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Development and evaluation of a human machine interface to support mode awareness in different automated driving modes

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ABSTRACT

With increasing implementation of automated driving technology it is expected that different automation modes will be present within the same vehicle and within a single trip. At all times during automated driving the driver needs to have 'mode awareness', which is an understanding of the automation mode and the corresponding responsibilities. Yet, research on HMI design to support mode awareness for multiple automation modes within a single vehicle and within a single trip is currently limited. The current work describes the development and evaluation of a Human Machine Interface (HMI) to support mode awareness while driving in different automation modes. The work exists of three phases: Phase 1 defines functional requirements for HMI design based on literature review and 5 experimental studies including 146 participants. Phase 2 implements the functional requirements in HMI design through expert and focus group sessions. Phase 3 evaluates and improves upon the HMI design employing virtual reality and the RITE (Rapid Iterative Testing and Evaluation) method with 18 participants. The result is a continuous and holistic HMI design creating mode awareness through ambience. Findings from Phase 3 and previous research indicate that this HMI is comprehended well, with a relatively low task load, and with a good experienced system usability. It is important to additionally evaluate the HMI design resulting from the current study in driving simulators and in on-road tests. Such tests will provide an opportunity to verify and expand on the current study's findings and to contribute to guidelines for HMI design.

1. Introduction

Automated driving has the potential to improve traffic safety, with automated technology handling (parts of) the driving task. Six modes of vehicle automation have been defined by the Society of Automotive Engineers (SAE) from a technological perspective, ranging from SAE Level 0 to SAE Level 5 (Society of Automotive Engineers International J3016, 2021). With SAE Level 0 no automated technology is engaged, while with SAE Level 5 the automation takes care of the complete driving task, regardless of the driving context. Levels in between describe driving with support technology activated while the driver needs to constantly monitor the driving

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situation (SAE Level 1 and 2) or describe the automation taking care of the driving task while the driver remains fit enough to take over when requested (SAE Level 3) or while the driver is able to completely 'out of the loop' as a take-over will not be required within the design domain (SAE Level 4). The driver's responsibility thus differs depending on the automation mode. It is expected that different levels of automation will be present within the same vehicle, depending on the operational design domain (ODD, Naujoks et al., 2019). This would mean that transitions between different modes, and therefore different responsibilities, could occur within a single trip. These transitions could not only include the automation switching off or on, but also switching from a lower to a higher automation level or vice versa. It is important that the driver understands the automation level, or automation mode, and his or her responsibilities at any time during automated driving, which is referred to as 'mode awareness' (Kurpiers et al., 2020; Sarter et al., 2007). In the absence of mode awareness 'mode confusion' can occur. This refers to confusion about the activated automation mode and its associated capabilities. Such confusion can be dangerous because it can lead to incorrect actions from the driver or 'mode errors' (Boos et al., 2020; Sarter & Woods, 1995). For example, in Boos et al. (2020) participants missed a silent failure of the automation and ended up in the hard shoulder of the road. Mode awareness can be supported by a well-designed Human Machine Interface (HMI, Carsten & Martens, 2019). Mirnig et al. (2017) examined academic publications and industry patents on transition interface designs in automated vehicles. They also examined how these systems inform drivers on the mode. It was concluded that most implementations are in essence a binary 'on versus off'. However, ensuring mode awareness in multiple automation modes could enable drivers to better comprehend and take on their role in the different modes (Tinga et al., 2022). Approval was recently obtained for an SAE Level 3 system in Germany, the Mercedes traffic jam assist, which takes over the driving task in highway traffic jam situations (Templeton, 2021). Yet, these systems work only in specific situations, implicating that at other times lower levels of automation might be activated. Communicating effectively on multiple automation modes could potentially be an enabler for implementation of multiple modes in a single vehicle.

Efforts to design an HMI communicating effectively on multiple automation modes within a single vehicle are undertaken in the 'MEDIATOR' project (No 814735). The MEDIATOR project is a European Union's Horizon 2020 four-year project in which researchers and industry are collaborating. In the project, an HMI is being developed that mediates between driver and automation, with respect to the driving context, taking into account who is fittest to drive. In this way the project works towards recommendations for HMI design. The HMI being developed in MEDIATOR does not only focus on assuring mode awareness, but also on aspects such as assessing and predicting driver fatigue or inattention, assessing and predicting the capabilities of the automation, and facilitating safe transitions. While all these aspects are of importance for a safe transition towards automated driving, the focus of the current work will be on assuring mode awareness when communicating on different automation modes during automated driving.

To ensure mode awareness through HMI design it is first of all important to establish the different types of automation modes not only from a technological perspective (e.g., the SAE Levels), but also from a human-centered perspective. This allows for determining which distinctive modes are relevant to be communicated to the human driver. Research is being undertaken to consider modes from a user's perspective (e.g. Homans et al., 2020). Activities by the MEDIATOR consortium to define human-centered automation modes (see also Christoph et al., 2019; Cleij et al., 2020) resulted in four different automation modes: 1) Manual; 2) Continuous Mediation; 3) Stand-By; and 4) Time-to-Sleep. First, 'Manual' (M) mode describes the case in which no automation technology is active. In this mode the driver is in charge of the complete driving task. This mode is equivalent to SAE Level 0. Second, 'Continuous Mediation' (CM) describes lower-level driving assistance technology being active which requires the driver to be involved in the driving task continuously as the technology can instantly stop working without prior notice. In other words, there needs to be continuous mediation between the automation and the driver to assure mode awareness. This mode covers SAE Level 1 and 2. Third, 'Stand-By' (SB) describes a higher level of automation in which the driver can hand over full control to the automation until the driver is requested to take back control again because the operational design domain ends or because of a system failure. The human driver is the backup when the automation cannot handle the driving task anymore. Therefore, in this mode the driver should continuously be prepared, or be on stand-by, to resume control in a short period of time. This mode resembles SAE Level 3. Fourth and last, 'Time-to-Sleep' (TtS) describes driving with high automation allowing the driver to be completely out of the loop for long periods of time. While driving in this mode it will not be required for the human driver to take over the driving task at any time as the automation is able to bring the vehicle to a safe stop in the event of a system failure. This provides the opportunity to the driver to engage fully in non-driving related tasks and to even fall asleep (when this would be legally permitted). This mode is similar to SAE Level 4.

The current work, as part of the MEDIATOR project, describes the development and evaluation of an HMI to support mode awareness in four automation modes from a human-centered perspective (i.e., the modes discussed above). The focus will not be on effectively guiding a transfer between modes, but on assuring mode awareness while driving in a certain mode. The development and evaluation occur in three phases. An overview of the aim and methodology of the three phases is presented in Table 1. In Phase 1 functional requirements for the HMI design are defined based on literature and experimental studies. In Phase 2 the functional requirements are implemented in design through expert and focus group sessions. The resulting design is evaluated and improved upon in Phase 3. In the next sections the methodology and findings for each of the three phases will be presented and discussed.

Table 1
Overview of the aim and methodology of the current study's three phases.

Phase	Aim	Methodology
Phase 1	Defining functional requirements for the HMI design	Literature review and five experimental studies
Phase 2	Implementing the functional requirements in the HMI design	Expert and focus group sessions
Phase 3	Evaluating and improving the HMI design	Rapid Iterative Testing and Evaluation (RITE) in virtual reality

2. Phase 1: Functional requirements

In Phase 1 functional requirements related to ensuring mode awareness during driving in the four automation modes from a human-centered perspective are identified. To this aim a literature review and five experimental studies are conducted for which we will summarize the methods and outcomes resulting in the functional requirements. Details are discussed in Deliverable 1.5 of the MEDIATOR project (van Grondelle et al., 2021).

