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Design of head-up display interfaces for automated vehicles

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ABSTRACT

This study aimed to identify which information should be displayed on a head-up display (HUD) in semi-automated vehicles to enable the driver to maintain better situational awareness during the manual operation of the vehicle. It further explored how does the size of the field of view of the HUD affects such information presentation, while taking into consideration user's personal preferences and opinions. Four head-up display interfaces were developed differing in the amount, frequency and field of view of visual information presentation, and were implemented in a simulated semi-automated vehicle. The HUDs were evaluated in a user-study with a within-subject design with 30 participants. The obtained results revealed that versions with smaller and larger field of view HUDsevoke similar driving performance, levels of cognitive load, user experience and perceived usability, suggesting that the HUD's field of view size does not have an overall significant effect on the driver's situational awareness. The results reveal that display of information, which can help with obtaining and maintaining higher situational awareness levels, contribute to better driving performance. Drivers on the other hand, prefer also display of information for lower situational awareness levels.

1. Introduction

1.1. Background and motivation

Situational awareness (SA) plays an important role in any process of dynamic human decision making, as it provides the state of knowledge needed for making effective decisions and taking appropriate actions (Endsley, 1995). To ensure driving safety, it is necessary for drivers to maintain a certain level of SA in any vehicle that has less than level four or five of automation (ADL4 or ADL5, see Table A 1) (SAE, 2016). Based on the SA theory (Endsley, 1995), for achieving SA it is necessary to have perception on the elements of the environment (SA level 1 – SAL1), have a comprehension on their meaning (SA level 2 – SAL2) and be able to project their status in the near future (SA level 3 - SAL3) (please see Table A 2). The three levels are set in hierarchical order, with SAL3 being the highest. Although methods for SA were first introduced for the assessment of machine operators, SA has been since recognized also as an important factor in the automotive domain as it provides important information on the driver, their state and driving abilities. Monitoring it can be helpful in the process of design and evaluation of advanced driver assistance systems (ADAS) (Kridalukmana et al., 2020), which are intended to help the driver with the performance of the driving task and increase of the vehicle's level of automation (Winner, 2016). For example, parking sensors, back rear camera, lane-departure warning and blind spot sensor systems are some examples of ADAS that contribute to increase driver's SA.

Another, and more common way to help the driver regain and/or maintain situational awareness, are in-vehicle user-interfaces (Scholtz et al., 2005). Visual display of vehicle performance indicators and warning signals, on top of the obligatory primary driving information (speedometer, fuel levels, turning signals, tachometer, etc.), such as lateral deviation information, collision warnings or route information has become available in almost all vehicles nowadays. However, in order to help the driver maintain all three levels of situational awareness, i.e. monitor the environment (SAL1), comprehend it (SAL2) and receive information to help with the prediction of driving-related events in near future (SAL3), much more information (for example warnings for potential hazards) is needed (Van Doorn et al. 2021). Adding more information on the other hand, can lead to attentional and cognitive overload (De Jong, 2010), which can have opposite of the desired effects. Furthermore, the level of SA the driver is supposed to maintain during driving changes with the vehicle's level of automation. For example, the task of monitoring the environment is performed by the driver in ADL1 and ADL2 conditions throughout the whole trip, but is performed by the driver only when automation is not available in ADL3 (SAE, 2016). The latter is especially challenging during takeover from

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Table 1
Amount and frequency of information presented in all four HUD interfaces.

	MIN HUD		MAX HUD	
Information presented in HUD	FoV_S	FoV_L	FoV_S	FoV_L
Speed limit displayed throughout the whole drive.			✔	✔
Speed limit displayed at each cross section 150 m before and 150 after the road sign in the driving environment.	✔	✔		
Vehicle speed displayed (in white) throughout the whole drive.			✔	✔
Vehicle speed displayed in white changes to red colour when driving over the speed limit (indication of speeding).			✔	✔
Available ADAS in white in ADL0, and active ADASs in green colour.	✔	✔	✔	✔
Distance to vehicle in-front of ego vehicle < 3s.			✔	✔
Distance to vehicle in-front changes from white to red when driving with distance < 1.5 s.			✔	✔
Level of automation the vehicle is operating in at a specific moment (ADL0 or ADL3).	✔	✔	✔	✔
Road sighs (such as Stop sign, Pedestrian crossing, Yield sign, Bus stop, etc.) are displayed 150 m before and 150 after the road sign in the driving environment.	✔		✔	
Road sighs (such as Stop sign, Pedestrian crossing, Yield sign, Bus stop, etc.), exploiting AR, are highlighted with green bounding boxes around the sign in the driving environment, 150 m before and 150 after the road sign in the driving environment.		✔		✔
Route directions are provided as simple GPS directions in form of an icon replicating the intersection and indicating the direction with an arrow pointing towards the intended route.	✔		✔	
Route directions are provided as blue lines, exploiting AR, displayed directly on the road lanes at each intersection indicating the direction towards the intended route.		✔		✔
Display of short text messages (such as “You have arrived at the final destination”).	✔	✔	✔	✔

Table 2
Driving performance indicators observed in the study.

Driving performance indicator	SA level
Following traffic rules for speed	
Speed limit 50 km/h	SAL1
Speed limit 30 km/h	SAL1
Change of speed limit from 30 km/h to 50 km/h without a speed limit sign	SAL3
Reaching final destination	SAL2
Keeping safety distance	
Distance < 3 sec	SAL3
Distance < 1.5 sec	SAL3
Takeover performance	SAL3

automated mode, as the driver usually has few seconds to regain SA of the driving environment and resume the task of driving after being out of the driving loop for some period of time. Consequently, most of the available literature on in-vehicle information interfaces for semi-automated vehicles focuses on the design of user interfaces for communication of information *during takeover* (as evident from several reviews of related work in recent years by Gabbard et al., 2014; Frison et al., 2020; Riegler et al., 2021b).

However, the task of driving in semi-automated vehicles does not end after the takeover. The driver has to operate the vehicle for as long as the vehicle is not capable of resuming the task of driving. This requires the driver to be able to safely and successfully operate the semi-automated vehicle as if it was a vehicle with lower or no automation. Yet, contrary to available literature on interfaces for takeover situations, there are very few studies on human-machine interfaces for communication of information *during other operational states or the whole trip* in a semi-automated vehicle. As defined by SAE (2016), in ADL3 the driver is still responsible to operate the vehicle and monitor the environment when automation is impaired or not available at all. Decreased engagement in the driving task can result in reduced levels of situational awareness (knowing what is going on around you), thus putting all of the identified benefits of vehicle automation at risk of being lost, and instead of increasing safety, could lead to additional road accidents due to inappropriate driver's behaviour.

Motivated by this gap, in this paper, we explore different human-machine interface designs, which are displayed throughout the whole trip (in manual mode, automated mode and during take-over), with a specific focus on helping the driver with the operation of a semi-automated vehicle particularly when automation is not available. In this study, we decided to focus on visual interfaces. As defined by SAE (please see Table A 2), the driver is not required to monitor the environment during automation but only during manual driving in semi-automated vehicles. Since the interface remains the same throughout the whole drive, the rationale behind our decision to present the information visually is due to the assumption that visual information is in the modality the driver can most easily decide to follow or not by redirection their attentional gaze, which is not the case with auditory and tactile ques.

The goal of this study is twofold. First, it aimed to identify which road and driving-performance related information should be presented to the driver in order to help them keep appropriate levels of situational awareness and achieve better driving performance when operating a semi-automated vehicle. As second, it aimed to identify does the size of the field of view of presenting (visual) information has an effect on the driver's situational awareness and their driving performance of a semi-automated vehicle.

The chosen medium for presenting information was a head-up display. A head-up display (HUD) in vehicles is a type of interface that displays a variety of information as visual cues on the windshield in front of the driver. Although not as common as the classic head-down displays (HDD), primarily due to lack of technological implementation advancements at this point of time, past studies have shown that (prototypes of) HUD can enhance driving performance, reduce distraction and improve the overall driver's decision-making on the road (Ablassmeier et al., 2005; Charissis & Papanastasiou, 2010; Jakus et al., 2015; Riegler et al., 2021a). The reasoning behind it is usually credited to the assumption that HUDs can positively affect the ability of drivers to visually attend to the outside world relative to HDD, as the driver's gaze still remains in the direction of the road rather than inside the vehicle. Depending on how the information are clustered, HUDs can be used to present information projected on a dedicated location on the windshield, or, by overlapping visual cues at different positions and with different focal lengths while utilizing the whole wind-shield area. The latter displays information in a dispersed manner creating an augmented reality (AR) experience.

1.2. Related work

The effects of the visual enhancements in HUDs depend on the type, complexity, and visual allocation of the graphical elements in the interface. Although intended to be of help, a poorly designed HUD can, due to visual clutter, contribute to information and cognitive overload, have a negative impact on both the driving performance and driver safety (Ward & Parkes, 1994; Gish & Staplin, 1995; Tufano, 1997; Pauzie, 2015). This can be especially challenging while using AR HUDs, which due to their increasing complexity, require frequent changes in attentional allocation (Feierle et al, 2019; Riegler at al., 2021a). Consequently, multiple studies have tried to shed some light on how to approach the design of HUDs.

