videos, we instructed the driver to follow exactly the same route and stick to the speed limits as it would be expected from an AV.



Route A: Eindhoven Central (main station) | Route B: TU/e Campus | Route C: HTC Campus

Fig. 6. Maps of the three routes selected for recording the driving video. Each route has several speed limit sections and takes around 6 -7 minutes. Map data from OpenStreetMap (openstreetmap.org/copyright).

5.1.2 *Adding Emergency Situation to the Driving Videos.*

Our concepts also include showing vehicle information during emergency situations. However, it was not possible to record emergency situations such as braking in front of a pedestrian due to safety and ethical constraints and traffic regulations. Thus, we instructed the driver to stop the vehicle when it is completely safe to do so, and separately recorded a pedestrian walking video to superimpose the walking pedestrian onto the driving video. For each drive, we added one emergency situation by recording three different pedestrian crossing videos, which were added near to the end of the driving video.

5.1.3 *Implementation of Vehicle Information Concepts and NDRA.*

The vehicle information display concepts were implemented using *Unity 3D*[4]. The prototype was developed according to the framework proposed in prior work [8]. To display the vehicle information, we created game objects and animated them for each individual information containing either text or pictograms (WSD) or color bars (LBD). For the NDRA task display, we placed a white screen at the location described in the concept section for both concepts and also the baseline condition. The following are the dimensions of different elements of the concept for the 49" TV screen: The length of the vertical light bars was 37 cm, and the horizontal light bar was 70 cm, while the width of the three light bars was 0.7 cm. The display area of pictograms and numbers was 20.6 × 8.5 cm, and the NDRA area had a size of 21.6 × 12 cm.

[4]Unity 3D: https://unity.com/, last access: January 2022

5.2 Procedure

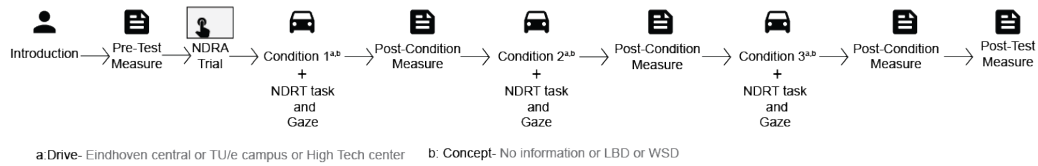


Fig. 7. In-lab simulator study procedure. The sequence of drive location and concept was counterbalanced.

As illustrated in Figure 7, the experiment started with the introduction of the study, simulator setup, taking the written consent form and pre-test measure questionnaire from the participants. Followed by this, the participants underwent a NDRA trial session in the driving simulator to understand the NDRA task and accompanied by the experimenter explaining the procedure. The NDRA trial session was set for 1 minute and participants had the choice to continue the trial until they felt comfortable enough with the NDRA task. Subsequently, the three drives followed, each with the respective concept of vehicle information and destination. The average time to complete the study was 70 minutes. While we instructed participants upfront that they will receive information on the vehicle's movement (in some conditions), we were interested in understanding the user's unbiased (=not instructed) first-time exposure and how it impacted trust and UX. That's why we did not include a familiarization phase or pre-condition explanations of individual messages. Instead, we checked understanding after each condition by asking open-ended questions about each concept. The destination and condition were counterbalanced across participants using Latin square method to reduce the effects of a fixed sequence of concepts and fixed destination (video) for each concept. After each condition, participants had to fill the post-test measure questionnaire. Finally, after the three conditions, a semi-structured interview was conducted including feedback for preferred vehicle information design.

5.3 Measures

5.3.1 Pre-Test Measures. After the introduction of the experiment, we recorded demographic data such as age, gender, education, driving license (owning a driving license was not obligatory to take part in the study as it is for fully automated vehicle). In addition to demographic data, the pre-test questionnaire also included general attitude towards AVs adapted from Rieg et al. [51] and Löcken et al. [41] and the *Affinity towards technology scale* [20].

