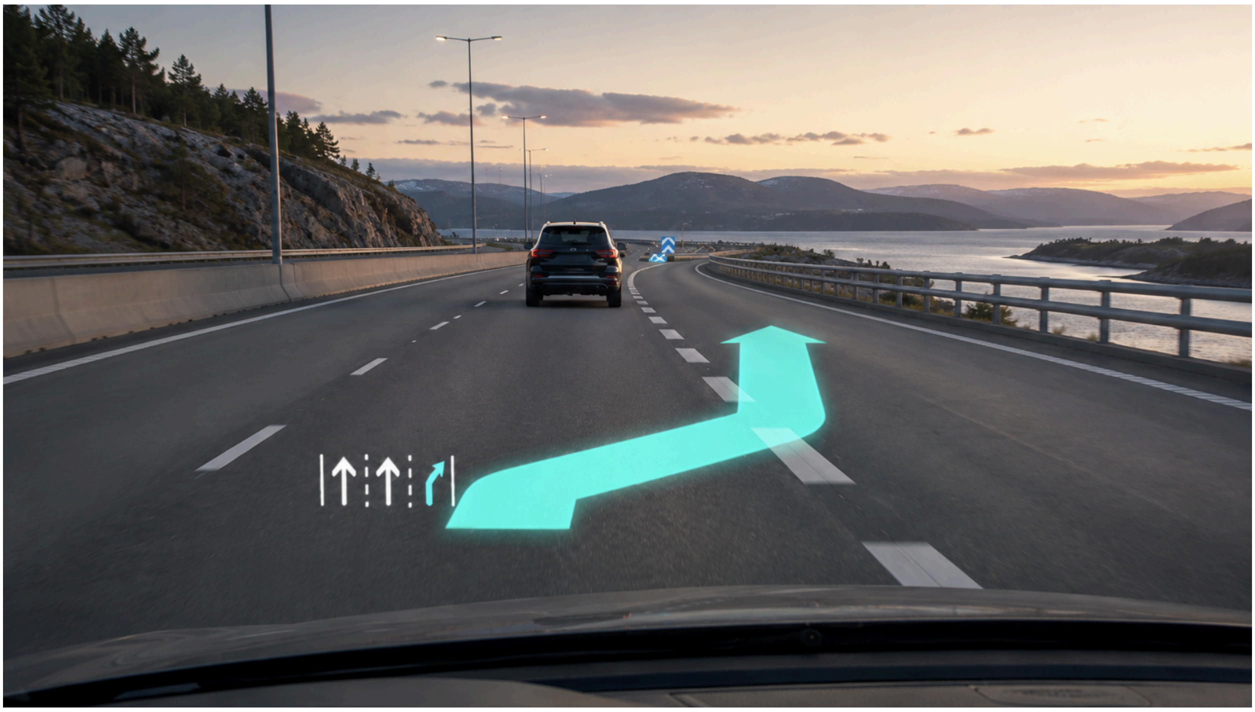

Interaction Design of Augmented Reality Head-Up Displays and Its Impact on Driver Behaviour

User study for Augmented Reality Head-Up Displays

Master’s thesis in Computer Science and Engineering

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Gothenburg, Sweden 2026
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Cover:
[An enhanced illustration of this thesis' designed AR-HUD visualisation through the windshield.]
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Abstract

As modern vehicles become increasingly digitalised, drivers are exposed to a large amount of information through in-vehicle displays and navigation systems. While these systems are designed to support driving, they may also contribute to visual distraction and increased cognitive workload. Augmented Reality Head-Up Displays (AR-HUDs) have emerged as a potential solution by presenting navigation information directly within the driver's forward field of view (FoV), with the aim of supporting more intuitive and road-focused interaction.

This master's thesis, conducted in collaboration with Volvo Cars Corporation, investigates how AR-HUD navigation visualisations influence driver behaviour compared to a non-HUD condition during real-world driving. The study focuses on visual attention distribution, perceived workload, situation awareness and user experience. A mixed-methods approach was applied, combining eye-tracking, raw NASA-TLX, SART-inspired questionnaires and semi-structured interviews. A within-subject design was used with 20 participants, where each participant experienced both AR-HUD and non-HUD conditions across two driving routes.