As mentioned in the Introduction, most past research has focused on how to present information during takeover after the vehicle has operated in automated mode. With automation of driving functions, the concept of driving performance and safety changes as users of such vehicles change their role from active drivers to passive riders several times during a single driving session. Particularly in takeover situations, human-machine interaction is of critical importance and HUD solutions proved to offer several significant advantages over other cluster-based displays. Langlois and Soualmi (2016) focused on the performance of HUDs in take-over situations by comparing traditional 2D AR HUD with fixed virtual image distance and an AR enriched HUD with dynamic virtual image distance. While the traditional 2D AR HUD showed only a set of visual icons on the predefined space on the windshield, the AR HUD visually highlighted some important objects directly in the driving environment (speed, speed limit, navigation by showing the road to follow, vehicle ahead, vehicle behind, etc.). Their proposed AR HUD had showed no advantages over the 2D HUD in the take-over situations but improved the operational level of driving by enabling better situational awareness in lane changing and similar maneuvers. Automation allows for performance of non-driving related tasks, which would not be safe to perform during human driving. HUDs have been therefore also used for completion of non-driving related tasks in critical situations such as takeover. Li et al. (2020) studied driver's eye movements during take-over situations when using HUD and mobile device displays for showing non-driving-related activities to the driver. Besides reporting on significant changes in pupil diameter as indication of decreased cognitive load, and increased number of areas of interest during take-over situations for both displays, they specifically reported that using a HUD for performing non-driving related tasks resulted in less distractions from the driving task and helped drivers maintain visual attention forward and collect visual information from higher number of sources. They concluded that using a HUD for performing non-driving related tasks such as, watching a video during semi-automated vehicles, is better than using a mobile device display to help maintain driver's attention on the road most of the time.

Some researchers have focused on how to display information when the vehicle is in automated mode, in order to improve the driver's experience with automation and help them understand its intentions and reasons for intervention in safety-critical scenarios. Karatas et al. (2020) proposed a dynamic-based field of view AR HUD concept for conveying appropriate information about the reasons for action to the driver of an automated vehicle when automation takes over and intervenes in safety-critical scenarios. The AR-based interface visually highlighted the hazardous objects in the environment to warn the driver of the automated action and therefore reduced surprise and increased trust. In their experiment, the proposed AR HUD also outperformed a standard static 2D HUD display with predefined visualization area (smaller field of view) on the windshield as it provided significantly shorter recognition time of the danger. However, participants' subjective responses collected with Acceptability Questionnaire and credibility analysis did not show meaningful differences between the two interfaces, indicating that the recognition of danger does not affect the level of acceptance of the technology by the drivers. Significant differences between traditional static HUD and dynamic AR HUD with bigger field of view were reported also by Feierle et al. (2019) when they compared the two solutions in communicating automated vehicle's actions to its users and observe a combination of objective and subjective responses to a particular design. As expected, gaze durations on the road were prolonged in AR HUD condition enabling faster drivers' reactions and better recognition of dangerous events. However, majority of participants indicated that in the case of AR HUD they had to remember more details indicating (too) high information density potentially leading to cognitive stress and decreased safety. They concluded that the appropriate amount of information show in AR HUDs is still to be explored and defined.

Furthermore, the amount and complexity of information presented in HUDs, primarily focusing on how their use affects drivers' situation awareness and perception in automated vehicles, was explored by Currano et al. (2021). By presenting participants with videos of driving situations in two driving environments, three variations of information complexity were tested: without a HUD, HUD with minimal amount of information (with cues to pedestrians and other critical road objects and signs), and HUD with higher amount of complex information (most relevant information in the environment, including navigation and vehicle status). While the high complexity of a HUD had a negative effect on the driver's situation awareness, it was also revealed that the factors that made up the complexity of the scene may have a greater negative impact on the situation awareness than the actual complexity of the HUD design (Currano et al., 2021). Different HUD concepts using 2D presentation of information, presentation of information directly in the environment as augmented reality AR, birds view presentation and combinations among them, have also been used to observe potential effects on the driver's trust in automation (von Sawitzky et al., 2019). The results revealed that visual feedback on the vehicle's route while in automated mode presented with a HUD can positively affect driver's trust in automation. This was most evident for the AR interfaces, as the participants indicated birds view or indication on a map did not provide them a direct connection between the vehicle and environment surrounding them.

While the effect of HUDs on the driving performance and driving safety may be often considered of highest importance, for a holistic understanding of HUDs and their real-world application, it is necessary to additionally understand "how to design the automotive HUD system to best serve the driver" (Back et al., 2019, p. 1936). In that regard, a user survey, conducted with participants who had extensive HUD experience in manually operated vehicles, examined several aspects related to user experience and user-perceived design improvement points of (different) existing commercial HUDs (Beck et al., 2019). A set of eleven priority HUD information items was considered: 1) speed control, 2) highway driving, 3) engine/transmission control, 4) wayfinding, 5) sign/warning detection, 6) audio player control, 7) accuracy of HUD information, 8) individual and context-specific HUD information needs, 9) visibility of HUD images, 10) visual aesthetics of HUD interfaces, and 11) HUD location and layout issues. The results showed that safety-related elements (speed, speed limit, cruise control, traffic signs) and navigation information displayed in the HUD are helpful in driving and complying with speed limits in manually operated vehicles. For vehicles with automated features more or different information should be displayed (such as for example ADAS). It further revealed that the user-experience is highly affected by the execution of the HUD and the context it was used in, asking for future studies to take this into consideration when designing for better driver's user experience with HUDs in vehicles.

Perceived usability of and user experience with new systems are frequently mentioned as main drivers for providing sufficient level of trust and acceptance of this technology. Usability and potentially reduced visual demand of AR HUD during conditionally automated driving was studied by Schömig et al. (2018) where more than 80% of participants preferred such visualization method over the traditional cluster-based display. Their visual displays were additionally supported also by acoustic and haptic feedback system for issuing different warnings and urgent messages. The main reported advantage of AR HUDs was the higher information content and therefore better understandability and usefulness. They also reported on better user experience due to less requirements for off-road glances.

In summary, the information needs of the different HUD solutions users vary considerably; also according to the driving environment. For example, some participants prefer a more realistic user interface design, while others want a more appealing visual esthetic. There are also different preferences for the amount of information and the display/location of multiple information points (Beck et al., 2019). Further field research based on more objective measures are therefore needed to better understand the users' information needs and preferences, and how to address them when designing HUDs. This is also in line with Park & Park (2019) review conclusions, noting that individual differences in the acceptance levels of visual complexity should also be included in any design processes.

1.3. Our contribution

In this paper we present our efforts on shedding some light on how to design a HUD to help drivers maintain situational awareness and achieve better driving performance when operating a semi-automated vehicle. We also want to provide some answers to the question proposed by Feierle et al. (2019) on which are the most appropriate information to be presented on such visual displays by taking into consideration user preferences. In that regard, we tried to answer the two main questions presented below.

- RQ1: Does increasing the field of view (FoV) with augmented reality improve situational awareness and driving performance compared to smaller fixed-positioned FoV presentation of information in HUDs in a semi-automated vehicle?

Based on the available literature, our hypothesis is that AR enriched HUDs with increased FoV will help the driver to better maintain situational awareness and improve their driving performance in a more favourable manner compared to smaller FoV HUDs due their higher information content (Schömig et al., 2018) and prolonged gaze durations to the road, which also enable faster drivers' reactions and better recognition of dangerous events (Feierle et al., 2019). This hypothesis is also based on the findings by Langlois and Soualmi (2016), which suggest that presentation of information with AR can improve the operational level of driving and help with specific driving manoeuvres.

- RQ2: Which visual information, and how much of them, should be presented to the driver in a semi-automated vehicle to improve their situational awareness, and how are they related to specific situational awareness levels?

As revealed by Ward & Parkes (1994), Gish & Staplin (1995), Tufano (1997), Pauzie (2015), the amount of information should be reasonable, as it can otherwise quickly introduce visual clutter and cause information and cognitive overload, which can have negative effects on driving performance and driver safety. By presenting information that have been recognized to improve situational awareness and enhance driving performance, our hypothesis is that HUDs with more safety-related and navigation information compared to HUDs with less information will still result in better SA and driving performance, without the introduction of information and cognitive overloads.

The different HUD versions that were developed to help us answering these questions are presented in 2.2. Visual Interfaces.

Driving performance indicators are used as indirect indicators of different levels of SA. However, to be in line with conclusions from past related work and to perform a holistic evaluation of such displays, driver's subjective opinions on usability, user-experience and personal preferences are also taken into account. With this approach, we aim to draw comprehensive conclusions and provide concrete guidelines for design of visual HUDs for semi-automated vehicles.

2. Methodology

2.1. Experimental set-up

The study was conducted in a simulated driving environment consisting of a motion-based driving simulator (Vengust et al., 2017) with real car parts (seat, steering wheel and pedals) and a physical dashboard. The dashboard was not designed within this study, and mimics a dashboard of a typical manually operated personal vehicle. It displayed the vehicle speed, motor rotations per minute, fuel levels, and status of the indicators and lights. We decided to keep the dashboard on, as most vehicles that currently feature a HUD, still have also a physical dashboard.

The visuals were displayed on three 49" curved TVs full HD resolution (with 1920px x 1080px) ensuring a 145° field of view of the driving environment. The driving scenario was developed in SCANeR Studio (AVSimulation, France). It lasts for 13 km (8.08 mi) and simulates a route from a suburban area to a city center.

2.2. Visual interfaces

To address the research questions, four different interfaces for HUDs were developed and implemented to the driving simulator (Vengust et al, 2017) using SCANeR software (AVSimulation, France). The interfaces were implemented as DLL files (using OpenSceneGraph toolkit) as augmentation of the default SCANeR VISUAL module. The icons used in the HUD prototypes were designed and drawn in Adobe Illustrator.