5.3.2 Measurement During Each Vehicle Information Condition.

NDRA Performance: To evaluate the performance of the NDRA for different vehicle information display designs, semantic sentences were displayed at the NDRA area of the windscreen display and participants were required to rate the semantic correctness of each sentences using *Correct* and *Incorrect* buttons. The task was based on the reading-span task by Daneman and Carpenter [30] and was selected due to its similarity to typical office tasks, such as email/document writing, that requires reading, interpreting, and responding, and is still comparable between conditions and users. For each condition, a database of 120 sentences was created and equally distributed between correct and incorrect sentences in randomized order. We further performed the Flesch-Kincaid readability test [32], to ensure all the sentences of the three conditions were comparable in terms of their readability. The mean Flesch-Kincaid score of 120 sentences in the three conditions was between 95 – 100, with an *SD* range of 13 – 15. Thus, the sentences of all three conditions were easy to read [32]. The participants were instructed to rate the sentences on their semantic correctness, as fast but also as correct as possible. Each sentence was displayed for 10 seconds, and after each response, written feedback was given on the NDRA display for 2 seconds with a green checkmark and a text *"You are right. Semantically correct/semantically incorrect"* for a right answer and red crossmark with a text *"You are wrong. Semantically correct/semantically incorrect"* for every wrong answer. If the participant failed to respond to a sentence in 10 seconds, a time-over icon was displayed with a text *"Time over, you missed"* for two seconds. Additionally, a live score was shown for encouraging the participants (+10 points for each correct answer and −5 points for each wrong answer). All the answers and time to answer of the semantic sentence task, including missed sentences were exported to calculate average time to answer (Att) and the number of missed sentences per minute for NDRA performance.

Gaze Behaviour: For fully automated vehicles, gaze behavior can provide important insights into task concentration and time required to perceive vehicle information. Thus, gaze data (X and Y position on screen) was extracted with 30 Hz frequency throughout the drive for all the conditions, to generate a gaze map and calculate the gaze duration for different areas of interest.

5.3.3 Measurement After Each Vehicle Information Condition . After each condition, we measured the UX using the *AttrakDiff Scale* [22] followed by measurements of the perceived trust using *Trust in Automation scale (TiA)* [34]. In addition to the subjective measurements, we asked some direct questions regarding the concept and drive and asked to rate individual vehicle information displayed through the two concepts using a 5-point Likert scale.

5.3.4 Post-Test Measure. After completing all conditions and their measurements, a semi-structured interview followed where we asked 4 questions: most liked and disliked concept, need of more information than presented, effect of vehicle information on trust, and which information required through multiple modality. Additionally, we asked participants to give their feedback on each individual information on how it should be displayed i.e., either through *LBD* or *WSD* or through both, or if it is not required.

5.4 Participants

We recruited 18 participants (14 male, 4 female) aged between 24 and 30 ($M = 26.22, SD = 1.81$) using university mailing list and all of them were living in the Netherlands. 15 participants were in possession of a valid driver's license, however, not owning a driver's license did not restrict participants from taking part in the study as the vehicle was fully automated. The mean of value for the attitude towards automated vehicles reported by participants was 3.84 ($SD = 0.57$), which means participants had overall a positive attitude towards AVs. The affinity for technology questionnaire provided a mean score of 4.33 ($SD = 0.74$), which means that the participants assessed themselves as having a high affinity for technology [20].

6 RESULTS

6.1 User Experience

We evaluated the subscales of the *AttrakDiff questionnaire:* Attractiveness, Hedonic Quality-Identification (HQ-I), Hedonic Quality-Stimulation (HQ-S), and Pragmatic Quality (PQ) for each condition. As shown in Table 2, *No information* has the lowest median values for all the subscales ($Mdn = -0.29$), while *LBD* achieved the highest median ($Mdn = 1.57$). We analyzed each subscale using a non-parametric Friedman test, revealing a significant difference for all subscales except for PQ (see Table 2). We further performed Bonferroni-adjusted post-hoc tests to detect significant differences between the conditions per scale. Table 3 shows the results of the post-hoc tests: *LBD* scored significantly higher compared to *No information* for all the subscales except PQ, whereas the

	Attract-iveness	HQ-I	HQ-S	PQ
No Information	-0.29	-0.64	-0.21	0.29
LBD	1.57	1.14	1.50	1.14
WSD	0.64	0.64	0.71	0.86
$\chi^2(2)$	16.54	18.11	23.07	4.254
p	0.001	0.001	0.001	0.119

Table 2. The median value of each condition per subscale of the AttrakDiff Questionnaire. Test statistics for the Friedman test measures are shown below the median.