The results indicate that the AR-HUD condition reduced perceived workload, particularly in terms of mental demand, effort and frustration. Eye-tracking results further showed reduced visual attention toward the Center Stack Display (CSD), suggesting more road-focused visual behaviour. Participants also described the AR-HUD as intuitive, supportive and easier to follow during navigation tasks. In addition, the AR-HUD improved navigation confidence and understanding of guidance information, especially in more complex driving situations. However, the findings also indicate that system effectiveness is dependent on design factors such as timing, spatial positioning and information density.

Overall, this study provides empirical insights into AR-HUD use in real-world driving and contributes knowledge relevant to the design of future in-vehicle navigation systems aimed at improving driver attention, workload and user experience, which could increase safety.

Keywords: *Interaction Design, Augmented Reality Head-Up Display, Eye-Tracking, User Experience, Automotive, Driver Behaviour, Visual Attention, Cognitive Load, Situational Awareness, Safety*

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Firstly, we would like to express our deepest gratitude to our supervisor, David Hermann, from VCC. His guidance, support and knowledge within display systems have been invaluable throughout this thesis. His feedback helped shape both the technical development of the AR-HUD prototype and the direction of the user study.

We would also like to thank our academic supervisor, Thommy Eriksson, at Chalmers University of Technology, for his valuable advice and feedback during the project. His guidance supported the academic quality of the thesis and helped us reflect on our work from a broader research perspective.

A special thank you goes to the researchers and collaborators within the SCREENS II project at RISE. Their expertise and support contributed greatly to the eye-tracking analysis.

We would like to thank all participating drivers. Their involvement in the user study made it possible to collect data and evaluate the AR-HUD prototype in a real-world driving context.

We are also grateful to our examiner, Jasmina Maric, at Chalmers University of Technology, for her feedback and for assessing our work.

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Ida Allander, Sana Hassan, Gothenburg, 2026-05-29

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List of Abbreviations

AI	Artificial Intelligence
AOI	Area Of Interest
AR	Augmented Reality
AR-HUD	Augmented Reality Head-Up Display
CSD	Center Stack Display
DIM	Drivers Information Module
FoV	Field of View
HDD	Head-Down Displays
HMI	Human-Machine Interface
HUD	Head-Up Display
NASA-TLX	NASA Task Load Index
RISE	Research Institute of Sweden
SART	Situation Awareness Rating Technique
UX	User Experience
VCC	Volvo Car Corporation
VID	Virtual Image Distance

1. Introduction

Road traffic injuries are one of the leading causes of death worldwide. According to the World Health Organization (WHO), approximately 1.19 million people die each year due to road traffic crashes, making road safety a major global public health challenge (WHO, 2026). Human error remains a key contributing factor to traffic accidents, where driver distraction and inattention play a central role. Even short periods of visual or cognitive distraction can negatively affect driving performance and increase the risk of a crash.

In recent decades, rapid digitalisation has changed how humans interact with complex systems across many domains such as transportation, healthcare and communication. In the automotive domain, this change has led to an increased integration of advanced in-vehicle information systems, including navigation, infotainment and driver assistance technologies. These systems aim to enhance comfort, efficiency and safety by continuously providing relevant driving information. However, if not carefully designed, they may also increase visual demand and cognitive workload, potentially contributing to driver distraction (Regan et al., 2011; Young et al., 2003).

A particular challenge arises in navigation systems, where drivers are often required to divide their attention between the road environment and Head-Down Displays (HDD), such as the instrument cluster or center stack display (CSD). During complex driving situations, including lane changes, exits and roundabouts, repeated gaze shifts toward in-vehicle displays can increase visual distraction and mental workload. This has motivated research into alternative display concepts that better support continuous road-focused attention.

To address these limitations, Head-Up Displays (HUDs) were introduced to present critical information within the driver’s forward field of view (FoV), thereby reducing the need for off-road glances. HUD technology was originally developed in military aviation, where pilots needed continuous access to flight information while maintaining awareness of the external environment (Cameron, 2015). In automotive contexts, HUDs have been adapted to support more continuous visual attention to the driving environment (Weinberg et al., 2011). Research has shown that HUDs can reduce glance frequency away from the road and help maintain driver attention on the driving scene (Le & Shi, 2025).