To investigate does increasing the field of view (FoV) with augmented reality improve situational awareness and driving performance compared to fixed-positioned smaller FoV presentation of information in HUDs in a semi-automated vehicle (RQ1), two different interfaces were designed:

- HUD with a smaller FoV (FoV_S), which was designed as a semi-transparent projection on the windshield placed above the steering wheel with a fixed location and smaller FoV for information presentation, and
- HUD with a large FoV (FoV_L), which combined projections of elements on a fixed position on the windshield above the steering wheel, and projections of elements directly in the driving environment exploiting the size of the whole simulated windshield (e.g. highlighting road signs with green bounding boxes and displaying navigational directions directly on the road lanes). This configuration enabled a much larger FoV because it utilized the whole windshield for presentation of information.

The HUDs were displayed on the center TV screen. Since the displays were integrated in the driving simulation, the virtual image distance (VID) was the same for both versions, as the driver's seat was placed in front of the central screen at a driver's head distance of 140 cm. In the FoV_L HUD, we tried to further simulate the effect of different virtual image distance by superimposing elements of the HUD to objects in the driving simulation (for example, putting bounding boxes around road signs as shown in Figure 2).

The FoV_S and FoV_L HUD both displayed information in a way that they did not require the driver's gaze to move away from the road, hence reducing the need for eyes off road enabling them continuous monitoring of the environment. The designs followed past related works (Currano et al., 2021; von Sawitzky et al., 2019; Ma et al.,2021), to enable comparisons, but also included enhancements that were added to improve past designs to explore the full potential of HUDs.

To investigate *which* visual information and how much of them should be displayed (RQ2), two additional versions of both the FoV_S and FoV_L interfaces were developed, which differed in the amount and frequency of information they displayed:

- FoV_S MIN HUD and FoV_L MIN HUD displayed information such as road signs, GPS directions, and current level of automation of the vehicle (ADL0 or ADL3), and
- FoV_S MAX HUD and FoV_L MAX HUD displayed all of the information of the MIN HUD interfaces (e.g. vehicle speed, current speed limit), and additional information such as driving over the speed limit, distance to the vehicle in front, and too short distance to the vehicle in front (TTC shorter than 2 seconds).

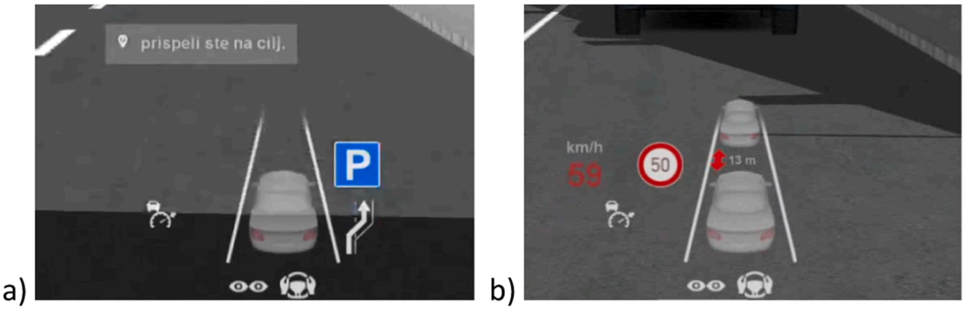

Fig. 1. FoV_S HUD interfaces in L0: a) FoV_S MIN HUD (in ADL0), b) FoV_S MAX HUD (in ADL0); Text in a) reads "You have reached your destination".

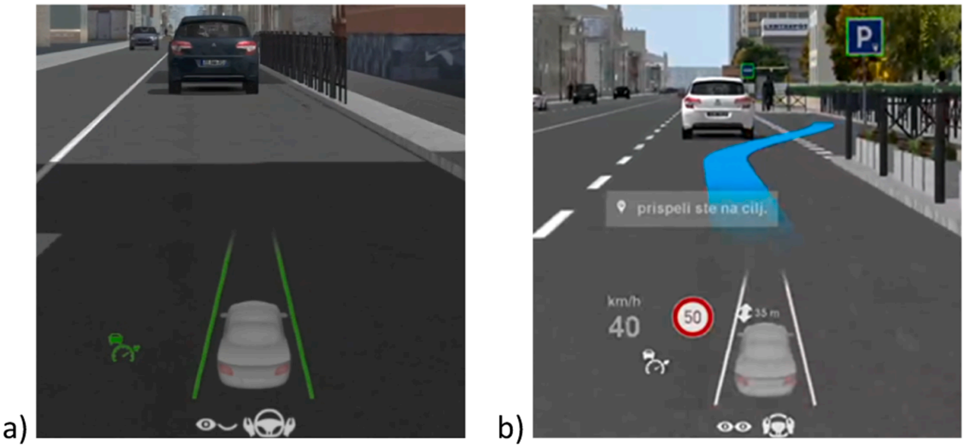

Fig. 2. FoV_L HUD interfaces: a) FoV_L MIN HUD (in ADL3), b) FoV_L MAX HUD (in ADL0); Text in b) reads "You have reached your destination".

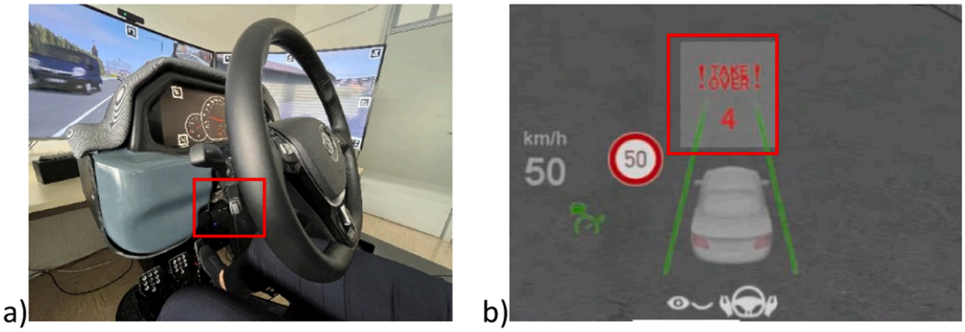

Fig. 3. a) Button used for engagement of ADS and b) Takeover notification and countdown of remaining time until ADS turns off.

The MIN version provided information only when needed. For example, the speed limit was displayed only at crossroads, as crossroads cancel out any previous speed limitations that differ from the general limits in cities or highways. It also avoided repeating information that was available elsewhere, such as the current speed of the vehicle, which was displayed on the classic dashboard. Considering De Jong's cognitive theory (2010), this version tried to avoid driver's cognitive overload.

The MAX version on the other hand, tried to implement all information that have been identified to contribute to better driving performance and safety (for example, Tufano, 1997; Pauzie, 2015; Back et al., 2019; Park & Park 2019), and did not adhere to any information limitations.

The signs and colors used in the HUDs followed the ISO 2575:2021 (ISO, 2021) guidelines. The icons that indicate the ADL the vehicle is currently operating in were created following the guidelines for ADL indication for HMIs in automated vehicles proposed by Mörtl et al. (2020). Previews of the FoV_S MIN and FoV_S MAX HUDs are presented in Figure 1, and previews of the FoV_L MIN and FoV_L MAX HUDs are presented in Figure 2. Table 1 shows a comprehensive overview of each of the HUD interfaces.

2.3. Experiment design

A simulated semi-automated vehicle with ADL3 of automation was used for all of the trials. Participants were informed when the ADL3 was available with a pre-recorded voice message telling them to turn on the autonomous driving system (ADS). The ADS could be turned on by pressing a specifically dedicated ADS button on the bottom left lever of the steering wheel (see Figure 3, a)). When the ADS was no longer available, the test participants received a visual and auditory takeover notification 5 seconds prior to the ADS turning off on itself. The visual takeover notification was a text message "Takeover", which was presented with a 5 second lead time (Sanghavi et al., 2021) and accompanied with a countdown from 5 to 0, showing the time remaining for takeover (see Figure 3, b)). The auditory notification was a 4000 Hz pure tone (Stojmenova et al., 2018), which was played at 65 dB from the start of the takeover notification until the driver took over control of the vehicle. Participants were able to take over control of the vehicle by pressing on the brake or gas pedal for at least 40 N, steering the wheel for at least 6° or by pressing the ADS button on the bottom left lever of the steering wheel.

Each trial featured four requests to turn on the ADS and four requests to take over control of the vehicle with the aim of covering different aspects and situations that may be experienced by the driver in a semi-automated vehicle. Two takeover requests occurred due to a critical situation – a pedestrian crossing or complicated crossroad, which required the driver to not only takeover control of the vehicle but also try to avoid collision or change lane respectively. Two takeover requests occurred due to non-critical events; this was intended to simulate the vehicle simply losing communication to the infrastructure or vehicle sensors' system failure. The trial would always start and end in manual driving mode. This resulted in five manually driven intervals, and four intervals in automated mode, which lasted approximately 6.5 km (4.04 mi) each, which corresponded to half of the whole route.

2.3.1. Driver's tasks

The test participants' main task was to drive safely and successfully reach the final destination, which was defined as parking on a designed side road parking lot in front of an office building. To achieve this, they were guided to the parking spot with a navigation system, which was part of the interfaces.