	No Info. vs. LBD	No Info. vs. WSD	LBD vs. WSD
Attract-iveness	0.001	*n.s.*	*n.s.*
HQ-I	0.001	0.014	*n.s.*
HQ-S	0.001	*n.s.*	0.018
PQ	*n.s.*	*n.s.*	*n.s.*

Table 3. The results of the Bonferroni-adjusted post-hoc analyses per subscale of the AttrakDiff Questionnaire.

WSD was significantly better only for HQ-I compared to *No information*. A comparison between *LBD* and *WSD* shows significant differences for HQ-S only.

6.2 Trust

For the Trust scale we also conducted Friedman tests: The results shows significant differences between the three conditions as shown in Table 4. The *No information* condition achieved lowest trust scores (Mdn = 2.63) while the trust scores after experiencing the *LBD* (Mdn = 3.60) and *WSD* (Mdn = 3.53) are almost equally high. We also calculated the subscales of TiA: Reliability and Trust in Automation. The results for the two subscales also show significant differences between the three conditions. We further performed Bonferroni-adjusted post-hoc tests to detect significant differences between the conditions per scale. Table 5 shows the results of post-hoc tests, *LBD* and *WSD* are significantly higher from *No information* for TiA and the two subscales, while a comparison between *LBD* and *WSD* does not show any significant difference for the three scales.

	TiA Scale	Reliability	Trust in Automation
No Information	2.63	2.91	2.0
LBD	3.60	3.83	4.0
WSD	3.53	3.67	4.0
$\chi^2(2)$	16.817	19.826	21.709
p	0.001	0.001	0.001

Table 4. The median value of each condition of TiA, Reliability and Trust in Automation. Test statistics of the Friedman tests are shown below the median.

	No Info. vs. LBD	No Info. vs. WSD	LBD vs. WSD
TiA Scale	0.003	0.001	*n.s.*
Reliability	0.001	0.001	*n.s.*
Trust in Automation[a]	0.001	0.003	*n.s.*

Table 5. The results of the Bonferroni-adjusted post-hoc analyses of the TiA and its subscales.

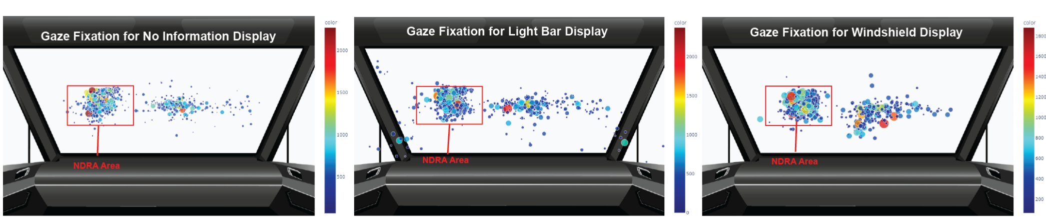
In addition to the trust measure for each condition, we were also interested to see the effect of the sequence of the condition *No Information* display on trust. Participants who had the *No information* condition as first rated the trust highest (Mdn = 3.09), followed by who had second (M = 2.63) and who had the no information condition last rated the lowest (M = 2.37). However, Friedman test showed that the sequence did not lead to any statistically significant difference, neither for *LBD* nor for *WSD*.

6.3 NDRA Performance

The average time to answer (Ata) was almost similar for the three conditions with $M = 3.73$ for *No information*, $M = 3.68$ for *LBD* and $M = 3.69$ for *WSD*. The data was normally distributed for Ata and the assumption of sphericity had not been violated. A one-way repeated measures ANOVA showed no significant difference in Ata for the three conditions, $F(2, 34) = 0.070$, $p = 0.932$. For missed sentences, the data was not normally distributed, thus a Friedman test was performed to determine if there were differences in missed sentences for the three conditions. The *No information* condition had the highest number of missed sentences per minute ($Mdn = 0.2$), that means 0.2 sentences were missed in a minute or in other words 1 sentence in 5 minutes ride. The *LBD* and *WSD* conditions had a lower number of missed sentences per minute (both: $Mdn = 0.13$), but the differences were not statistically significant between the three conditions, $\chi^2(2) = 2.310$, $p = .315$.