Building on this concept, Augmented Reality Head-Up Displays (AR-HUDs) extend traditional HUD functionality by spatially integrating digital information into the real-world driving environment. Instead of presenting information at a fixed virtual location, AR-HUD systems can overlay navigation cues, lane guidance and warnings directly onto the road scene. By aligning digital information with real-world elements, AR-HUDs may improve intuitiveness, reduce cognitive processing effort and support situation awareness by minimising the need for mental translation between interface and environment (Gabbard et al., 2014; Kim & Dey, 2020).

Despite growing industrial interest in AR-HUD technology, empirical research on its effects in real-world driving conditions remains limited. Most existing studies have been conducted in simulator or laboratory settings, which may not fully reflect the complexity, variability and unpredictability of real traffic environments. Furthermore, relatively few studies have combined objective measures of visual attention, such as eye-tracking, with subjective evaluations of workload, situation awareness and user experience.

Building on this context, this master's thesis was conducted in collaboration with Volvo Cars to investigate how AR-HUD navigation visualisations influence driver behaviour compared to a non-HUD condition in real-world driving. The study focuses specifically on navigation support and examines differences in visual attention distribution, perceived workload, situation awareness and user experience. A mixed-methods approach was applied, combining eye-tracking data, NASA-TLX workload ratings, SART-inspired situation awareness measures and qualitative interviews to provide a comprehensive understanding of how AR-HUD systems affect drivers in realistic driving conditions.

1.1 Research Question

The thesis is guided by the following research question:

How does driver behaviour differ between AR-HUD and non-HUD conditions in terms of (1) visual attention distribution, (2) perceived workload, and (3) situation awareness during real-world automotive driving?

1.2 Aim

The aim of this thesis is to investigate whether AR-HUD navigation support can influence driver behaviour by improving visual attention distribution, reducing perceived workload, and supporting situation awareness and user experience during real-world driving. The goal was to compare driver behaviour with and without AR-HUD navigation support, in order to answer the research question and better understand how AR-HUD systems affect the driving experience.

1.3 Limitations

This thesis was limited to navigation-related AR-HUD visualisations. Other types of vehicle-related information, such as speed, GPS, sensor-based warnings, ADAS functions and surrounding traffic data, were not included in the prototype. This limitation was mainly due to the technical setup, as the AR-HUD system used in this study did not have access to the vehicle's internal data and functioned as a separate prototype system. Because of this, adding real-time vehicle data would have required additional technical integration beyond the scope of the project. Due to time constraints, the prototype therefore focused on navigation support, where visual cues could be designed and controlled without direct access to the car's internal systems.

The study was also limited to two predefined driving routes and relatively short driving sessions. Therefore, the findings primarily reflect short-term interaction with the AR-HUD system rather than long-term adaptation. Additionally, the study was conducted under relatively stable weather and daylight conditions, which means that the results may not fully represent AR-HUD usage in more challenging driving environments such as night driving, heavy rain or snow.

1.4 Stakeholders

In this thesis, the two master's students, Ida Allander and Sana Hassan, planned, conducted and analysed the study. Volvo Cars Corporation (VCC) was a central stakeholder, as the thesis was carried out in collaboration with VCC and the company provided access to the vehicle, AR-HUD system and technical equipment. Chalmers University of Technology supported the academic process through supervision, examination and research guidance. Research Institute of Sweden (RISE) and the SCREENS II research initiative (Vinnova, 2023) also contributed as important stakeholders by providing valuable feedback, expertise and support during the project. Finally, the stakeholders also extend to the drivers who interact with these systems, as well as automotive engineers, designers and researchers who may benefit from the findings when developing and implementing future vehicle display technologies.

2. Background

The development of digital in-vehicle display technologies has changed the driving environment. Modern vehicles increasingly incorporate advanced systems such as Head-Up Displays (HUDs) and Augmented Reality Head-Up Displays (AR-HUDs). These systems are intended to support drivers by presenting relevant information within the forward field of view (FoV), explained in the theory section, which may reduce distraction and support safer driving. However, there is still limited empirical evidence on how these technologies affect driver attention, situation awareness and cognitive workload in real-world driving conditions.