2.1. Methods

Regarding the literature review, literature was explored on driver's information needs and preferences, driver's capabilities and limitations and the type of information that can support those needs, preferences, capabilities and limitations. Searches for the literature review were conducted in personal libraries of the researchers involved and in scientific databases such as Web of Science and Google Scholar from April to October 2020. Combinations of search terms such as 'automated driving', 'automated vehicle', 'mode awareness', 'driver', 'information needs', 'preferences', 'capabilities' and 'limitations' were used. In addition, pearl growing, snowballing and citation search were used to identify additional relevant articles.

Regarding the five experimental studies, the first three experiments were dedicated to exploring main HMI design principles and HMI elements to confirm findings from the literature review and to address knowledge gaps (e.g., is it better to inform the driver on the automation's status or on the driver's required/allowed tasks). These three experiments were followed by two experiments that were dedicated to evaluating the effectiveness of and experience with a combination of elements incorporated into a single HMI concept. Sample sizes throughout these experiments were based either on sample sizes of similar studies or on a priori power analyses. Therefore, the sample sizes of the experimental studies vary from study to study. The explored HMI elements and concepts were specifically created for these experiments based on previous research identified through the literature review. The first experiment used interviews, questionnaires and brainstorming with experts, users of automated vehicles and non-experts ($N = 68$). The second experiment used questionnaires on interpretation and experience for directions of HMI design ($N = 24$). The third experiment employed questionnaires on interpretation and experience for specific HMI elements ($N = 29$). The fourth and fifth experiment employed questionnaires on, amongst others, comprehension and preferences and let participants think aloud (details about the think-aloud methodology are described in the methodology section for Phase 3). Users of cars with automated functionalities ($N = 16$) participated in the fourth experiment and users of cars with and without automated functionalities ($N = 9$) participated in the fifth experiment. Special focus was on ensuring mode awareness while driving in one of the four automation modes and how to make the distinction between those different modes clear. This exploration through literature and experimental studies provided insight into the type of information that could be relevant to communicate, when to communicate it and how to communicate it.

Analyses of the data collected in the five experimental studies ranged from thematic analysis and clustering of qualitative data to analysis of variance and linear mixed effects modeling of quantitative data.

Functional requirements were defined based on the outcomes of the literature review and the experimental studies, taking the varying sample size across the experimental studies into account.

2.2. Results and discussion

The outcomes of the literature review and experimental studies resulted in a total of eight functional requirements which are presented in Table 2. This section will discuss each functional requirement and its foundation in more detail. Functional requirement #1, 'the HMI must communicate the current mode continuously' is in line with the first usability heuristic for general user interface design developed by Nielsen (1994) and is also included in a checklist for supporting evaluation of HMIs developed by Schömig et al. (2020). Moreover, functional requirement #1 is supported by the literature indicating that information on the mode is essential and facilitates awareness about the automation's capabilities and the driver's responsibilities (Beggiato et al., 2015; Feierle et al., 2020; Hecht et al., 2019; Hoeger et al., 2011). Yet, it should be ensured that drivers do not overlook this information (Large et al., 2017). Schömig et al. (2020) suggest to present this type of information close to the driver's expected line of sight and by using commonly

Table 2
Functional requirements resulting from the literature review and five experimental studies. The necessity for implementation of each functional requirement is indicated based on three levels, following RFC 2119 (Bradner, 1997): 1) 'Must' indicates that implementation is required, 2) 'should' indicates that implementation is desired, and 3) 'may' indicates that implementation is somewhat desired.

Number	Functional requirement
1	The HMI must communicate the current mode continuously.
2	The HMI must communicate the time left in the current mode/time to the next mode continuously.
3	The communicated information by the HMI supporting mode awareness must be intuitive and easy to understand.
4	The communicated information by the HMI supporting mode awareness must not induce information overload.
5	The HMI should communicate what the next mode will be when a change in mode will occur or will be available shortly.
6	The HMI should nudge the driver in what s/he should (not) do.
7	The HMI should communicate the foreseen automation mode(s) throughout the route when requested by the driver.
8	If the driver has never used the HMI, the HMI may guide the driver through its functionalities and how these functionalities relate to the capabilities of the automation and responsibilities before offering driving with automation functionalities enabled.

accepted or standardized symbols or non-standard symbols that should be supplemented by additional information (Schömig et al., 2020). The outcomes of the experimental studies supported the importance of communicating the current mode. Moreover, these outcomes indicated that information on the current mode should be provided continuously in an unambiguous but non-invasive way, for example through providing an ambience in the vehicle through ambient light in combination with icons.

The outcomes also indicated that 'the HMI must communicate the time left in the current mode/time to the next mode continuously' (functional requirement #2). This information is shown to be able to support mode awareness, including appropriate engagement in non-driving related activities (NDRTs; Beggiato et al., 2015; Hecht et al., 2019; Hecht et al., 2020a; Pokam Meguia et al., 2015; Wandtner et al., 2018). This type of information can for example be communicated through a visual representation including a horizontal bar that depletes over time (Wandtner, 2018) or through a countdown (Hecht et al., 2020a). The experimental studies demonstrated that communicating time left in the current mode/time to the next mode, combined with what the next mode will be when the next mode is imminent (functional requirement #5), supported understandability and usability of the communicated information without causing information overload or overreliance.

As mode awareness is essential, it was also concluded that it is required that the communicated information is intuitive and easy to understand (functional requirement #3; Naujoks et al., 2019). Moreover, the communicated information must not induce information overload (functional requirement #4), in order to ensure the driver is able to process the information (Schneider, 1987). It is suggested by Schömig et al. (2020) that no more than five colors should be consistently used for communicating mode information and that these colors should be in accordance with common conventions and stereotypes.

There are also some studies that report providing information on the required or allowed task for the driver (e.g., whether monitoring is needed or not) can provide benefits, including enhancing take-over performance (Yang et al., 2018; Lu et al., 2019) and increasing situation awareness and hazard detection (van den Beukel et al., 2016; Yang et al., 2018). Findings of the experimental studies, however, indicated that this information should not be communicated too directly to the driver (e.g., communicating when the conditions allow the driver to work on a laptop). Rather, 'the HMI should nudge the driver in what s/he should (not) do' (functional requirement #6) by providing conditions in which the driver can choose the right task.

Hecht et al. (2020b) demonstrated that providing information on the foreseen automation mode(s) throughout the route (functional requirement #7) can aid drivers in planning their trip. This finding was also supported by the experimental studies in Phase 1 of the current work. In order to prevent information overload, however, this information should only be presented when requested for by the driver.

Finally, in order to support understandability and usability of the presented information, the HMI may guide a first-time user through its functionalities and how these functionalities relate to the capabilities of the automation and responsibilities before offering driving with automation functionalities enabled (functional requirement #8; see also Khastgir et al., 2018).

3. Phase 2: Design implementation

In Phase 2 the functional requirements resulting from Phase 1 were implemented in design. The current section will present the methods and outcomes of Phase 2.