6.4 Gaze Behaviour

An exemplary heatmap depicting the visual fixations of a participant (*P09*) for the three conditions is illustrated in Figure 8. To analyze how gaze is distributed across the different areas (NDRA area, vehicle information display area, and other area) for the three conditions with different video time, we calculated gaze duration percentage by dividing the number of gaze points lying inside these areas of interest by total gaze points. We used raw gaze data to analyze the gaze duration, as some information will not require a gaze fixation to grasp, especially the *LBD* that gives information using peripheral interaction [53]. The gaze duration in percentage for the NDRA area, vehicle info area, and other area were analyzed of all the participants, and its mean and standard deviation is shown in Table 6.



a: No Information display Condition b: Light bar display Condition c: Windshield display Condition

Fig. 8. A participant's gaze fixation (max dist = 50pixel, minimum duration = 50ms) during the ride for No Information condition (a), light bar display condition (b) and windshield display condition (c).

Overall, the gaze percentage at the NDRA areas of the three conditions were almost similar. Thus, to check the statistical significance we performed one-way repeated measures ANOVA. The data were normally distributed as assessed by Shapiro-Wilk's test and the assumption of sphericity had not been violated. The result does not show a statistically significant difference between the three conditions ($F(2, 34) = 1.195$, $p = 0.315$, partial $\eta^2 = 0.066$). We further statistically analysed the gaze percentage for vehicle information area using paired-sampled t-tests. The data was normally distributed, as assessed by Shapiro-Wilk's test ($p = .473$). The results shows that the vehicle information through WSD (7.08%) has higher gaze percentage compared to vehicle information through LBD (2.05%), 5.03%, 95% CI [2.65, 7.41], $t(17) = 4.469$, $p < 0.001$.

6.5 Post-Condition Feedback

After each vehicle information condition (no information, *LBD*, *WSD*), we asked the participants some direct questions related to their overall automated drive experience with the conditions and

	NDRA area	Other areas	Vehicle Info. Area
No Information	72.96% (SD=12.15%)	27.64% (SD=13.04%)	N.A.
LBD	75.24% (SD=12.20%)	24.73% (SD=16.22%)	2.05% (SD=1.73%)
WSD	71.09% (SD=12.61%)	23.14% (SD=16.83%)	7.08 (SD=5.37%)

Table 6. The mean percentage gaze of each area for all the three conditions with their standard deviation.

how they felt during the emergency situation while experiencing no information or information through the two designs. After the two information display conditions (*LBD* and *WSD*), we asked the participants if/how they understood the different types of information provided. All the participants stated that they understood the information provided through *WSD* as it is straightforward and similar to the traditional instrument cluster, while for the *LBD* participants mentioned that it took a few repetitions to understand the light patterns and their relevance as they were experiencing the patterns for the first time. But after getting the essence of it, it was very understandable. In this section, we highlight the overall feedback received after each condition.

No Information Display: When asked about the overall experience of the journey, 38% ($n = 7$) said it was satisfactory, while 61% ($n = 11$) said that it was unpleasant and distracting (e.g., *" I can focus more on my work compared to other two but at the same time it was in a weird way more distracting as I didn't have to look outside in other concepts to get the information"*, P#14). Participants also said that they were confused as they did not know what was happening. For the emergency situation, participants mentioned that they were startled (e.g., *"You are not able to predict what is going to happen, so there is ambiguity"*, P#14). Most of the participants 88% (N=16) felt that they were missing something and later mentioned that they were missing information such as basic vehicle information (11 times), reason of action, and future plan (3 times).

Vehicle information through Light bar display: In contrast to *No information*, 88% ($n = 16$) found the journey to be pleasant, relaxing, and comfortable (e.g., *"I think it is really nice that it uses kind of peripheral vision to show what the car is doing and I think that is really nice because I felt a lot more relax when I was answering the questions"*, P#04) and only 11% ($n = 2$) found it unpleasant and distracting (e.g., *"It was fine, although there were a distraction from the system"*, P#15). Regarding the emergency situation, participants found the design well communicated the emergency situation (e.g., *"Yes, the color red shows the emergency with blinking which was really catching"*, P#17).

Vehicle information through windshield display: Similar to the light bar display condition, 88% ($n = 16$) rated their journey as clear and fine, however, some of them also mentioned that it was more demanding than with the *LBD* (e.g., *"It was fine, it just took a bit of effort to find the right information I wanted to see about the journey"*, P#06). Whereas, 11% ($n = 2$) rated that their journey as very challenging (e.g., *"it was the number that was moving and human mind automatically wants to read that is moving so it was hard to read that, focus on my task, and the road"*, P#13). Regarding the communication in the emergency situation, participants mentioned that the emergency situation was well communicated through the blinking braking symbol, but it was not as captivating and eye-catching as the red blinking animation of *LBD*.