2.1 Related Research

Previous research on automotive display systems has primarily focused on traditional HUDs and their ability to reduce off-road glance behaviour compared to traditional Head-Down Displays (HDDs). HDDs present information on screens located below the driver's line of sight, typically in the Driver Information Module (DIM) or Center Stack Display (CSD). In contrast, HUDs project information onto the windshield, allowing drivers to access information while maintaining visual attention closer to the forward road scene.

2.1.1 Driving Simulator Study

Weinberg et al. (2011) compared HUD, HDD and audio-only interfaces in a driving simulator study, focusing on how drivers interacted with in-vehicle information while driving. Their results showed that participants looked away from the road more when using the HDD compared to the HUD. On average, participants looked away from the forward roadway **11.24%** of the time in the HDD condition, compared to **2.81%** in the HUD condition. The HUD was also preferred by participants and was described as a promising alternative to HDDs, particularly when considering both task efficiency and user satisfaction.

These findings support the idea that placing information closer to the driver's forward field of view can reduce the need for downward glances and may support visual attention during driving. However, the study also highlights that HUD design must be adapted to the head-up context, rather than simply moving existing interface layouts from HDDs to the windshield. This is relevant for the present thesis, which builds on the same general principle but explores it through AR-HUD navigation visualisations in a real-world driving context.

2.1.2 User Study for In-Vehicle Displays

A closely related thesis was conducted by Le and Shi (2025) within Volvo Cars and the SCREENS II research context. Their study investigated how a conventional HUD influenced driver behaviour during real-world traffic navigation using eye-tracking in a Volvo XC60. The study compared HUD and non-HUD conditions and used a mixed-methods approach, combining gaze dwell time, NASA-TLX scores and qualitative participant feedback. Their findings indicated that the HUD reduced visual attention toward HDDs, although some usability concerns related to the navigation interface were also identified.

This thesis builds directly on that work by continuing the investigation of driver attention and in-vehicle display use in real-world driving. Both studies are connected to the SCREENS II research initiative, which provides a broader research context for studying automotive interfaces and driver behaviour. Le and Shi also acknowledged support from RISE, Smart Eye and iMotions, which is relevant since the present study used the same eye-tracking system and similar technical system for collecting gaze data.

However, the focus of the present thesis differs from their work by evaluating an AR-HUD prototype rather than an existing conventional HUD. While Le and Shi studied a production HUD in a Volvo XC60, this thesis developed and tested AR-HUD navigation visualisations in a Volvo EX90. The study design was also influenced by their work, particularly in relation to real-world testing, the use of eye-tracking and the comparison between HUD-based and non-HUD conditions. Similar route principles were used, with predefined routes containing several navigation changes, selected to create relevant situations for evaluating display support during driving.

In this way, the present thesis extends previous Volvo Cars research by moving from conventional HUD navigation support toward AR-HUD navigation visualisations. This makes it possible to explore whether more spatially integrated and dynamic visual guidance can further influence visual attention distribution, perceived workload and situation awareness during real-world automotive driving.

2.1.3 Visual Design in AR-HUD

Studies investigating AR-HUD design parameters show that small visual design choices can strongly influence how the system is perceived and used. Lopez and Moacdieh (2025) investigated opacity in car AR-HUDs and found that opacity affects both visual attention and situation awareness. Their study focused on navigation-related AR-HUD imagery and showed that AR-HUD elements need to be visible enough to support the driver, while also remaining transparent enough to avoid blocking important information in the road environment. They also highlight that there is still limited guidance for how AR-HUD visualisations should be designed, especially since factors such as opacity, lighting and background complexity can affect the level of distraction.

This is relevant for the present thesis, as the AR-HUD prototype also used navigation-based visualisations projected into the driving scene. The design therefore needed to balance visibility and subtlety, so that the arrows and symbols could guide the driver without becoming visually dominant or obscuring the road. While Lopez and Moacdieh studied AR-HUD opacity in controlled video-based scenarios, this thesis extends the topic by evaluating AR-HUD navigation support in real-world driving conditions.