3.1. Methods

In order to translate the functional requirements to an HMI design a core team of two industrial (automotive) designers and three human factors in vehicle automation experts met frequently (i.e., about once or twice a month) for about a year. Additionally, four interdisciplinary focus group sessions with other partners of the MEDIATOR project (about 20 people were involved in total) took place to get their input on design choices whenever deemed valuable. In a research-by-design process and through rapid prototyping the HMI was being designed by one of the core teams' industrial designers with support from a team of junior designers. In this process specific events while driving in the automation modes and changes between automation were taken into account (such as planned and unplanned transitions and driving in a specific automation mode, but also corrective actions for distraction or fatigue; for a description of these specific events see also Cleij et al., 2020). HMI design components included multisensory signals, in order to implement the functional requirements sufficiently. The other members of the core team thought along and provided feedback on preliminary prototypes. The functional requirements were always central to this process.

The lead designer embraced several design guidelines, of which an holistic design approach was the most important one: This approach entailed that functional requirements in addition to the ones for ensuring mode awareness were taken into account and that all components of the HMI design cooperate consistently. Two design guidelines were embraced to elicit intuitive learning. Firstly, components were designed from existing affordances, which entailed that components relate to contemporary vehicle HMI design in order to be perceived as familiar. Secondly, a ritual that forms the basis for all user-automation interaction was employed in order to facilitate learning of the interactions. Moreover, design guidelines to design for user acceptance and to design for industry acceptance were adopted to facilitate acceptance of the HMI design. In about the last half year of this phase, a designer with expertise in virtual reality (VR) was also involved in order to implement and facilitate reviewing design choices through experiencing the design in an immersive virtual environment. Details about the apparatus involved in this VR implementation are discussed in the apparatus section of Phase 3.

3.2. Results and discussion

Regarding functional requirement #8 it was decided by the core team that this requirement would not be implemented for the purpose of the current study. Guiding the driver through the HMI's functionalities and how these functionalities relate to the capabilities of the automation and responsibilities before offering driving with automation functionalities enabled can be implemented after it is ensured that the seven other functional requirements are fulfilled by the design. In this way, the focus is on making the information communicated by the HMI intuitive and easy to understand without depending on a procedure guiding and assisting the driver in his/her understanding. All other functional requirements were implemented in the HMI design.

In translating the functional requirements to HMI design the four human-centered automation modes as defined in MEDIATOR (M, CM, SB and TtS) were named with three labels to communicate to the driver. These labels were: 1) 'Manual driving', covering the M mode; 2) 'Assisted driving', covering the CM mode, as the driver is assisted in driving (through either adaptive cruise control [ACC] or lane keeping assist [LKA] or both) but still needs to maintain all responsibility over the driving task; and 3) 'Piloted driving', covering both the SB and TtS modes, as during driving in these modes the driving task is performed by the automation and therefore the automation takes over the piloting task. Although SB and TtS impose different responsibilities on the driver (e.g., needing to be able to take-over the driving task when requested versus not needing to be able to take-over), it was chosen to not distinguish between these modes in how they are labeled for the driver as it is foreseen that the mode will change from SB to TtS automatically when TtS becomes available. This is foreseen as in 'Piloted driving' the driver is expected to always seek the highest comfort available, which should be determined by the automation only. Thus, the HMI design still includes four driving modes, but the driver can only select from three of those. Moreover, in this way it was thought that information overload and confusion caused by presenting more labels would be prevented. Yet, subtle differences in the way in which the HMI design communicates to the driver through its elements were incorporated in order to subtly communicate the difference in driver responsibilities between SB and TtS.

Next, the HMI design resulting from Phase 2 will be presented and it will be discussed how the design is related to the functional requirements. See Fig. 1 for a depiction of the HMI design in each automation mode resulting from Phase 2.

The current automation mode was communicated through color to ensure distinguishing between the four different modes is intuitive, as color is able to facilitate recognition and processing of visual information (Jansson et al., 2004; Tanaka & Presnell, 1999; Wolfe & Horowitz, 2004). Taking into account the photopic sensitivity of the human visual system (Werner, 2018) different (shades of) colors were employed to continuously communicate on the current mode: M was communicated in white, CM in amber and both SB and TtS in purple. The purple was dimmed in TtS to subtly communicate the difference in responsibility between SB and TtS. Multiple HMI components were continuously colored in the color of the respective mode, namely LED-bars on the dashboard and steering wheel, the light of the logo on the steering wheel (the logo's light was turned off in TtS, to indicate the steering wheel doesn't need to be used), light emitted from the shifter, several graphical user interface elements, and the ambient light emitted from below the dashboard and sides of the doors. More details on the function of HMI elements such as the shifter are provided below.

Fig. 1. The HMI design in the four different modes resulting from Phase 2 (stills from the VR environment). The design is communicating the 'Manual' (M) mode in the upper left picture, 'Continuous Mediation' (CM) in the upper right picture, 'Stand-By' (SB) in the lower left picture and 'Time-to-Sleep' (TtS) in the lower right picture.

The LED-bars on the dashboard and steering wheel additionally communicated the time left in the current mode/time to the next mode in an abstract way (see Hecht et al., 2022 for a concept that also communicates timing information through an LED-bar). The LED-bar on the dashboard 'depleted' towards the center of the steering wheel and the LED-bar on the steering wheel 'depleted' towards its middle with decreasing time when a change in mode was imminent. In this way, both LED-bars 'depleted' towards the same location from the point of view of the driver. The time left in the current mode/time to the next mode is foreseen as a likely estimated, but not certain, time (following Cleij et al., 2020). This estimation can probably be based for a large part on the ODD in combination with relevant route information, for example using information from HD maps such as TomTom RoadCheck. Such estimations can be improved by using vehicle sensor information. In future traffic scenarios sensor ranges could even be extended through technological advancements such as cooperative perception prediction (Kim et al., 2013; Naujoks et al., 2015; Rauch et al., 2012). In addition to the LED-bars depleting with decreasing time left in the current mode/time to the next mode, only half the length of the LED-bar was employed in CM and SB while the full length was employed in M and TtS to communicate that the driver needs to be able to take over from the automation in a relatively short period of time in CM and SB.

Additionally, one long rectangular display was implemented in the dashboard (Fig. 2) consisting of three sections (from left to right): 1) one section straight in front of the driver; 2) one next to the steering wheel; and 3) one in line with the center console. The section straight in front of the driver (Fig. 3) continuously displayed a timer representing the time left in the current mode/time to the next mode when automation is activated (i.e., while driving in CM, SB and TtS). Moreover, this section displayed an icon indicative of the current mode. The timer and mode icon are presented on a schematic representation of a road which has the color of the current mode and shows the color of the next mode coming up when a change in driving mode is imminent. On the lower right, one icon for ACC and one icon for LKA were presented that only lighted up while driving in CM, as only in CM these driving assistance technologies are activated. Additionally, the display showed navigation information (e.g., an arrow and '6 KM' when going straight for 6 km), speed and an icon for warnings.

The section of the rectangular display next to the steering wheel showed more detailed navigational information, including a map. The route was indicated on the map in the color of the current mode and showed the color of the next mode coming up from the point at which this next mode will be active/available (for further details see also Fig. 7 for a depiction of how this was communicated at the end of Phase 3; note, however, that this communication looked slightly different in Phase 2 than at the end of Phase 3). The idea is that the driver can request the map to provide an overview of the complete route with the parts highlighted in the color of the mode which will be active/available during that part of the route.