6.6 Results of semi-structured interview

After the experiment, we asked the participants to name their most liked and disliked concept of providing vehicle information. The *LBD* scored best and was liked by 72.22% ($n = 13$) as it was in the periphery (5 times, e.g., *"It was in my periphery and I didn't have to read anything and it is like I can just interpret different lights rather than reading it and interpreting"*, P#16), simple and intuitive

(8 times, e.g., *"it was very natural and instinctive in the way it communicated and it was not too distracting while I was doing my task"*, P#18). It was followed by the *WSD* concept (27.77%, $n = 5$) as they found it less distracting (2 times, e.g., *"The information is there and it is not really distracting as I can just look at it whenever I want to."*, P#8) and familiar (3 times, e.g., *"I was familiar with the signs and it was present in a more mild manner at the center location."*, P#15). The condition of providing *No Information* was most disliked 72.22% ($n = 13$) because it was confusing and uninformative (10 times, e.g., *"I never knew what was happening."*, P#2) and uncomfortable and distracting (3 times, e.g.,*"it was distracting and could lead to panic during turns"*, P#14).

Need for more information: The majority of the participants (15/18) said that they do not need additional information other than what is presented through *LBD* and *WSD*. Only one participant mentioned that the lane change and speed limit information were not required, while 3 participants wanted to have additional information that includes fuel/battery level, navigation, and distance to destination, in addition to what was presented through *LBD* and *WSD*.

Required information over time: We asked the participants if they expect their preferences or need of information to change over time and, if so, which information they might consider unnecessary in the future. 13 out of 18 participants expect their preference to change and assume that the change depends upon the automation driving style of the AV (e.g., aggressive vs. conservative/cautious) or familiar/unfamiliar roads (e.g., *"I think it depends upon the road I am going on if it is a similar road then I maybe do not need any other information, but if I go to a new road then I would probably want more info."*, P#13).

Effect of vehicle information on trust: Regarding the effect of vehicle information on trust, the participants said that the display of vehicle information plays a major role in building up trust. 15/18 said it affects a lot (e.g., *"I did not realized it, I tried to place my trust for no information condition. Especially with the pedestrian running in front, I looked up, of course immediately at the pedestrian, but when I had the information, then I realized, no, I didn't trust the system (no information) as much that is why I looked suddenly like I was shocked"*, 3/18 said it is directly proportional, and other two people said it affects to some extent.

Multimodal Information Presentation: We asked the participants if they would like to see some information with multiple modalities such as audio, vibration, and speech. 10 participants mentioned that they expect multiple modality for the emergency situation through audio (8 times, e.g.,*"I would definitely need some audio cues for the emergency situation*, P#5) or vibration (2 times). Other information required with multiple modalities were ETA with speech or audio, low fuel with text, and arriving at the destination with audio.

6.7 Preferred design for vehicle information

Overall, participants preferred to see most of the vehicle information using the *LBD*, while for some information they would prefer to see the information through both the displays (*LBD* and *WSD*). This includes ETA and speed (5 times, e.g., *"I like having the exact info through WSD and subtle information through LBD as well"*, P#6), braking and emergency braking e.g., *"I would like to have emergency braking information from both types to have a clear vision"*, P#12). 50% of the participants felt that the traffic signal information and the speed limit were not required and the information conveyed through the light bar display was sufficient. Additionally, participants also mentioned some new designs for different vehicle information through an *LBD*. For example, for an upcoming turn, the light bar could increase its opacity with decreasing distance to the turn. For the obstacle location, the yellow light at the dashboard could change its size according to the distance to the obstacle (the closer the obstacle is, the larger is the length of the yellow light bar).

7 DISCUSSION

The goal of this study was to evaluate which vehicle information display design (*LBD* or *WSD*) would lead to higher trust and UX ratings compared to no information display while conducting a NDRA and to investigate the impact of the vehicle information display on the task performance of the NDRA.