The test participants were instructed to engage in a secondary task - play the game 2048 on a mobile phone - when the vehicle was in automated mode. 2048 (Cirulli, 2014) is a puzzle calculus game where players have to add numbers with the same value to reach a sum of 2048 (or higher). All of the numbers are power of two, and they can be added by sliding numbers in up, down, right or left direction on a 4×4 cell grid. The reasoning behind using a game played on a mobile phone was to simulate a non-driving related task which drivers may engage into when the vehicle is in automated when using a semi-automated vehicle. Since the goal of the secondary task was just to simulate some kind of engagement, which was the same for all participants, the scores of the secondary task were not recorded and were not taken into consideration in the results analysis. By using the same game and device to play it, we wanted to simulate a task that would have similar mental and physical load on the participants, and hence would set the same conditions to regain SA.

2.3.2. Counterbalancing

The study had a within-subject design. Each participant completed four trials: one with each HUD interface version. To be able to compare the driving performance results, we used the same driving scenario route for every trial. Since they would always drive on the same route, to avoid, or at least reduce anticipation and learning effects, two versions of the same driving scenario were created. In them, the driving route remained the same, however the locations of the requests to turn on the automated driving function and to take over control of the vehicle, were at different (this was possible due to multiple crossroads in the driving scenario). Since each participant had to complete four trials (with the FoV_S MIN, FoV_S, FoV_L MIN and FoV_L MAX HUD version) and there were two driving scenario options for each of them (with different request locations), this resulted in eight possible trial orders, which were randomized using Latin square design technique. Additionally, to avoid fatigue and any feelings of discomfort, the participants were asked to complete the whole experiment over the period of two days - two trials in one day and the other two a week later. Before the experiment, the participants went through a test trial, in which they got familiar with the driving simulator, learned how to operate the vehicle in ADL0 and ADL3, and were presented all of the features of the HUD interfaces.

2.4. Participants

30 participants (16 male), aged from 23 to 55 (M=36.767, SD=8.891) with driving experience varying from 1 up to 36 years (M=17.200, SD=8.856) participated in the study. 80% of them reported to drive every day, 10% few times a week and 10% few times a month. 30% of the test participants stated to have never driven a vehicle with any level of automation (with any ADAS), one participant (3.333 %) stated to have driven it once, 13.333 % to have driven it few times, and 53.333 % to have driven such a vehicle multiple times. Participation in the study was on voluntary bases, and the participants could stop their participation at any point. As a thank you for their participation in the study, the participants were given a gift voucher for 10 €.

The experiment was designed and completed following The Code of ethics for researchers and Guidelines for ethical conduct in research involving people issued by University of Ljubljana.

2.5. Variables

Two main independent variables were observed in this study:

- Amount of information: MIN and MAX interfaces, and
- Mode of presentation of information: FoV_S and FoV_L interfaces.

To answer the three research questions, the following groups of dependent variables were observed:

- Driving performance
- Cognitive load
- User's preferences and opinions

2.5.1. Driving performance

Driving performance indicators were taken into account to evaluate how the amount and mode of visual presentation of information affects driving performance when semi-automated vehicles were driven manually (operated by the driver). We tried to incorporate at least one parameter per SA level. Table 2 presents the observed driving performance indicators and the required SAL for each of them. In continuation, rationale behind why these specific driving parameters were chosen is presented in detail.

The first driving performance indicator was following traffic rules for speed (SAL1 or perception of the environment). The current speed limit was visible at all times in the MAX HUD interfaces (see Figure 1 b), and Figure 2 b)) and only after a crossroad at the MIN HUD interfaces. For most of trip, the speed limit was 50 km/h (31.07 mi/h), except for one kilometre (0.6 miles) near a school area, where the speed limit was reduced to 30 km/h (18.6 mi/h). The change of speed limit was indicated with a speed limit sign of a 30 km/h, and the end with the road sign that indicates "End of all previously signed restrictions", which is a common sign for ending speed exceptions in Slovenia (the country where the experiment was conducted in). With the latter, because the driving scenario is based on a city road, the speed limit changes to 50 km/h, without the need for an additional speed limit sign indicating 50 km/h (SAL3 or have a comprehension of elements in the driving environment and be able to project their status in the near future). As a result, the following traffic rules for speed was observed for: 1) areas where the speed limit is 50 km/h (SAL1), 2) area where the speed limit is 30 km/h (SAL1), and 3) one kilometre after the speed limit changes from 30 km/h to 50 km/h (SAL3).

The second driving performance indicator was reaching the final destination based only on following cues from the navigation system (SAL2). These were different in the FoV_S and FoV_L HUD interfaces as shown in Figure 1 a), and Figure 2 b). The driving scenario included multiple crossroads and asked test participants to park on a side road parking when reaching the final destination. As a result, reaching the

Table 3
PPQ questions and SA levels.

Information presented in HUD	SA level
Vehicle speed	SAL1
Driving over the speed limit	SAL2
Speed limit	SAL1
Active/Available ADAS	SAL2
Level of automation the vehicle is in	SAL2
Distance to vehicle in front < 3s	SAL3
Too short distance to vehicle in front (distance < 1.5s)	SAL3
Display (FoV_S) / Highlight road signs (FoV_L)	SAL1
GPS directions	SAL2

final destination was observed as the number of correct turns in each crossroad, and parking in the indicated parking area when reaching the final destination. The latter was indicated also with a text message (see Figure 1 a), and Figure 2 b)).

The third driving performance indicator was keeping safety distance from the vehicles in front. This was calculated as the length between the vehicle in front the ego vehicle, and in our case was observed for two values: 1) distance < 1.5 s, which was considered as too short distance (SAL 3) and indicated with red in the MAX HUDs, and 2) distance < 3 s, which was considered as an information that the distance to the vehicle in front is short (SAL 3). The MIN HUDs did not display this information. The 3 second "distance" was defined based on the 3-second rule commonly recommended in the USA and suggested by the National Safety Council (NSA, 2019). This distance was shown in white, as an information that the distance to the vehicle in front is short. The 1.5 second "distance" was based on the 2-second rule commonly recommended in EU countries, (however not a general rule as shown by the Conference of European Directors of Roads, 2010). Since this distance was shown in red, it aimed to notify dangerous behaviour, so we reduced the distance notification from 2 to 1.5 seconds. This is based on the national regulation (the study took part in Slovenia), which will fine drivers if driving with a safety distance equal or lower than 1.5 seconds.

Lastly, the forth driving performance indicator was take over performance (SAL3 – being able to project the status of objects of the environment in near future. After the takeover from automated to manual driving, we looked for data on collisions with other road participants (other vehicles and pedestrians) or the road infrastructure and defined a takeover as unsuccessful if it resulted in a collision. We did not focus typical takeover performance indicators such as reaction and response times, as these begin during the time the vehicle is in automated mode (this study focuses on the effects of HUDs on the manually operated intervals in semi-automated vehicles) and have, as presented in the Introduction, already explored in detail in past studies.

2.5.2. *Cognitive load*

Changes in pupil dilation were observed as indicators for changes in cognitive load. Past studies have shown that there is correlation between the pupil size and level of cognitive load experienced by drivers (Palinko et al., 2010), which can be captured with eye trackers (Čegovnik et al., 2018). In this study, the pupil size was recorded with Tobii Pro Glasses 2 eye tracker (Tobii, Sweden), a head worn eye tracker, which has a sampling rate of 50 Hz. Before the start of each trial, the eye tracker was calibrated with the Tobii Pro controller software, which requires the driver to look at a calibration card (black and white concentric circles with a black dot in the middle of them) for few seconds. Participants were instructed to not touch or move the glasses after the calibration until the end of the trial. As pupil dilation can be affected by light, the room was completely dimmed before the start of each trial. As a result, there were no additional light sources in the room except the light emitted by the 3 TV screens used for the driving simulator.

The Tobii Pro Glasses 2 eye tracker measures and records the pupil size data separately for the let of and right eye. The eye tracker records the exact measure of the pupil diameter; however, we were not interested in the absolute but rather on the relative difference in the pupil diameter of our participants between the different HUD versions. In order to minimize the individual differences in pupillary responses, the percentage change of pupil size was used as an indicator of changes in pupil diameter (Iqbal et al., 2005) as a cognitive load measure.

Although there are many definitions, cognitive load is often simply defined as a function of supply and demand of attentional and processing resources (Tsang & Vidulich, 2006). It is restricted by the limited short-term (working) memory of the operator and its processing resources are influenced by the operator's domain knowledge in the long-term memory (Matthews et al., 2001). More experienced operators have wider set of skills and can hence process larger or more complex information within their working memory. At the same time, the higher the workload, the more attention is needed for task performance, thus less resources are left for being aware of the situation (Tsang & Vidulich, 2006). In that regard, higher levels of cognitive load can affect the task of maintaining situational awareness on all three SA levels.

2.5.3. *User's preferences*

Three questionnaires were used for collecting data on the user's perceived user experience with the HUDs, usability of the HUDs and preferences on which information they would like to see in HUDs. The perceived user experience was collected with the User-Experience Questionnaire (UEQ) (Laugwitz et al., 2008) while the perceived usability was assessed with System Usability Scale (SUS) (Bangor et al., 2008). User preferences on which information should be displayed in a HUD were collected with a proprietary personal preference questionnaire (PPQ) featuring a statement for each of the explored information as presented in Table 3. For all three questionnaires, a 7-point Likert scale was used, ranging from 1 - Completely disagree to 7 - Completely agree. With this scale, values ranging from 1-3 can be considered as negative ratings, the value of 4 as neutral, and the values from 5-7 as positive ratings.