The rectangular display's section in line with the center console was designed as being dedicated to infotainment. It displayed icons of apps that are both available and unavailable in the current mode. The unavailable app icons were grayed out (i.e., in M and CM only phone calls, music, navigation and settings are available, while in SB and TtS social media apps, internet and email are additionally available). The section next to the steering wheel also becomes dedicated to infotainment in TtS. These design choices were made to indirectly emphasize the responsibilities of the driver during the current driving mode in order to nudge the driver in what s/he should (not) do. Additionally, this section of the display presented an icon of the automation mode and information on temperature and time.

A head-up display (HUD) was included as another component of the HMI. The HUD showed navigation information in M, CM, and SB. This information was not displayed in TtS, in order to nudge the driver in paying more attention to the driving task in M, CM, and SB than in TtS.

Another component of the HMI was the shifter (the shifter is visible in Fig. 1; see also Fig. 8 on the left for a depiction of the shifter at the end of Phase 3 with further details; note, however, that the shifter looked slightly different at the end of Phase 3 than in Phase 2). The shifter communicated which mode is currently activated through its color, its position and through the highlighted abbreviation.

Fig. 2. The three sections on the long rectangular display (from left to right: (1) in front of driver, (2) next to steering wheel and, (3) in line with the center console) of the HMI's display and the head-up-display (HUD) in 'Stand-By' (SB), as designed in Phase 2.

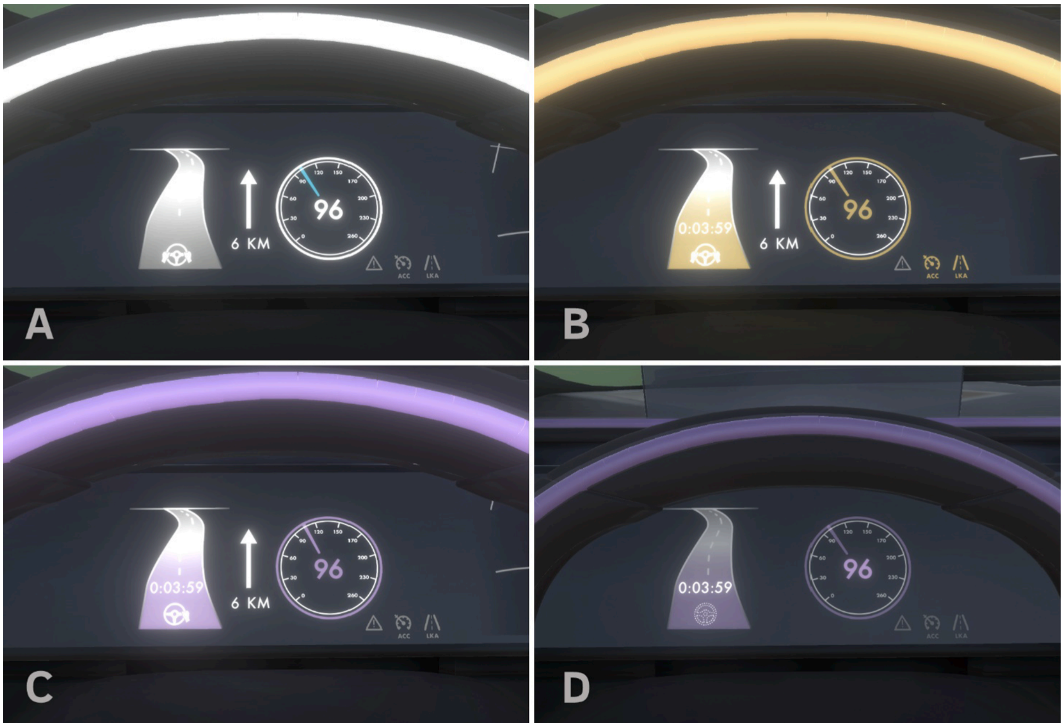

Fig. 3. The section of the HMI's display straight in front of the driver, as designed in Phase 2. A: The display is communicating the 'Manual' (M) mode. B: 'Continuous Mediation' (CM). C: 'Stand-By' (SB). D: 'Time-to-Sleep' (TtS).

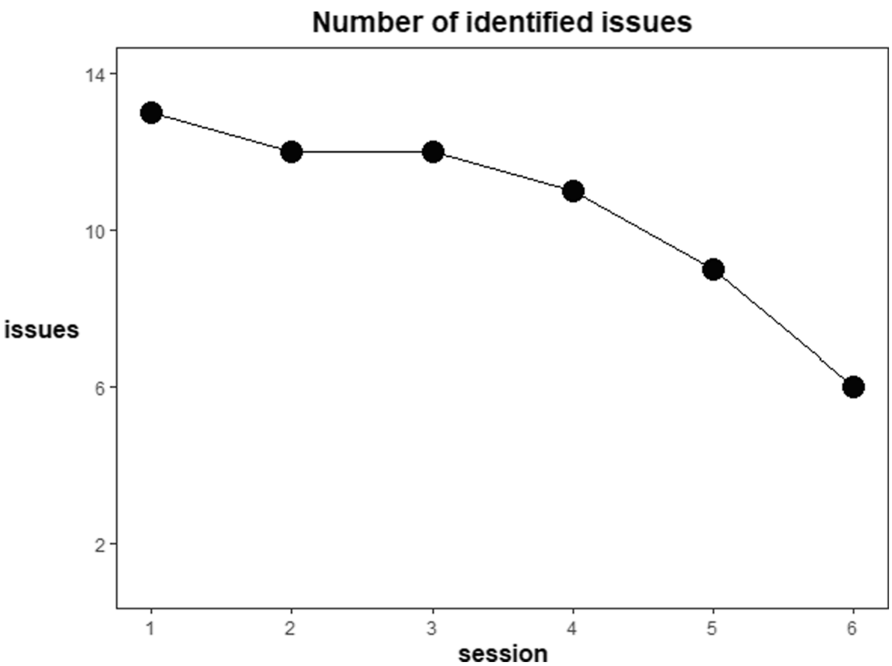

Fig. 4. Overview of the number of issues identified by the team members per session.

The abbreviations were matched to the manual drive pattern that people are currently used to (i.e., D-N-R-P) and to the labels employed to communicate the driving modes to the driver. The following abbreviations were used for the shifter: D (Manual), D_A (Assisted driving) and D_P (Piloted driving).