7.1 RQ1: User Experience and Trust

Previous studies found that using ambient light displays to show the intentions of an AV was considered useful and that this improved the UX [38, 56]. Our study results indicate a similar direction and confirm that communicating all the required vehicle information through a light bar display and in addition, a windshield display, improve the UX for all the subscales of AttrakDiff (Attractiveness, HQ-I, HQ-S and PQ) compared to the *no information* condition. Our statistical analysis shows that the *LBD* results in a significantly higher rating for the three sub-scales Attractiveness, HQ-I and HQ-S, whereas the *WSD* statistically performed better than the no information condition only for subscale HQ-I. Only the PQ subscale did not show any statistical difference between the three conditions, which could be due to the fact that the driving behavior in all the conditions was similar and was in a well-mannered traffic. However during the emergency situations, the lack of vehicle information affected the perception of PQ (usefulness and efficiency) as it was revealed in the qualitative analysis. The perceived trust increased significantly with both display designs (*LBD* and *WSD)* compared to no information. This indicates that the providing vehicle information is still important in SAE level 5 vehicles, which is in line with previous studies showing the importance of vehicle information [38, 65] for building up trust and situational awareness [65].

When comparing the UX ratings between *LBD* and *WSD*, *LBD* outperformed the *WSD* with regard to HQ-S only. However, qualitative results revealed that the majority of the participants (72%; N=13) like the *LBD* the most as they can access information through peripheral vision and find it less distracting when engaged in NDRA. Thus, this supports our initial assumption of providing information through peripheral interaction, which is in line with previous findings [38], additionally while performing NDRA. For trust, there was no significant difference between the LBD and WSD. Therefore, we can conclude that the vehicle information display through either *LBD* or *WSD* improves the trust compared to no information display, while the *LBD* performed better for UX compared to the *WSD*.

Additionally, the differing percentages of gaze duration at the vehicle information areas of *LBD* vs. *WSD* indicate that the *WSD* requires a higher visual effort to grasp information compared to an *LBD*, which was also confirmed in the qualitative analysis and which is in line with literature, which states that focal vision is required for the tasks requiring judgment of fine details (e.g., object detection or reading), while ambient vision can be employed for tasks related to the perception of orientation and motion [28, 62]. Therefore, we can state that the information given through a light bar using peripheral interaction requires less (visual) effort compared to vehicle information given at a center location using pictograms and numbers.

Overall, the results of the study highlight that implicitly providing information (LBD) can outperform the traditional and explicit way of providing vehicle information (pictograms and numbers) in fully automated vehicles (when users are fully engaged in NDRAs). Further research could investigate whether other forms of implicit feedback can further enhance information conveyance.

7.2 RQ2: Effect on NDRA Performance

The purpose of designing the vehicle information display was to enable the user to focus on an NDRA. Although previous studies have proposed various novel vehicle information displays (e.g., [26, 38]) and investigated the effect of NDRAs on take over performance (e.g., [55]), the focus of these studies was not on the NDRA performance while receiving vehicle information. Therefore, we located the NDRA display at the front of the user and at eye level so that users could focus on the NDRA while the vehicle information was presented in the peripheral field of view. Overall, the results show that the NDRA performance was not affected by providing vehicle information through *LBD* and *WSD* compared to the *no information* condition as measured by the average task response time and the number of missed sentences. This was also confirmed by the percentage of gaze points at the NDRA area across all conditions, which did not show any statistically significant differences between the three conditions. Thus, we can conclude that the task performance was not affected by the vehicle information display through the two designs (*LBD* and *WSD*). Additionally, *LBD* further helps in keeping the performance of NDRA high compared to *WSD* by using ambient vision instead of focal vision to provide vehicle information as multiple tasks requiring the same source (focal vision) may affect the performance of one or both tasks [63].

7.3 Preferred Vehicle Information Design

In addition to evaluating the two concepts, we were also interested in knowing the preferred design for individual vehicle information. For most types of the provided vehicle information, the *LBD* concept was the preferred display design, which was also rated as the best overall concept. The comparable levels of trust and higher scores on AttrakDiff imply that the lack of explicit information (as used in the *WSD* condition) did not negatively affect the the *LBD*. However, some information should still be given through a *WSD* (using pictograms and numbers) interface as well: This includes ETA, current speed, and emergency braking, which enable a more detailed information representation compared to the *LBD* concept. Additionally, the emergency situation should also include audio cues to make the users vigilant. This is also the preferred method by the participants in the study of Schartmüller et al. [55]. Furthermore, the information given through the *LBD* was sufficient as reported by the participants. Thus, they may not need speed limit and traffic signal information. This is contrary to the findings of Feierle et al. [17], who concluded that the speed limit should be displayed all the time. Apart from this, the acceleration and general braking should be removed from LBD to make it more subtle and less occupied. Additional required vehicle information mentioned by the users includes battery level, vehicle condition, and distance to destination. Lastly, any vehicle information display should allow for personalization by the user, for instance, to allow turning on or off specific information for a familiar route.