The UEQ and SUS questionnaires were completed after each trial with a different interface, whereas the PPQ was completed after completing both trials with the FoV_S HUD or FoV_L HUD interface. In each questionnaire, the participants were asked to rate the perceived usability/usefulness/preference with HUD in a semi-automated vehicle.

The UEQ questionnaire consists of 26 questions, which are used to provide a scores on six aspects of perceived user experience - Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation and Novelty. The UEQ scores scale ranges from -3 (horribly bad) to 3 (extremely good). However, the authors state that because the scores represent the calculations of means, it is extremely unlikely to get scores above 2 or below -2. Values between -0.8 and 0.8 are considered as neutral, whereas scores above 0.8 represent a positive, and scores below -0.8 represent a negative user experience evaluation.

The SUS questionnaire consists of 10 questions, which are all used to provide the score of perceived usability of the evaluated system. In order to be consistent with the other two questionnaires, we used a 7-point scale, while the original proposes a 5-point Likert scale. The answers were than normalized to be able to use the original SUS scoring system (Bangor et al., 2008). SUS provides a scores on a scale from 0-100, where the score of 68 is set as a discriminatory limit – a score below 68 indicates below average, whereas a score above 68 indicates an above average perceived usability.

The PPQ asked participants to rate the importance (with a 7-point Likert scale) of displaying each information presented in the HUD (please see all elements in Table 3) during the whole drive in semi-automated vehicle. This questionnaire was mainly intended for collection of data needed to answer (from a user perspective) RQ2 – *which* visual information to should be presented to the driver in a semi-automated vehicle.

The results for UEQ and SUS cannot be directly related to the SA levels; these results were collected to investigate "how to design the automotive HUD system to best serve the driver" (Back et al., 2019, p.

Table 4
Driving speed statistics.

HUD version	Mean speed at 50 km/h speed limit		Mean speed at 30 km/h speed limit		Mean speed in the 1km after the speed limit change from 30 km/h to 50 km/h	
	M	SD	M	SD	M	SD
FoV_S MIN	43.200	8.928	24.100	4.223	52.098	4.586
FoV_S MAX	42.120	8.172	22.743	3.141	48.666	3.119
FoV_L MIN	43.920	9.252	25.599	7.902	51.563	3.717
FoV_L MAX	42.840	7.236	23.489	4.498	49.646	3.449

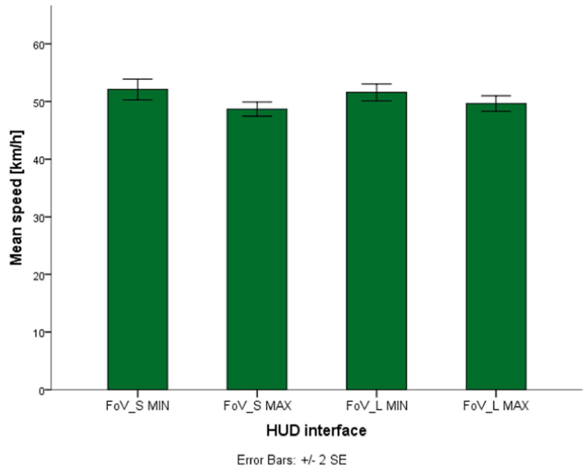

Fig. 4. Mean speed in the one kilometer interval after speed limit changed from 30 km/h to 50 km/h.

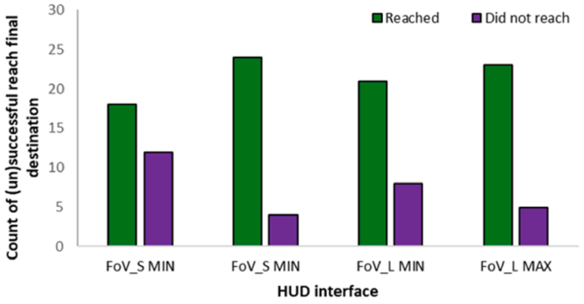

Fig. 5. Number of successful and unsuccessful reach of the final destination for every HUD interface.

1936). Although this was the primary goal also behind the PPQ, based on the meaning they provide, rated information in the PPQ can be allocated to SALs as shown in Table 2.

3. Results

The results analysis focused on answering the questions using one or more of the observed dependent variables. Consequently, to answer RQ1 (how to present) and RQ2 (which information), the data was analyzed by comparing the following groups:

- FoV_S MIN vs. FoV_S MAX (RQ2),
- FoV_L MIN vs. FoV_L MAX (RQ2),
- FoV_S MIN vs. FoV_L MIN (RQ1), and
- FoV_S MAX vs. FoV_L MAX (RQ1).

User's personal preference on which information (RQ2) should be displayed was captured also with the PPQ scores.

3.1. Driving performance

A linear model for one-way ANOVA with repeated measures analyses of variance with Bonferroni post hoc test was used (Bonferroni adjustment for multiple comparisons was applied). The equality of variances was assessed with Levene's test and Shapiro-Wilk test was used for exhibiting the normal distribution of each group of data. The driving data was normally distributed ($p > 0.05$), therefore one-way ANOVA parametric test was used to analyze the data. Outlier checks were performed with box plots for every observed variable. If outliers were detected, the data was transformed to reduce the influence their effect. Mauchly's test was used for assessment of sphericity and, when violated, the degrees of freedom were adjusted with Greenhouse-Geisser correction when calculating the p-value. Association between variables was explored with Chi-Square test for association.

3.1.1. Following speed limits

The analysis of the vehicle speed showed that the test participants on average drove within the speed limit with all four HUD versions throughout the manually operated intervals of the trials, where the speed limit was 50 km/h. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated for the driving speed data (50 km/h), $\chi^2(5) = 9.192$, $p = 0.102$. The mean speed values (please see Table 4) were higher with the MIN HUD interfaces, but not statistically significant, $p > 0.05$. We further looked at the manually operated intervals where the speed limit was 30 km/h. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated for the driving speed data (30 km/h), $\chi^2(5) = 10.736$, $p = 0.057$. There were no statistically significant differences between the HUD interfaces in the mean speed values also in the 30 km/h area, $F(3, 75) = 1.943$, $p = 0.130$ (please see Table 4).

There were however statistically significant differences in the mean speed values (please see Table 4) between the HUD interfaces in the area of one kilometre after the change of speed limit (from 30 km/h back to 50 km/h), which was indicated with a road sign "End of all previously signed restrictions" rather than with a speed limit sign, which required higher level of situational awareness and understanding of the driving environment, $F(3, 75) = 7.341$, $p < 0.001$ (see Figure 4). The results showed that the test participants drove faster and above the speed limit with the MIN HUD interfaces (which do not display the vehicle speed or the speed limit) compared to the MAX HUD interfaces (which display vehicle speed and speed limits at all times). The Bonferroni post hoc tests (adjusted for multiple comparisons) revealed these differences were statistically significant, with the participants driving faster and above the speed limit when using the FoV_S MIN HUD and FoV_L MIN HUD compared to the FoV_S MAX HUD and FoV_L MAX HUD, respectively, $p < 0.05$.

3.1.2. Reaching final destination

Most of the test participants successfully followed the navigation directions. However, not all of them participants were successful in reaching the final destination, and would continue driving after passing the final navigation cue. In both FoV_S HUD versions, this cue was indicated as a simple directional icon (see Figure 1, a)), whereas in the FoV_L HUDs this was indicated directly on the road (see Figure 2, b)). Despite the fact the notifications were same for the FoV_S MIN and the

Table 5

Takeover performance per HUD.

HUD version	Number of unsuccessful takeovers Count	Mean % of unsuccessful takeovers (out of all) M	SD
FoV_S MIN	7	0.233	0.430
FoV_S MAX	9	0.321	0.548
FoV_L MIN	12	0.400	0.724
FoV_L MAX	6	0.214	0.498

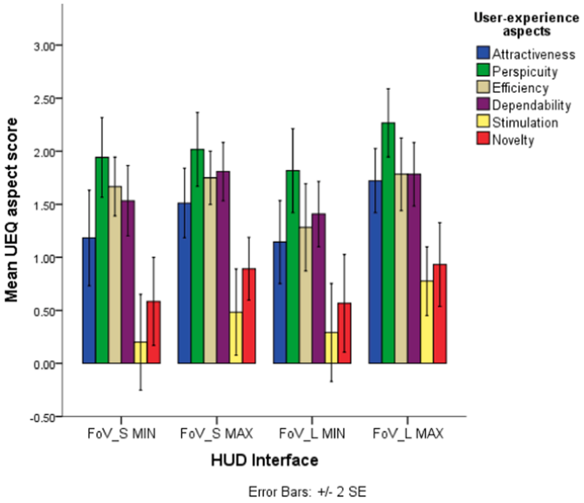

Fig. 6. UEQ scores for every HUD interface.

FoV_S MAX HUD interfaces, and same for the FoV_L MIN and FoV_L MAX HUD interfaces, the MIN resulted in less successful navigation following to the MAX interfaces: FoV_S MIN = 12, FoV_S MAX = 4, FoV_L MIN = 8, FoV_L MAX = 5 out the possible 30 per HUD (see Figure 5). A Chi-Square test for association revealed that there are statistical associations between the HUD type and the number of successful navigation following when comparing the FoV_S HUDs: FoV_S MIN vs. FoV_S MAX $\chi^2(1) = 4.794$, $p = 0.029$, however this was not the case with the FoV_L HUD versions: FoV_L MIN vs. FoV_L MAX $\chi^2(2) = 0.828$, $p = 0.661$. There were no statistically significant associations between the modes of the HUDs (FoV_S vs. FoV_L).