The last component of the HMI was the steering wheel. In TtS the steering wheel was moved away from the driver, to subtly indicate

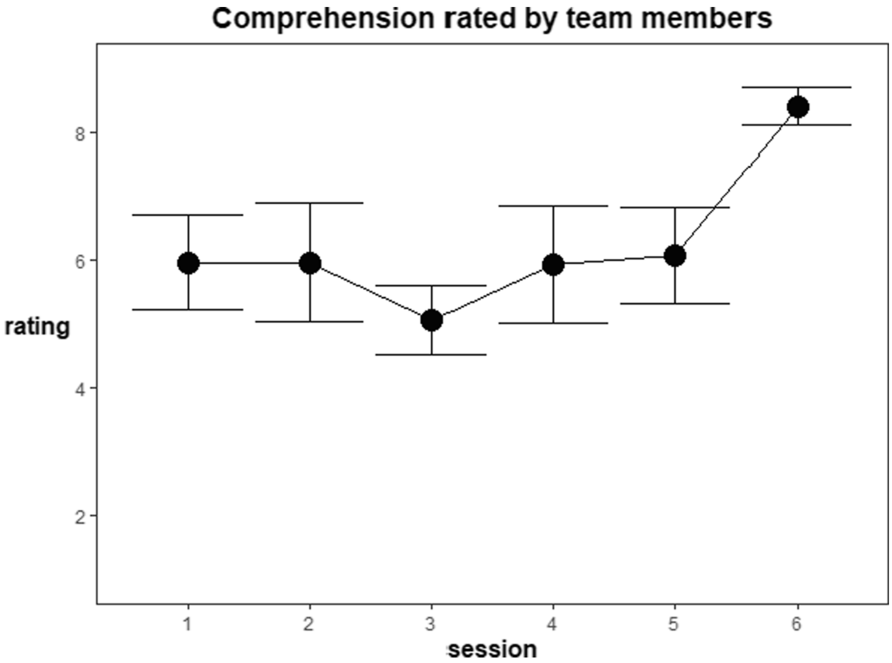

Fig. 5. Overview of the level of comprehension (on a scale from 1 to 10) rated by the team members per session. Error bars represent standard error of the mean.

Fig. 6. The HMI design in the four different modes resulting from Phase 3 (stills from the VR environment). The design is communicating the 'Manual' (M) mode in the upper left picture, 'Continuous Mediation' (CM) in the upper right picture, 'Standby' (SB) in the lower left picture and 'Time-to-Sleep' (TtS) in the lower right picture.

that in this mode the driver doesn't have the responsibility to steer and will not need to carry out this responsibility for a relatively long period of time. The steering wheel was in its original position in M, CM and SB, in order to nudge the driver in paying more attention to the driving task during these automation modes.

Fig. 7. The three sections (in front of driver, next to steering wheel and in line with the center console) of the HMI's display and the head-up-display (HUD) in 'Continuous Mediation' (CM) with 'Standby' (SB) becoming available in 15 s, resulting from Phase 3.

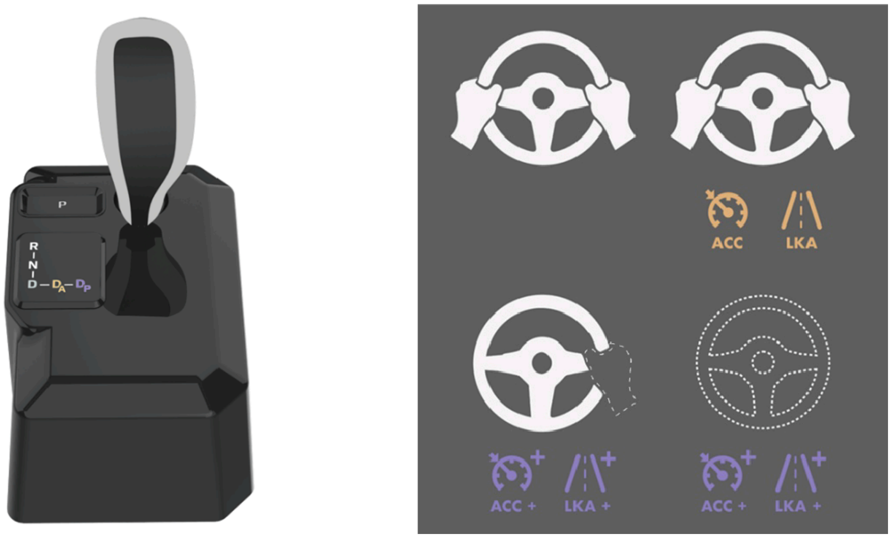

Fig. 8. On the left: The redesigned shifter resulting from Phase 3. On the right: The redesigned mode icons and ACC(+) and LKA(+) icons resulting from Phase 3 for 'Manual' (M) on the upper left, 'Continuous Mediation' (CM) on the upper right, 'Stand-By' (SB) on the lower left, and 'Time-to-Sleep' (TtS) on the lower right.

4. Phase 3: Evaluating and improving design

In Phase 3 the HMI design resulting from Phase 2 was evaluated and improved upon using the RITE method (Medlock et al., 2002). RITE stands for Rapid Iterative Testing and Evaluation. This method allows for rapidly iterating on a prototype by focusing on fixing designs rather than just finding problems. RITE has been originally developed in the context of software development (Medlock et al., 2002). The method has, however, also been applied successfully to develop effective visual communication ranging from videos and animations for health education (Adam et al., 2019; Kayler et al., 2020; Kayler et al., 2021) to effectively visualizing brain activity data (Pike et al., 2012) or other sensor data (Bock et al., 2016) to even making an effective report including its content and layout (Skelton et al., 2017). Moreover, the RITE method is a good solution to researching a potential design space that is quite large for traditional experimental methodology (Medlock et al., 2005). In the case of the current design, the design has many elements and each element can be shaped in many different ways. A traditional experimental study would entail manipulating one or two elements with two to three different ways in which they are shaped. Using such methodology would provide interesting knowledge but would be limited in evaluating a holistic design and would not be focused on improving the design. Therefore, for the purposes of the current work, the RITE method was considered to be more suitable than a traditional experimental method.

In general, as described by Medlock et al. (2002, 2005) the RITE method involves evaluating a design with 1–3 participants (e.g., through errors or think aloud), making changes to the design when an issue and the solution to the issue are clear and then evaluating the improved design again with 1–3 participants, etc. Issues and solutions should be identified by a team of observers and should be evaluated against the critical thinking ability of the observers. This team should involve product decision-makers, including people that are able to make changes quickly to the design, people with strong knowledge of the design, and people with expertise on the domain and problems typically experienced in the domain. The team should agree on changes to be made and should agree on when a sufficient performance is reached by the design. All these recommendations for applying the RITE method were taken into account in the current study to ensure its successfulness.

4.1. Methods

4.1.1. Participants

Eighteen participants, eleven female, seven male, mean age = 33.06 years, *SD* = 13.85, min = 21, max = 66, were included in the study for Phase 3. All participants had a valid driver's license (for an average of 6.89 years, *SD* = 3.53) and had no history of epilepsy. The study was approved by the Research Ethics Committee of the Dutch Institute for Road Safety Research (SWOV).

4.1.2. Apparatus

The HMI design (including visual and auditory information) was presented in VR using an Oculus Quest 2 (resolution: 1832 × 1920 pixels per eye, refresh rate: 90 Hz) and Unity 3D 2020.2.6f1. Using VR allowed for a realistic visual experience with the HMI design (see also the stills from the HMI design in VR in for example Figs. 1, 6 and 9), and for inducing the feeling of the virtual car with the HMI design moving on a (simplistic) road. Moreover, using VR combined with Unity 3D allowed for quickly implementing changes to the design.

Fig. 9. An example of the start-up sequence in 'Continuous Mediation' (CM). Upper left and upper right: The first and second picture of the start-up sequence respectively. Lower left and lower right: The third and fourth picture of the start-up sequence respectively.

4.1.3. Measures

4.1.3.1. Think-Aloud.. The concurrent think-aloud method (Eccles & Arsal, 2017) was applied to gain insight into how the HMI design was experienced and understood by participants. This method entails participants speaking aloud anything that comes to their mind during a certain task. The concurrent think-aloud method has been demonstrated to validly provide insight into participants' thinking (Charters, 2003) and has been recommended as a way to gain insight into the experience of a design when using the RITE method (Medlock et al., 2005). Moreover, this procedure has proved to be effective in gaining insight into the understandability and usability of information communicated by HMI design in a previous study by Tinga et al. (2022).