Earlier work by Boström and Ramström (2014) also explored how HUDs can enhance user experience in vehicles. Their thesis developed and evaluated a working HUD prototype in a Volvo XC90, with the aim of improving how information is presented to the driver. Their findings suggest that HUDs can improve user experience when information is designed specifically for the HUD context, kept at a modest level, and adapted to support the driver's focus on the road. They also emphasise that moving suitable information from HDDs to the HUD may reduce perceived inattention and support situation awareness.

Together, these studies show the importance of designing HUD and AR-HUD content carefully. They also support the focus of the present thesis, where navigation visualisations were developed specifically for an AR-HUD and evaluated in relation to visual attention distribution, perceived workload and situation awareness during real-world automotive driving.

2.1.4 Colour in AR-HUD Navigation

Hansols (2022) also investigated interaction design for AR-HUD navigation in collaboration with Volvo Cars. The thesis focused on designing visual navigation information for AR-HUD and evaluating perceptual, attentional and safety-related aspects in a realistic driving context. One relevant finding for the present thesis concerns colour use in AR-HUD navigation. In the competitor analysis, Hansols observed that most existing AR-HUD navigation concepts used variations of blue, often with a cyan hue, for navigation elements. The report also notes that cyan has been suggested as a stable and reliable colour for HUD graphics against real-world backgrounds.

This influenced the visual direction of the present AR-HUD prototype, where cyan-blue was used for the dynamic navigation arrows. The colour choice was therefore not only aesthetic, but also motivated by previous AR-HUD design work and by the need for the navigation graphics to remain visible against the road environment. At the same time, Hansols' test drive of a Volkswagen ID3 showed that cyan graphics can become difficult to perceive when they are small or projected far away, which highlights the importance of combining colour with suitable size, contrast and timing.

2.1.5 Content in AR-HUD

Research on AR-HUDs suggests that spatially aligned visual cues, such as lane-level navigation and hazard highlighting, may enhance situation awareness and reduce the need for drivers to shift attention between the road and separate in-vehicle displays. Gabbard et al. (2014) describe automotive AR as a promising way to present driving directions, notifications and hazard cues directly on the windshield, without requiring drivers to take their eyes off the road. They also distinguish between screen-fixed and world-fixed AR graphics. World-fixed cues can appear connected to the real driving environment and may therefore be especially useful for primary driving tasks such as wayfinding and hazard detection.

At the same time, Gabbard et al. (2014) emphasise that AR-HUD design introduces several perceptual and attentional challenges. If the graphics are poorly placed, visually cluttered or not well aligned with the real world, they may obscure important road information or draw attention away from the driving task. This is particularly relevant for navigation visualisations, where the AR content needs to be clear enough to support decision-making, but subtle enough not to interfere with the driver's view of the road.

However, much AR-HUD research has been conducted in simulated driving environments or short laboratory-based studies. While these settings allow for controlled experimentation, they may not fully capture the complexity, variability and cognitive demands of real-world driving. The present thesis therefore builds on this research by evaluating AR-HUD navigation support in a real vehicle and real traffic environment, focusing on how the system influenced visual attention distribution, perceived workload and situation awareness.

2.2 Research Gap

The related research shows that HUDs can reduce off-road glances compared to HDDs, and that AR-HUDs may further support navigation by placing information closer to the real driving environment. Previous studies also highlight that design factors such as colour, opacity, timing and placement are important for how AR-HUD information is perceived.

However, the existing research is still limited. Some studies focus on conventional HUDs, while others focus on specific AR-HUD design parameters in controlled settings. Many are based on simulators, short experiments or video-based scenarios rather than real traffic. As a result, there is still a need for more knowledge about how a developed AR-HUD navigation prototype performs in real-world driving, especially when compared directly to a non-HUD condition and evaluated through both eye-tracking and subjective driver experience.

2.3 Motivation For This Study

The motivation for this study arises from the increasing integration of advanced display technologies in modern vehicles and the corresponding need to ensure that these systems support, rather than hinder, safe driving. While AR-HUDs are often promoted as tools for enhancing attention and situation awareness, there is insufficient empirical evidence demonstrating their effectiveness in real traffic conditions, as mentioned in the introduction.