3.1.3. *Keeping safety distance*

The safety distance was considered as too short when the it fell below 1.5s. The analysis was made on the percentage of time when test participants drove with distance below 1.5s out of the whole manually operated interval within one trial. The analysis did not reveal any statistically significant differences, F(3, 6884E-5) = 0.339, p = 0.797. The intervals were very short for all HUDs – less than 1% out the whole time the vehicle was operated manually.

3.1.4. *Takeover performance*

In each individual trial all of the 30 test participants had to take-over control of the vehicle four times, resulting in 120 takeovers per HUD. The number of unsuccessful takeovers (UTO) per HUD was relatively low, with the highest number of unsuccessful takeovers for the FoV_L MIN HUD version (please see Table 5). As shown in Table 5, the mean amount of unsuccessful takeovers which resulted in collisions differed among the different HUD versions was low. The results of the Chi-Square test for association did not reveal any statistical association between the

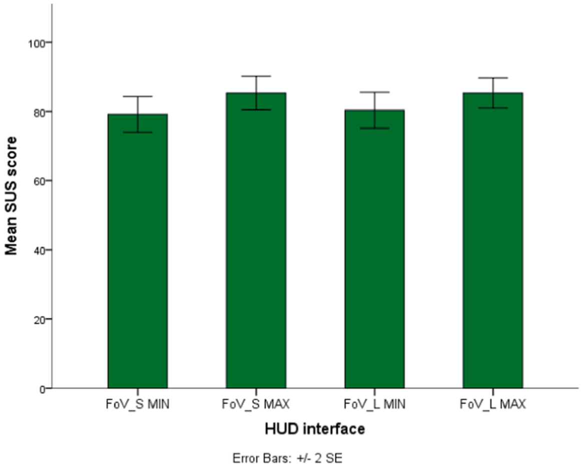

Fig. 7. SUS scores for every HUD interface.

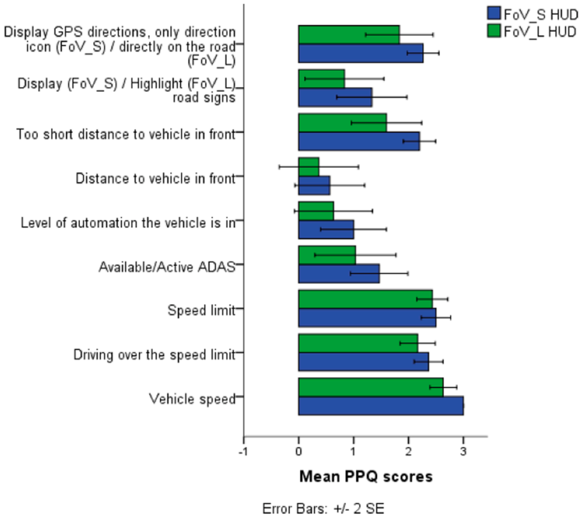

Fig. 8. PPQ scores for information to be visually displayed in a HUD in semi-automated vehicle.

Table 6

UEQ scores per UEQ aspects for all four HUD prototypes.

UEQ Aspect	FoV_S MIN		FoV_S MAX		FoV_L MIN		FoV_L MAX	
	M	SD	M	SD	M	SD	M	SD
Attractiveness	1.183	1.230	1.511	0.898	1.144	1.074	1.722	0.827
Perspicuity	1.942	1.031	2.017	0.951	1.817	1.085	2.267	0.881
Efficiency	1.667	0.761	1.750	0.689	1.283	1.127	1.783	0.939
Dependability	1.533	0.909	1.808	0.753	1.408	0.845	1.783	0.819
Stimulation	0.200	1.236	0.483	1.114	0.292	1.265	0.775	0.889
Novelty	0.583	1.138	0.892	0.809	0.567	1.259	0.933	1.081

Table A1

. Situational awareness levels as defined by Endsley's Situational Awareness Theory (Endsley, 1995).

Situational awareness levels	Operator's tasks
SAL1 Perception of the elements in the environment	Lowest level of SA, which is associated with the perception of information from the environment about the machine (its instrumentation and every other aspect affecting it) the operator is operating.
SAL2 Comprehension of the elements in the given situation	The second level of SA is associated with the comprehending of the meaning and significance of the elements in the environment in a given situation. This level of SA allows the operator to understand whether the machine is operating in the manner as it is intended to.
SAL3 Prediction of future status	The highest level of SA is associated with the ability to not only (assumable accurately) perceive and comprehend the meaning of the environment, but based on this information, also predict future statuses of the elements in the environment (for example potential hazards in the driving environment). This level of SA is important for planning and mitigation strategies in order to be able to perform time-critical actions and ensure the machine operates as is intended to.

Table A2

. Vehicle automation as defined by the Society of Automotive Engineers (SAE, 2016).

Levels of automation	Vehicle capabilities and driver's responsibilities
ADL0 No Automation	Zero autonomy; the driver performs all driving tasks.
ADL1 Driver Assistance	Vehicle is controlled by the driver, but some driving assist features may be included in the vehicle design.
ADL2 Partial Automation	Vehicle has combined automated functions, acceleration and steering, but the driver must remain engaged with the task and monitor the environment at all times.
ADL3 Conditional Automation	Driver is necessary, but is not required to monitor the environment during automation. The driver must be ready to take control of the vehicle at all times with notice.
ADL4 High Automation	The vehicle is capable of performing all driving functions under certain conditions. The driver mays have the option to control the vehicle.
ADL5 Full automation	The vehicle is capable of performing all driving functions under all conditions. The driver may have the option to control the vehicle.

number of unsuccessful take-overs (number of collisions) and mode or amount of information of the HUD versions: FoV_S MIN vs. FoV_S MAX $\chi(2) = 1.142$, $p = 0.565$; FoV_L MIN vs. FoV_L MAX $\chi(3) = 1.842$, $p = 0.606$; FoV_S MIN vs. FoV_L MIN $\chi(3) = 2.091$, $p = 0.554$; FoV_S MAX vs. FoV_L MAX $\chi(2) = 1.027$, $p = 0.598$.

3.2. *Cognitive load*

Although we recorded data for both eyes, the analysis were made using the data only for the right eye as the results are very similar. Mauchly's test of sphericity indicated that the assumption of sphericity was violated $\chi^2(5) = 18.852$, $p = 0.002$. Consequently, the degrees of freedom for these aspects were adjusted with Greenhouse-Geisser correction when calculating the p-value. The repeated measures ANOVA showed that the mean pupil size differed statistically significantly among the trials with the different HUDs, $F(1.938, 48.439) = 3.410$, $p = 0.043$. The Bonferroni post-hoc test with adjustment for multiple comparisons revealed that the pupil size was statistically significantly smaller (the level of cognitive load was smaller) when the test participants drove with the FoV_S MIN HUD compared to the FoV_S MAX HUD, $p = 0.025$. Although the pupil size was smaller when the test participants drove with the FoV_L MIN HUD compared to the FoV_L MAX HUD, this difference was not statistically significant for the set confidence level of 95% ($p = 0.089$). The post-hoc analysis did not reveal any other statistically significant differences between the mode of information presentation - FoV_S HUD and FoV_L HUD comparisons.

3.3. *User's preferences*

For all three questionnaires, a 7-point Likert scale was used, ranging from 1 - Completely disagree to 7 - Completely agree. With this scale, values ranging from 1-3 can be considered as negative ratings, the value of 4 as neutral, and the values from 5-7 as positive ratings. Considering this, the visual presentation of the actual effect of the obtained scores is between 0 and 3, and is obtained after subtracting the negative and neutral from the positive scores.

The reliability of the questionnaire scores was assessed with Cronbach's alpha.

3.3.1. *User-experience*

The reliability of the UEQ scores was assessed with Cronbach's alpha for each of the HUD versions ($\alpha_{\text{FoV\_S MIN}} = 0.828$, $\alpha_{\text{FoV\_S MAX}} = 0.796$, $\alpha_{\text{FoV\_L MIN}} = 0.763$ and $\alpha_{\text{FoV\_L MAX}} = 0.752$). The results show an acceptable level of internal consistency, as they all have α value above 0.70 (George & Mallery, 2003). Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the UEQ aspects attractiveness ($\chi^2(5) = 14.073$, $p = 0.015$), efficiency ($\chi^2(5) = 12.365$, $p = 0.030$) and dependability ($\chi^2(5) = 16.363$, $p = 0.006$). Consequently, the degrees of freedom for these aspects were adjusted with Greenhouse-Geisser correction when calculating the p-value. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated for UEQ aspects perspicuity ($\chi^2(5) = 3.242$, $p = 0.663$), stimulation ($\chi^2(5) = 2.560$, $p = 0.768$) and novelty ($\chi^2(5) = 2.742$, $p = 0.697$).

Based on the UEQ results, all four HUD interfaces were in average rated positively in terms of perceived user-experience (see Figure 6 and Table 6). Best scores were obtained for the aspects on pragmatic quality (perspicuity, efficiency and dependability). Lowest scores were obtained for stimulation, which is the only UEQ aspect for which the HUDs were rated neutrally (nor positive, nor negative). Statistically significant differences between the observed UEQ aspects were found for attractiveness ($F(2.234, 64.779) = 6.927$, $p = 0.001$), efficiency ($F(2.308, 66.924) = 3.602$, $p = 0.027$), dependability ($F(1.503, 65.834) = 3.133$, $p = 0.440$) and stimulation ($F(3.000, 87.000) = 4.286$, $p = 0.007$). The Bonferroni post hoc tests (adjusted for multiple comparisons) revealed that the FoV_L MAX HUD was perceived to be more attractive ($p < 0.001$), efficient ($p < 0.05$), provide better dependability ($p < 0.05$), and evoke better stimulation ($p < 0.05$) compared to the FoV_L MIN HUD. There were no other statistically significant differences between the FoV_S HUD versions or between the FoV_S and HUDs in terms of the rest of the user-experience aspects.