4.1.3.2. Semi-Structured interview. A semi-structured interview was conducted asking participants about what aspects of the HMI design were difficult to understand and what aspects facilitated understanding of the status of the automation and of the responsibilities as a driver. It was also asked why the mentioned aspects were difficult to understand or facilitated understanding. Additional questions were asked about the meaning of specific aspects of the HMI design, including the ambient light, the icons, the length of the LED-bars and the timer. Finally, participants were asked what they thought could be improved in the design to facilitate their understanding of the communicated information.

4.1.3.3. Questionnaires. The ITC-SOPI spatial presence scale and negative effects scale (Lessiter et al., 2001) were used to evaluate whether a sufficient feeling of presence was induced in the virtual environment without inducing negative effects (on a scale from 1 – 5). This evaluation was considered to be of importance, as a sufficient feeling of presence (without experiencing negative effects such as dizziness and nausea) would support the validity of the findings in the current study. Participants were asked to rate on a scale from 1 – 5 to what degree the HMI supported their understanding of the status of the automation, their understanding of their responsibilities, their understanding of when they needed to pay attention to the road or focus attention somewhere else. The System Usability Scale (Brooke, 1986) was used to gain insight into how participants rated the usability of the HMI design. This scale measures system usability from 0 to 100. Moreover, participants rated to what degree the HMI design supported understanding of the status of the automation, their responsibilities as a driver, when they needed to pay attention to the road and when they were allowed to do something else than pay attention to the road on a scale from 1 to 5. The shortened NASA-TLX (Hart & Staveland, 1988) was used to gain insight into information load induced by processing the presented information by the HMI design, with each of the items rated on a 100-points range with 5-point steps.

The ITC-SOPI spatial presence scale and the NASA-TLX were shortened for the purpose of the current study. A few items were discarded that were not applicable to the current study. In this way, only applicable items were answered by the participants. This approach is applied more often in research (e.g., Hart, 2006; Tinga et al., 2022; Tjon et al., 2019). Regarding the NASA-TLX, three items on mental demand, temporal demand and frustration level were selected. Regarding the ITC-SOPI, five items on spatial presence were selected, omitting the items of the spatial presence scale focusing on physical interaction, following Tinga et al. (2022) and Tjon et al. (2019). In this way, items were excluded which do not apply to a passive task such as receiving information through HMI design.

Additionally, questions on demographics (i.e., age, sex) and driving experience (i.e., years of having a driver's license, kilometers driven each year, whether someone has a car with automated functionalities such as LKA, ACC) were used.

4.1.3.4. Predefined evaluation items. Participants were observed by a team according to predefined evaluation items. These items involved each team member individually writing down mistakes made and issues experienced by the participants and any other remarkable observations. Moreover, after each tested participant, questions were answered individually by each team member about what issues are underlying the mistakes that were made by the participant and the level of comprehension in each mode was rated on a scale from 1 to 10 (with 1 representing the lowest and 10 representing the highest level of comprehension). After testing three participants, each team member individually answered to questions about what issues were applicable to mistakes made by the participants, potential solutions to these issues and whether the team member thinks that another iteration on the HMI design is needed.

4.1.4. Procedure

The study involved multiple sessions each involving a team consisting of the HMI lead-designer, a designer and expert on the VR implementation of the design and an expert in human factors in vehicle automation. The members of the team have also been involved in the previous phases of the HMI design (and they were also part of the core team in Phase 2) and had a good understanding of the HMI design and its purpose.

Following recommendations for applying the RITE method (Lewis et al., 1991; Medlock et al, 2002 and 2005; Wixon, 2003), each session followed the following steps:

1. Testing the HMI design with three participants while all members of the team observed and (individually) evaluated the performance according to the predefined evaluation items.
2. Only after having tested three participants the team members discussed their findings and potential solutions together. When every team member believed that no other session is needed, the end goal was reached and the final design was reached. Alternatively, the end goal was reached when a maximum of seven sessions had been reached. As long as that was not yet the case, the next steps were followed.
3. The team made a list together of all identified issues, to come to an agreed upon list of issues.

4. Together the team decided for each identified issue: 1) is the issue clear? 2) what is the solution to the issue and is the solution to the issue clear? 3) can the solution be implemented before the next round of testing? If these three questions could be answered with 'yes', the solution was implemented. If too many issues and solutions were identified, it was decided which solutions would be implemented in the next version. If a solution could not be implemented before the next round of testing it would be implemented as soon as there was enough time in between two rounds of testing.
5. The solutions that were decided on to be implemented in the next version were implemented.
6. As soon as the implementations were finished the steps above were followed again.

Each test started with the participant providing informed consent. The participant then received information about automated vehicles. This information included that the degree to which the driver has to control and supervise the automated vehicle is dictated by the capabilities of the automated vehicle and that these capabilities and therefore the driver's responsibilities can change from moment to moment, even within a single ride. Moreover, the information included examples of what this could entail in practice (e.g., the driver needs to execute the complete driving task at one time as the automation cannot handle the driving task, while at another time the driver could focus attention on other activities such as watching a movie as the automation can handle the driving task). Note that at no point during the experiment any information was provided about elements of the HMI design and their meaning.

Participants also received instructions on the think-aloud protocol, that they also received when an appointment for the experiment was made to already familiarize themselves with the protocol. In these instructions the participant was asked to verbalize everything s/he is seeing and thinking, acting as if s/he is alone in the room speaking to him- or herself (following Eccles & Arsal, 2017; Jaspers et al., 2004). Moreover, the participant was informed that the experimenter would remain silent except for reminding the participant to keep talking when needed (following Jaspers et al., 2004). The instruction also included an example of how one would think aloud when searching for what one would like on his/her sandwich in the kitchen. A different setting was used in the example to avoid priming participants on content of a similar context as provided in the experiment. A similar approach to train the think-aloud protocol has been used by Key et al. (2016) and Tinga et al. (2022).

Next, the VR headset was set-up and a familiarization scene was shown to ensure a correct set-up and to accustom the participant to VR. In this familiarization scene the interior of the virtual car that would also be shown during the actual experiment was presented. However, no informative HMI elements were visible yet.

The four different modes were then shown in VR while the participant was thinking out loud and while the three team members were observing and evaluating. The order in which the four different modes were presented did not include three or more successive automation modes (either from highest to lowest or vice versa), to prevent participants from interpreting the design based on any order information. Block randomization (Goodwin, 2009) was used to ensure each participant was presented with 1 of 18 possible orders. Each mode was shown for three minutes, with a break of 30 s in between modes. During presentation of the modes, the experimenter prompted the participant to try to keep talking after the participant fell silent for a fixed interval of 15 s (following Jaspers et al., 2004). When presentation of a mode ended the experimenter asked the participant whether s/he wanted to mention anything else. In order to minimize practice effects, no feedback on the participant's thinking aloud and no further instruction was given (following Rose et al., 2019). After being presented with all four modes, the participant answered to the questionnaires, followed by the questions of the semi-structured interview. All three team members also observed and evaluated the semi-structured interview.