8 LIMITATIONS & FUTURE WORK

We are aware that the performed study has a few limitations. First of all, the experiment was performed in a lab setting, which limits motion cues and lacked the actual feeling of being driven. In line with prior work [2, 36], it is a common procedure to first start evaluating concepts in low-fidelity environments/simulators before deploying concepts in test vehicles and testing on test/tracks real roads. We see our experiment as one of these first steps to understand the actual viability of our proposed concepts and to inform the design and evaluation of higher fidelity prototypes and concepts. However, this might have impacted trust and UX especially for the *No information* condition. The static simulation also prevented us from assessing motion sickness, while we incorporated design principles for mitigating motion sickness for the display of the NDRA. Additionally, in this study we only focused on a single user. However, the proposed designs (both

LBD and *WSD*) and NDRA setup would also be usable for two front seat users as the LBD view will be similar for another front user while the location of WSD will be easily accessible for the other passengers too [52], though this needs to be verified in future studies.

We simulated both concepts on a digital screen which might have impacted the participant's impression of the *LBD* and *WSD*. This also restricted us to assess the optimal brightness of the *LBD* (it was set to 100%) as light conditions of the road cannot be simulated with this early setup in the study. Additionally, in the simulator setup, the screen-based eye-tracker forced us to not use a TV screen larger than 49" to display the windscreen of a car, which is small in comparison to the size of an actual car windshield. However, we reduced this drawback by keeping the distance between eye and screen minimal for achieving a higher FOV. Thus, follow-up research needs to verify our findings in a real-world setting, e.g., by using a Wizard-of-Oz (WoZ) vehicle or a dynamic driving simulator or an AV pod (for instance used in [45]) that comprises a suitable display setup. We chose the semantic task to simulate a NDRA in this study, which is similar to an office task. However, other NDRAs, such as sleeping, have different requirements for the design of the vehicle interior and the HMI. Nevertheless, we believe that the proposed design can provide a concept for vehicle information supporting selected NDRAs such as watching movies, listening to music, or reading, in addition to working. We are also aware that the gender ratio in our study was not equally distributed and the mean age of the participants was rather low (also due to Covid-19-related restrictions with regard to participant recruitment), and as men are more likely to rate new features of technology positively compared to women [59], which could have impacted the positive ratings for both the concepts. Nevertheless, we see values in this first evaluation but acknowledge that future studies in situations closer to real-world driving should also validate the effect in a more diverse sample.

As a future step, in addition to combining the *LBD* and *WSD*, the concept should be developed for complex and critical situations (e.g., multiple pedestrians crossing, roads with cyclists and cars) and other levels of automation (e.g., SAE level 4). Further iterations might be helpful to make the *LBD* more pleasant, subtle, and intuitive by selecting the most appropriate animation frequency, pattern, color and opacity and pictogram and numbers design and size for the *WSD*. Additionally, in the *LBD* concept, we purposefully placed the light bar on three sides of the windshield, leaving out the top side. However, as pointed out in the review process, it could be interesting to evaluate a light bar on the top side as well. It could for example be used to display traffic signal information.

9 CONCLUSION

In this paper, we present two concepts of showing vehicle information for a fully automated vehicle (SAE Level 5): one using a light bar in different color and animation patterns and one using pictograms and numbers displayed on a windshield display. The two concepts were designed to not interfere with the NDRA while also providing the necessary vehicle information. Our results show that the vehicle information conveyed through both concepts helped users to enhance their trust towards automated vehicles without affecting their task performance of NDRA as compared to not displaying information display. From a UX perspective and in line with our qualitative analysis, we found the *LBD*, which presented information in a more implicit way, to outperform the *WSD*, which presented information in a more explicit way (using pictograms and numbers). This indicates opportunities for future research to look more into implicit information presentation. Additionally, users would prefer a mix of both concepts for some types of information to have subtle feedback (as provided by the light bar) and exact information through numbers (as provided in the WSD).

Overall, we expect this work to contribute to the understanding of how to design vehicle information displays for future automated vehicles (SAE level 5) while particularly enabling users to focus on performing NDRAs.

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