3.3.2. *Usability*

The reliability of the SUS scores was assessed with Cronbach's alpha for each of the HUD versions ($\alpha_{\text{FoV\_S MIN}} = 0.735$, $\alpha_{\text{FoV\_S MAX}} = 0.723$, $\alpha_{\text{FoV\_L MIN}} = 0.823$ and $\alpha_{\text{FoV\_L MAX}} = 0.772$) indicating an acceptable level of internal consistency. Mauchly's test of sphericity indicated that the assumption of sphericity was violated, ($\chi^2(5) = 13.679$, $p = 0.018$). Consequently, the degrees of freedom for the SUS score were adjusted with Greenhouse-Geisser correction when calculating the p-value.

The SUS scores showed all four HUD interfaces were rated with a score above 68, which based on the SUS (Bangor et al., 2008), indicates above average perceived usability (see Figure 7). When compared, the analysis showed there were statistically significant differences in perceived usability between the four compared HUD interfaces ($F(2.343, 67.960) = 3.621$, $p = 0.026$). The Bonferroni post hoc tests (adjusted for multiple comparisons) showed that these differences were statistically significant between the FoV_L MIN and FoV_L MAX interface

($p = 0.019$), where the test participants indicated better perceived usability for the MAX HUD.

3.3.3. Personal preference

Similarly to UEQ, the PPQ scores for which information should be displayed visually in a HUD in semi-automated vehicles were also obtained with a 7-point Likert scale. Consequently, for a more comprehensive visual presentation, Figure 8 presents the mean obtained scores for which information should be displayed in a HUD, in FoV_S and in FoV_L, in a semi-automated vehicle, after subtracting the negative and neutral from the positive values.

The PPQ had Cronbach alpha α=0.632 for the FoV_S HUD versions, and α=0.777 for the FoV_L HUD versions. The results show an acceptable level of internal consistency for the FoV_L HUD, and lower (yet still above the poor and unacceptable) level for the FoV_L HUD version.

The results revealed statistically significant differences between the personal preference on information to be displayed in the FoV_S HUD interface ($F(8, 232) = 15.491$, $p < 0.001$), and the FoV_L HUD interface ($F(8, 232) = 6.794$, $p < 0.001$).

For information presented in FoV_S, vehicle speed was the most preferred information to be displayed in HUDs in semi-automated vehicles, with its score statistically significantly higher compared to all other information ($p < 0.05$). Higher preference scores (above 1.5, or over 50%) were found for information on driving over the speed limit, speed limit, too short distance to the vehicle in front and display of navigational cues. Least preferred information were distance to vehicle in front, the level of automation the vehicle is in, the available/active ADAS, and display of surrounding road signs. The Bonferroni post hoc test revealed that all four worse rated information were statistically significantly less preferred compared to information on vehicle speed and speed limit ($p <0.05$). The distance to vehicle in front was statistically significantly less preferred also compared to driving over the speed limit, too short distance to the vehicle in front and GPS information ($p < 0.05$), and the level of automation of the vehicle statistically significantly less preferred compared to driving over the speed limit and GPS information ($p < 0.05$).

Similarly to FoV_S, also for information presented in FoV_L HUD, higher preference scores (above 1.5) were found for vehicle speed, driving over the speed limit, speed limit, too short distance to vehicle in front and display of navigation directions. Least preferred information were the distance to vehicle in front, level of automation the vehicle is in, the currently available/active ADAS, and highlighting of surrounding road signs. The post hoc tests revealed all four of the worse rated information were statistically significantly less preferred compared to vehicle speed ($p < 0.5$). The level of automation the vehicle is in, the distance to vehicle in front and highlighting of road signs was statistically significantly less preferred compared to the information on speed limit ($p < 0.05$). Additionally, the level of automation the vehicle is in and the distance to vehicle in front were less preferred compared to information on driving over the speed limit ($p < 0.05$), and the distance to the vehicle in front less preferred also compared to the information on too short distance to the vehicle in front ($p < 0.05$).

The overall preference scores for the same information, were lower for presentation in FoV_L compared to FoV_S (see Figure 8). However, these differences were not statistically significant.

4. Discussion

This study aimed to identify some of the key elements that have to be taken into account when designing a visual interface, such as how does the size of the HUD's FoV (RQ1) and the amount and content of the HUD's information (RQ2) information, in order to help the driver maintain situational awareness to achieve better driving performance throughout the manual driven intervals in semi-automated vehicles. Additionally, it tried to obtain the user's perspective on HUDs in semi-automated vehicle by observing their user-experience and perceived usability while taking into consideration their personal preferences.

4.1. How to present information?

To find out how to present information, we compared HUD interfaces that displayed the same amount of information, but differed in the FoV of presentation (FoV_S or FoV_L). The results from the driving performance indicators did not reveal any statistically significant differences in the overall driving performance of the participants when comparing the trials with HUDs with different FoVs (FoV_S and FoV_L). These results differ to findings reported in past research, such as for example of Karatas et al. (2020), who reported that bigger FoV HUDs with AR functionalities can provide important advantages compared to static fixed-positioned 2D HUDs in time-critical situations such as takeover. To try to understand why we did not find any differences, we took a closer look at the driving performance indicators and which information were presented in the HUDs to help with their execution. Although we used different presentation of the speed signs in the HUDs with different FoV (the speed signs were displayed in the FoV_S HUD in a fixed position above the steering wheel and highlighted directly in the environment in the FoV_L HUD), finding differences between them could have been affected by other information presented in the HUDs, especially in the MAX versions. Namely, participants could see the information about the current speed limit versions at all times, as it was presented with additional information icons in the fixed-positioned part of the interface (please see Figure 1 b) and Figure 2 b)). Additionally, the MAX versions displayed information on the vehicle's speed and potential speeding, again helping the driver maintain situational awareness of the speed limits without necessarily looking at the speed limit signs (regardless of how they were presented in the HUDs). Potential differences in the driving performance for these driving performance indicators could be therefore seen only when looking at the MIN versions, where these additional information were not provided. However, as it will be discussed more in detail in the next subchapter, the information content seems to have a greater impact on the driving performance compared to where or how it is presented.

Following the navigational cues on the other hand did not have any redundant systems the participants could follow. Here, although again statistically not significant, we can see that the more participants did not reach the final destination when using the FoV_S compared to the HUD with FoV_L, especially in the trials with the FoV_S MIN. This is in line with line with the results reported by Langlois and Soualmi (2016), who suggest that AR enriched HUDs with increased FoV can support driving skills on the tactical level.

Our results did not reveal any statistical differences in the amount of cognitive load drivers experienced when comparing the HUDs with the same amount of information presented in different modes. Given that Feierle at al. (2019) reported than an AR HUDs have the potential to cause high cognitive stress or even overload if they feature too much information, the proposed AR HUD in this study seems to be effective, while at the same time not too demanding for drivers. This was also confirmed with the self-reported data, where the direct comparisons of the users' self-reported data did not reveal any statistically significant differences between the FoV_S and FoV_L HUDs in none of the observed variables, which could be interpreted as that the both sizes of FoV evoke similar user experience and usability.

4.2. Which information to present?

Contrary to the mode of information, the results on the amount of information showed a lot more statistically significant differences.

Firstly, participants generally drove slower when using the MAX HUDs, which displayed information on the current vehicle speed, speed limit and driving over the speed limit. On the other hand, participants obeyed speed limits with all four HUD versions, suggesting that the HUD display of speed information did not have an effect on SAL1. However, the results showed that the test participants performed worse with the MIN HUDs in the kilometre after the speed limit changed from 30 km/h to 50 km/h, since this change was indicated solely with a visual sign showing the end of restriction for driving 30 km/h. As a reminder, the MIN HUD does not display the current speed limit, the speed of the vehicle nor information on speeding. The "End of all previously signed restrictions" sign therefore requires SAL3 as it expects the driver to not only perceive and comprehend the meaning of the sign, but also be aware of the driving environment and road regulation (general rules for city roads) in order to adapt its behaviour appropriately. SAL3 is the highest level of SA, suggesting that display of speed information in HUDs may not be essential for lower SA levels such as for monitoring the environment (SAL1), but can help the driver with more demanding SA tasks.

Better driving performance was also observed with the HUDs with more information also for following navigation cues. To our surprise, despite the fact the notifications were same for the FoV_S HUD interfaces, and same for the FoV_L HUD interfaces, the MIN HUD versions resulted in less successful following of navigation cues compared to the MAX interfaces. Although the MAX versions did not provide any further information which could help with the performance of this task, we can hypothesise that the better performance is due to the fact the driver did not have to allocate attentional efforts for sustaining attention to information such as the speed limit or monitoring for speeding on the dashboard (SAL1), and could allocate them for other higher SA demanding tasks, such as following navigation cues and responding appropriately (SAL2).