4.2. Data processing and analyses

The data resulting from Phase 3 consisted of: 1) team members' evaluation, 2) participants' questionnaires, and 3) the implemented solutions and remaining issues. Regarding the team members' evaluation the number of identified issues per session and the average (and standard deviation) rated comprehension over all the modes per session were computed. For the questionnaires answered by participants averages (and standard deviations) for the first and last session were computed and evaluated in light of ratings obtained in previous studies. Data on implemented solutions and remaining issues were summarized. Note that no tests to determine statistical significance were applied on the data, as this was not deemed appropriate with a sample size of three participants per session.

4.3. Results and discussion

A total of six sessions were conducted, as in the sixth session all team members agreed that no other iteration was needed using the set-up of the current study. The outcomes of the six sessions will be presented and discussed below.

4.3.1. Team Members' evaluation

The number of issues identified by all team members together over the six sessions across all modes is depicted in Fig. 4. From the first to the last session the number of identified issues decreased from 13 to 6. The number of issues especially decreased during the last sessions, potentially because the team members already had the opportunity to observe the effect of implemented solutions multiple times and gained a better understanding about the type of solutions that could be effective. However, some issues remained after the last session of which the team members thought they should not be fixed by making changes to the design, but that should be addressed through other means. This will be addressed in more detail in the section 'Implemented Solutions and Remaining Issues'.

The level of comprehension (on a scale from 1 to 10, with 1 representing the lowest and 10 representing the highest level of comprehension) as rated by the team members individually over the six sessions across all modes is depicted in Fig. 5. From the first to the last session the average rated level of comprehension increased from 5.97 ($SD = 2.22$) to 8.42 ($SD = 0.90$). In the last session, each team member rated each participant's comprehension with at least 7.50 on average across all modes.

4.3.2. Participants' questionnaires

Participants rated spatial presence during the experiment on average with 3.57 (*SD* = 0.77), while rating negative effects on average with 1.74 (*SD* = 0.65) on a scale from 1 to 5. These obtained ratings indicate a similar feeling of presence as in earlier experiments in VR (Tjon et al., 2019) without inducing strong negative effects. These findings suggest that the feeling of presence was sufficient and that the data was largely unaffected by negative effects.

The support in understandability provided by the HMI was rated by participants on average with 3.83 (*SD* = 0.14) on a scale from 1 to 5 in Session 1. In Session 6, the rating was slightly higher with an average of 3.92 (*SD* = 0.72). These ratings indicate a relatively good understanding, especially in Session 6, as they are in the same range as the ratings for an HMI that was best understood in a previous study (Tinga et al., 2022).

System usability ratings increased from 66.67 (*SD* = 3.82) on a scale from 0 to 100 in Session 1 to 78.33 (*SD* = 18.93) in Session 6. This indicates that system usability increased from satisfactory to good (following Lewis & Sauro, 2018) from the first to last session.

Task load ratings showed a slight increase from 17.08 (*SD* = 13.37) on a scale from 0 to 100 in Session 1 to 18.33 (*SD* = 11.88) in Session 6. Note, however, that these scores indicate a relatively low task load in both sessions when comparing these scores to previous studies. Grier (2015) examined 237 publications in which task load was measured using the NASA-TLX. It was found that the measured load without any task was 12.00 or 14.80 and that averages across all types of tasks ranged between 45.29 and 48.74. Moreover, the standard deviation values in the current study indicate the variation in responses is rather high and therefore the slight increase from Session 1 to Session 6 might not be meaningful, pointing towards a relatively low task load in both sessions.

4.3.3. Implemented solutions and remaining issues

The HMI design in Session 6, and therefore the design that resulted from Phase 3, is depicted in Figs. 6-9. As solutions to identified issues in the previous sessions were implemented, this HMI design differs in several key aspects from the HMI design resulting from Phase 2 (see Figs. 1-3 for images of the design in Phase 2). First, the LED-bar on the dashboard was removed, as participants were sometimes confused by having two LED-bars and did not always understand that the two were linked. This resulted in one LED-bar on the steering wheel remaining. Second, while driving in M, the LED-bar and the light of the logo on the steering wheel were turned off to make it clearer that no automation systems were active. In line with this adaptation, the logo's light was turned on in the TtS mode (as well as in CM and SB) to indicate that the automation is active. Third, as soon as the LED-bar started to deplete to indicate a change in mode coming up, the outer sides of the LED-bar started to pulsate, a gently alerting sound was played, and the timer started to pulsate in synchrony with the LED-bar. This solution was implemented in order to prevent the depleting LED-bar being unnoticed and to enhance understanding about the relationship between the timer and the LED-bar. Fourth, the size of the mode icons was increased, an outline was added to these icons and the abbreviation of the mode in the color of the mode was added below the mode icon on the screen dedicated to infotainment. These adaptations were made in order to increase the mode icons' visibility to ensure they are being noticed. Fifth, in the design resulting from Phase 2 the ACC and LKA icons were only turned on in CM mode. It was confusing to people that these icons that indicate automation functionalities being activated were turned off during the modes SB and TtS. Therefore, in the design resulting from Phase 3 the icons turned also on during these automation modes, but with a '+' being visible next to the icons (Fig. 8 on the right), indicating more advanced automation technology being activated. Sixth, the mode icon in SB depicting one hand on the steering wheel was altered by displaying the one hand on the steering wheel in gray and with a doted outline instead of displaying the hand in solid white (Fig. 8 on the right). This solution was incorporated with the aim to prevent literal interpretation of the icon in which people think they have to keep holding the steering wheel with one hand. Seventh, to ensure mode icons being noticed and to enhance the understanding of what information of the HMI is related, a 'start-up sequence' was implemented. This sequence was presented when a new mode is activated. The sequence is depicted in Fig. 9. At the start of the sequence, the mode icon of the current mode was being presented together with the ACC(+) and LKA(+) icons (if applicable) in the colors of the current mode on the HUD. Together with this information a voice message was being played that tells which mode is being activated and this message was displayed additionally in text on the HUD. The mode icon on the HUD was being alternated with the abbreviation of the mode in the color of the mode in 6 s for the complete duration of the start-up sequence. This change was implemented to not only ensure the mode icon being noticed, but also to ensure the abbreviation of the mode was being understood. Next, the mode icons appeared on the instrument cluster, and the ACC and LKA icons (if applicable) next to the speedometer and the abbreviation below the shifter lighted up in the color of the mode. Next, the speedometer, the road icon, and the LED-bar and ambient light gradually got the color of the mode and lighted up in addition to the timer being presented. As a final step in this start-up sequence, the icons on the infotainment of apps that were available became visibly clickable and the information on the HUD disappeared. The complete start-up sequence lasted 20 s.

In addition to these key changes in the HMI design, some minor aspects changed. In the design resulting from Phase 3 compared to the one resulting from Phase 2 fewer navigational details were presented and the navigation display has been redesigned in order to present all navigational information gathered on the central display. Moreover, the shifter was also adapted (Fig. 8 on the left), including that non-selected abbreviations were in the color of their respective mode. Additionally, the movement of the wheel moving away from the driver in TtS was exaggerated to enhance the movements visibility.

Despite of the improvements resulting from the implemented solutions, six issues remained in the last session. For these issues it was not deemed useful to implement additional solutions in the design in another iteration. This will now be explained for each remaining issue. First, even though the movement of the steering wheel moving away from the driver in TtS was exaggerated in the final design, the movement was not always noticed. This might be due to limitations of (the perspective in) VR. This type of movement will probably be noticed when it would occur in a physical car. If the noticeability would still be an issue with actual implementation in a physical car, one could consider to additionally tilt back the backrest of the chair for example. Further testing would be needed to establish the effects of the movement of the steering wheel and/or the backrest in a physical car.