This thesis specifically addresses this gap by comparing AR-HUD and non-HUD driving conditions. By conducting user studies in real-world driving environments and extending test durations beyond typical laboratory studies, the research aims to provide a more realistic understanding of how these technologies influence driver behavior over time.

The findings of this study are expected to contribute design-relevant insights that can inform the development of future in-vehicle display systems at Volvo Cars and within the broader automotive industry.

3. Theory

This chapter presents the theoretical concepts used to understand and analyse the interaction between drivers and AR-HUD navigation support. These concepts provide the theoretical foundation for understanding how visual information in the driving environment can influence driver behaviour, perceived workload and the overall driving experience.

3.1 Interaction Design

Interaction design focuses on how users interact with products, systems and interfaces, and how these interactions can be designed to support users in achieving their goals in an effective and meaningful way. It is closely connected to user experience (UX), since the quality of an interaction often shapes how a product or system is perceived and experienced. While UX takes a broader perspective on the overall experience, interaction design focuses more specifically on the behaviour, flow and quality of the interaction. This includes how information is presented, how users understand available actions, and how the system provides feedback (Teo, 2025).

In this thesis, interaction design is central because the AR-HUD prototype was designed to support the driver's interaction with navigation information during real-world driving. From an interaction design perspective, the placement, timing and visual design of information can influence visual attention, perceived workload and situation awareness. The AR-HUD was therefore not only treated as a display technology, but as an interactive system that communicates navigation support to the driver in a specific driving context.

3.2 Augmented Reality (AR)

Augmented reality (AR) refers to technology that integrates contextual digital information into the user's real-world environment in real time, enhancing perception without fully replacing the physical surroundings (Azuma, 1997). While AR is often perceived as a recent development, the fundamental idea of overlaying digital information onto the real world has existed for decades. One of the earliest demonstrations was Ivan Sutherland's head-mounted display in 1968, which rendered computer-generated graphics onto a transparent view of the real environment, establishing foundational principles for AR visualization (Sutherland, 1968).

Since then, AR technologies have been applied across several domains such as gaming (e.g., Pokémon Go), education and industrial training. In recent years, AR has gained increasing attention in automotive human-machine interfaces (HMIs), where real and virtual elements are merged to support driver decision-making. In vehicles, AR systems can overlay navigation cues, speed information or hazard warnings directly onto the driving scene, potentially allowing drivers to maintain visual attention on the road while receiving guidance (Gabbard et al., 2014).

3.3 Head-Up Display (HUD)

A HUD is a transparent visual interface that presents important driving information, such as speed, navigation instructions and system alerts, within the driver's forward field of view (FoV), to reduce glances away from the road (Weinberg et al., 2011). The concept of HUDs originates from military aviation in the 1940s, where pilots required continuous access to flight data without diverting attention from the flight path (Cameron, 2015; Okabayashi et al., 1989). Automotive HUDs were later introduced commercially, with the first production vehicle HUD appearing in the late 1980s.

Traditional automotive HUDs aim to reduce visual distraction by positioning information in a fixed, forward-looking location; eliminating the need to look down at the driver information module (DIM) or the center stack display (CSD), collectively called the Head-Down Displays (HDD) (see Figure 3.1). Studies show that HUDs can reduce eye movements away from the road compared to conventional HDD, which reduces visual attention and supports safer driving behavior (Weinberg et al., 2011; Le & Shi, 2025).

Technically, an automotive HUD consists of a projection module that generates images and an optical system that reflects those images onto a transparent surface, typically the windshield. The projected virtual image appears floating at a virtual image distance (VID), the perceived distance between the driver and the displayed image, usually 2 meters ahead of the vehicle. This design helps drivers keep their gaze aligned with the road scene as the information is visible in the driver's FoV (Firth, 2019). While FoV defines how much of a scene is visible, VID defines the distance between the eye (or the camera lens) and the virtual image.

Figure 3.1: Placement of AR-HUD, DIM and CSD.

3.4 Augmented Reality Head-Up Display (AR-HUD)

AR-HUDs extend conventional HUDs by spatially aligning virtual graphics with real-world objects in the driving environment. Unlike the traditional HUDs that project the image only at a short image distance, the AR-HUDs can generate content at a longer VID, often between 8 and 10 meters ahead of the vehicle. This helps the brain integrate digital cues with physical road features (Firth, 2019). Instead of presenting abstract symbols or icons, AR-HUDs can display navigation arrows directly on the road surface, lane guidance or mark potential hazards in the context (Gabbard et al., 2014).