The analysis from the pupil size showed that while the increased number of information may have a positive effect on the driving performance, it has a negative effect on the driver's levels of cognitive load. The effect was more evident (statistically significant) for the FoV_S MAX HUD compared to the FoV_S MIN version, but higher levels are also present in the FoV_L MAX compared to the FoV_L MIN one. Cognitive load theory proposes that cognitive capacity in the working memory is limited, so if a task or set of tasks require too much capacity, processing of data will be obstructed and cognitive overload would appear (De Jong, 2010). While high attention load can eliminate (with selective attention) the processing of less important tasks, high cognitive load increases the processing of irrelevant tasks as well (Lavie, 2005). In a lot of everyday situations this phenomenon is completely unnoticed, but when driving it can have serious safety – related consequences.

As for the self-reported data, the results showed that the user experience and perceived usability of the HUD are influenced by the amount of presented information, but only when the HUD displays information in FoV_L mode.

4.3. *What do drivers want to see in a HUD?*

All of the featured information in the HUDs obtained (mean) positive ratings on the PPQ suggesting that the information selection was appropriate for HUDs in semi-automated vehicle. The scores for each information however ranged differently within the 0 to 3 scale. If the average scale is set at 50% (i.e. scores above 1.5), the PPQ results suggest that drivers would like to see in a HUD information on the vehicle speed (SAL1), the speed limit (SAL1), indication when driving over the speed limit (SAL2), indication when driving with too short distance to the vehicle in front (SAL3) and navigation cues and directions (SAL2). Given that PPQ followed the same Likert scale and results calculation as the UEQ, the obtained PPQ results could be alternatively interpreted using the UEQ scores definition, which suggests that values between -0.8 and 0.8 are considered as neutral, whereas scores above 0.8 represent a positive, and scores below -0.8 a negative user's evaluation. This would suggest that in addition to the above stated five information, and considering the mean scores for FoV_S and FoV_L HUDs (see Figure 8), a HUD interface in a semi-automated vehicle should also feature information on the vehicle's ADAS (available or active) (SAL2) and surrounding road signs (SAL1). The personal preference on having more information in such HUDs is in line also with the reported scores on user experience and perceived usability, which were, in general, higher for the MAX HUD interfaces compared to the MIN versions. These differences (in amount of information) were however statistically significant only for the FoV_L MAX HUD compared to the FoV_L MIN HUD (see Figure 6 and Figure 7), suggesting that the more information should be displayed when the interface displays information directly in the environment and not only when it changes position within the vehicle, for example, from the dashboard to a HUD projected on the windshield, which was seen also in the results reported by Ma et al. (2021).

Conclusions

The lack of statistical differences between the FoV_S and FoV_L HUDs in all of the observed driving performance variables gives the impression that the size of the HUD's FoV does not have an overall significant effect on the driver's situational awareness. Instead, the content of the presented information is what seems to have a higher effect on the driver's situational awareness. Similarly to findings reported by Langlois and Soualmi (2016) and Schöming et al. (2018), our study also revealed high user experience and high preference for some elements of the FoV_L HUD, but only when the appropriate amount of information was displayed. However, if considering the fact that an FoV_L HUD is much more technologically demanding to implement and it is harder to ensure its robust and reliable performance (for example, it is highly affected by the brightness of the environment), FoV_S HUDs may be a better alternative for semi-automated vehicles, as they perform similarly to FoV_L HUD without a risk for potential cognitive stress (Feierle et al. 2019).

Furthermore, the results from study show that information which help the driver to maintain higher SA levels (SAL2 and SAL3) should be primarily considered to be implemented in a HUD. Drivers on the other hand would like to have also SAL1 information, however the impact greater amount of information may have on the driver's cognitive load calls for caution when adding more information (to please the user's preferences) than the necessary ones (for obtaining better driving performance and safety).

When interpreting these results, it is important to take in consideration the testing environment the study was conducted in. As with many new technological solutions for vehicles, this study also used a driving simulator instead of a real vehicle. There are multiple reasons for choosing a simulated against real environment, from the fact that semi-automated vehicles are still not legally available in the greater part of world, technological limitations that not enable implementation in real vehicles, controllability of the situations to safety of the testing participants and other road participants involved in the study. However, simulators also have multiple pitfalls, which have to be considered when interpreting results obtained in them and before applying their findings in real vehicles. In this study, the driving simulator enabled us to test the HUDs in perfect conditions – due to the controlled lighting, all of the information in the HUDs was visible perfectly all times, which is not the case with HUDs in real vehicles. Additionally, the system never failed or displayed any incorrect information. This can have high effect on the perceived usability and user experience, and consequently also on the driver's situational awareness and their driving performance.

Another limitation of this study lays in the implementation of the HUDs. Because the FoV_S and FoV_L were both displayed on the screen, the actual virtual image distance was the same for both of these HUD versions. We tried to overcome this by simulating the FoV_S in a fixed position on the screen above the steering wheel, and tried to simulate dynamic VIDs for some of the elements of the FoV_L by rendering them in perspective, at appropriate locations. Regardless of our efforts and visual manipulations, we believe this could have had some effects on the study results, as the test participants did not have to change their focal depth as they would when using a HUD in a real vehicle. Despite these limitations, we believe that the results from this study can be applied in

HUD development for increasing driver's situational awareness in semi-automated vehicles. By taking in consideration the participants' personal preferences and subjective opinions on usability and user experience, we believe that these results can also contribute to better understand how to develop HUDs that will have higher acceptance rate and consequently higher willingness to use.

CRediT authorship contribution statement

Kristina Stojmenova Pečečnik: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **Sašo Tomažič:** Investigation, Resources, Writing – review & editing, Supervision, Project administration. **Jaka Sodnik:** Software, Validation, Resources, Writing – review & editing, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Table A1 and A2.

A.1. User-Experience Questionnaire (Laugwitz et al., 2008)

Please make your evaluation now.

For the assessment of the product, please fill out the following questionnaire. The questionnaire consists of pairs of contrasting attributes that may apply to the product. The circles between the attributes represent gradations between the opposites. You can express your agreement with the attributes by ticking the circle that most closely reflects your impression.

Example:

attractive	○	○	○	○	○	○	○	unattractive

This response would mean that you rate the application as more attractive than unattractive.

Please decide spontaneously. Don't think too long about your decision to make sure that you convey your original impression.

Sometimes you may not be completely sure about your agreement with a particular attribute or you may find that the attribute does not apply completely to the particular product. Nevertheless, please tick a circle in every line.

It is your personal opinion that counts. Please remember: there is no wrong or right answer!

Please assess the product now by ticking one circle per line.

	1	2	3	4	5	6	7		
annoying	○	○	○	○	○	○	○	enjoyable	1
not understandable	○	○	○	○	○	○	○	understandable	2
creative	○	○	○	○	○	○	○	dull	3
easy to learn	○	○	○	○	○	○	○	difficult to learn	4
valuable	○	○	○	○	○	○	○	inferior	5
Boring	○	○	○	○	○	○	○	exciting	6
not interesting	○	○	○	○	○	○	○	interesting	7
unpredictable	○	○	○	○	○	○	○	predictable	8
fast	○	○	○	○	○	○	○	slow	9
inventive	○	○	○	○	○	○	○	conventional	10
obstructive	○	○	○	○	○	○	○	supportive	11
good	○	○	○	○	○	○	○	bad	12
complicated	○	○	○	○	○	○	○	easy	13
unlikable	○	○	○	○	○	○	○	pleasing	14
usual	○	○	○	○	○	○	○	leading edge	15
unpleasant	○	○	○	○	○	○	○	pleasant	16
secure	○	○	○	○	○	○	○	not secure	17
motivating	○	○	○	○	○	○	○	demotivating	18
meets expectations	○	○	○	○	○	○	○	does not meet expectations	19
inefficient	○	○	○	○	○	○	○	efficient	20
clear	○	○	○	○	○	○	○	confusing	21

(*continued on next page*)

(*continued*)

impractical	○	○	○	○	○	○	○	practical	22
organized	○	○	○	○	○	○	○	cluttered	23
attractive	○	○	○	○	○	○	○	unattractive	24
friendly	○	○	○	○	○	○	○	unfriendly	25
conservative	○	○	○	○	○	○	○	innovative	26

System Usability Scale (Bangor et al., 2008)

1. I think that I would like to use this system frequently.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

2. I found the system unnecessarily complex.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

3. I thought the system was easy to use.

Strongly disagree				Strongly agree		
1	2	3	4	5	6	7

4. I think that I would need the support of a technical person to be able to use this system.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

5. I found the various functions in this system were well integrated.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

6. I thought there was too much inconsistency in this system.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

7. I would imagine that most people would learn to use this system very quickly.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

8. I found the system very cumbersome to use.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

9. I felt very confident using the system.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

10. I needed to learn a lot of things before I could get going with this system.

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

Personal Preference Questionnaire

Please rate how important you think it is to display each of the information presented bellow when driving a semi-automated vehicle, by using a scale from 1 to 7, where 1 stands for “I strongly disagree”, and 7 for “I strongly agree”.

1. Vehicle speed

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

2. Driving over the speed limit

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

3. Speed limit

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

4. Advanced driving assistive systems (information whether they are active or available)

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

5. Vehicle level of automation

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

6. Safety distance to vehicle in front

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

7. Too short safety distance to vehicle in front

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

8. Display (in FoV_S) / Highlight (in FoV_L) of road signs (for example pedestrian crossing, traffic light, priority road, stop sign, etc.)

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

9. GPS (navigation ques) as icons (in FoV_S) / directly on the road (in FoV_L)

Strongly disagree					Strongly agree	
1	2	3	4	5	6	7

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