Second, even though the mode icon in SB depicting one hand on the steering wheel was adapted in order to prevent literal interpretation, this issue was not completely avoided by this adaptation. It was decided not to make any further alterations, as the icon also facilitated understanding that still some attention to the driving task was needed. Literal interpretation can probably be prevented when the meaning of the icon is explained or learned.

Third, the LKA(+) and ACC(+) icons, and namely the abbreviation, were not understood by every-one. However, participants that were familiar with these automated functionalities (including just having heard about it) did understand this. The expectation is therefore that this issue will be nonexistent when these functionalities are explained or learned.

Fourth, the mode icons were not always noticed, even after making these icons larger, adding an outline to these icons, and presenting them on the HUD in the start-up sequence. The team members all thought that there should be no additional alterations being implemented to enhance the icons' visibility, as then it could distract or even block other important information. Moreover, with the final design, the mode icons facilitated understanding about the current mode when they were noticed, but even when a mode icon remained unnoticed, the other HMI elements did effectively communicate the mode.

Fifth, the difference between the employed length in LED-bars between TtS (full length) and CM and SB (half length) was not always noticed or understood. The question here is whether it is necessary to consciously notice and understand this difference. Participants did comprehend the differences in responsibilities between modes and that when the LED-bar depleted that an imminent change would require them to pay attention. Therefore, the main goal of the LED-bar was achieved and findings imply that potentially people will be (unconsciously) somewhat more alert when only half the length of the LED-bar is employed. Yet, this should be experimentally examined in more detail to be sure about this.

Finally, the sixth and last issue, the timer was sometimes linked to navigation, with participants thinking that in X minutes and X seconds they needed to pay attention because they or the automation need(s) to, for example, take a turn to a different road when the navigation indicates that a turn will come up. Yet, the navigational information shown in the design was not intended in this way. Although it is not an unplausible thought of participants that they need to pay attention due to road conditions. Additionally, as participants at least understood that attention was needed when the timer was almost hitting 00:00, this was not seen as a major issue. Again, this might be something that needs to be learned by people. Moreover, if actual transfers between modes would be experienced this will probably facilitate understanding about the communicated time left in the current mode/time to the next mode. Yet, the exact effects of experiencing actual transfers needs to be examined in future work.

5. General discussion

The current study described the development and evaluation of an HMI for continuous support of mode awareness during driving in different automated driving modes within a single trip. The development and evaluation occurred in three phases. In Phase 1 functional requirements for the HMI design were defined based on a literature review and five experimental studies including a total of 146 participants. This resulted in eight functional requirements to ensure mode awareness in different automation modes.

In Phase 2 the functional requirements were implemented in an HMI design through expert and focus group sessions over the period of about one year. The result was an HMI design that was endorsed by the experts involved in this phase.

Finally, in Phase 3 the HMI design was evaluated with a total of 18 participants and improved upon employing the RITE method (Medlock et al., 2002). The resulting final HMI design is presented in detail in the section 'Implemented Solutions and Remaining Issues' (see Fig. 6 for an overview in the different automation modes). The final HMI design is continuous and holistic and creates mode awareness through ambience. The outcomes of the evaluation of the final design indicate that the information communicated by the HMI was comprehended well as demonstrated by an increase in comprehension ratings and subjective understandability from Session 1 to 6 and the number and nature of the remaining issues. Additionally, subjective understandability was comparable to an HMI design for automated vehicles that was best understood in a previous study (Tinga et al., 2022). Moreover, compared to ratings of task load in 237 previous publications (Grier, 2015), the final design induced a relatively low task load. Finally, the final design had a good system usability (following Lewis & Sauro, 2018).

Yet, several issues remained with the final HMI design that were all thought to be unsolvable through changing the design in the set-up of the current study. These issues were considered to be potentially resolvable by the team involved in the evaluation in Phase 3 when the HMI design is being implemented in a physical car and by providing drivers with instructions about and/or more experience with the HMI. When the HMI is implemented in a physical car, issues that were thought to be related to limitations of (the perspective) in VR are expected to be solved. With instructions and/or more experience issues related to comprehension, such as not understanding the meaning of ACC and LKA or literal interpretation of the mode icon in SB depicting one hand on the steering wheel, might be solved. Future work could, however, also consider alternatives to certain HMI elements. For example, other types of mode icons have been proposed such as emoticons expressing (un)certainty of the automation (Beller et al., 2013) or a depiction of a car emitting a color reflecting the current mode (Lu et al., 2019). Note that in the current study no information about the HMI elements and their meaning was provided at all. This was valuable in designing the information to be as intuitive as possible. Yet, to ensure understanding in all drivers it is foreseen that a first-time user of the HMI should be guided by the HMI through its functionalities and how these functionalities relate to the capabilities of the automation and his/her responsibilities as a driver. Future work should examine guiding the driver through the HMI's functionalities, for example in an onboarding routine, to establish its exact effects.

In the current study's evaluation of the HMI no actual transfers between modes were experienced, as the focus was on ensuring mode awareness while driving in different automation modes. Yet, when different automation modes are experienced in an actual on-road implementation, the driver will also experience transfers between modes. The team involved in the evaluation in Phase 3 expected that the actual experience with mode transfers will aid in understanding the communicated information. For example, the information on the time left in the current mode/time until the next mode (i.e., communicated by the timer, the road icon and the length of the LED-bar) could be clearer when the driver has experienced what will happen when time runs out. Within the EU-project MEDIATOR HMI transfer rituals are designed and implemented that are in harmony with the way in which the HMI design communicates in ensuring mode awareness. For example, it is foreseen that when driving in M and CM becomes available the driver is informed about this (through the amber color of the CM mode showing up on the road icon and on the navigation map). When the driver confirms s/he wants to drive in CM, CM becomes activated and the start-up sequence as discussed in the section'Implemented Solutions and Remaining Issues' and as depicted in Fig. 9 is presented to the driver. Yet, the exact effects on mode awareness when also experiencing transfers between modes needs to be examined in future work. This can for example be done in a study comparable to Phase 3 of the current study, but by additionally coupling a physical steering wheel, a shifter and brake and gas pedals with the virtual environment (similar study setups have been proposed, e.g. Riegler et al., 2019a; Riegler et al., 2019b). Mode transfers can then be presented in addition to driving in the different modes and participants can respond to these transfers through the added physical components.

While the current study was focused on supporting mode awareness through HMI design, an HMI can also be valuable for other aspects. The MEDIATOR project focusses on developing an HMI that does not only assure mode awareness, but that also takes into account whether the driver or automation is fittest to drive through for example assessing driver fatigue or inattention and assessing the capabilities of the automation. It is important to assess whether mode awareness is still assured when the HMI also supports other aspects and whether those other aspects are also effectively addressed by the HMI.

Within the MEDIATOR project the current study's HMI design will be implemented in actual prototypes and these prototypes will be evaluated in driving simulators as well as in on-road tests. Such tests will provide an opportunity to verify and expand on the current study's findings and to address the effectiveness of the HMI design in supporting aspects in addition to mode awareness. The results of these tests will contribute to guidelines that can support future HMI design for automated vehicles.

Author statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication.

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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

The authors do not have permission to share data.

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