This contextual visualization enables drivers to interpret information more intuitively and keep their gaze on-road, potentially reducing cognitive processing time and improving situation awareness (Smith et al., 2021). Research emphasizes that factors like field of view, depth placement and display brightness are key parameters that influence how well AR-HUD content blends with the real world (Gabbard et al., 2014).

3.5 Visual Focus, Virtual Image Distance & Eye Fatigue

A HUD projects information onto the windshield through an optical system, creating a virtual image that appears to float in front of the vehicle rather than on the physical glass. The driver therefore does not focus on the windshield itself, but on the perceived virtual image. In a conventional HUD, the VID is typically around 2 metres, while an AR-HUD can place the virtual image further ahead, often around 8-10 metres, as illustrated in Figure 3.2.

This distance is important because the human visual system must adjust focus depending on how far away an object appears. Human vision is naturally optimized for focusing on distant objects during driving, typically beyond six metres (Texas Instruments, 2021). When important information is shown at a much shorter distance, such as in the DIM or CSD, the driver's eyes must repeatedly refocus between the display and the road. A DIM typically has an image distance of approximately 60-80 cm, which can cause more eye fatigue than a regular HUD. Traditional HUDs reduce this issue by placing the information further away, but with a VID of approximately 2 metres, drivers may still need to refocus between the HUD content and the road scene. This repeated accommodation can contribute to eye fatigue and reduced visual comfort over time (Firth, 2019).

Compared to head-down displays, HUDs can therefore reduce the need for drivers to look down and refocus on close display information. This means that important information normally shown in the DIM can instead be presented in the HUD, closer to the driver's forward field of view. AR-HUDs can further reduce the need for focal adjustment by projecting information at a longer VID, closer to the natural focal distance used during driving. This can make the information feel more integrated with the road environment and may improve visual comfort and user experience.

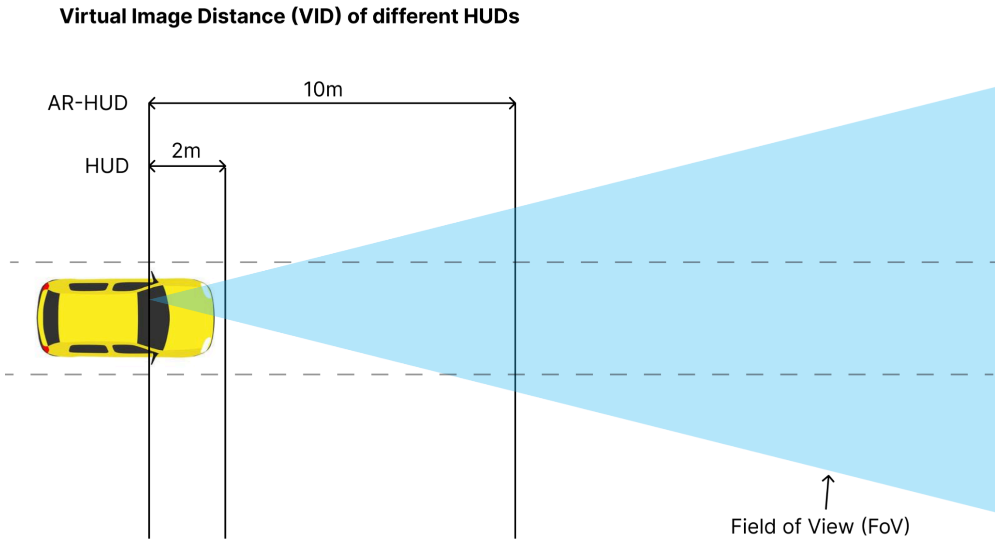


Figure 3.2: VIDs of different HUDs.

Figure 3.3 shows how an HUD image is created and perceived by the driver. The same principle goes for AR-HUD, but with an extended VID. The visual content is first generated in the picture generation unit (PGU), where the display image is produced. The light from this image is then guided through the optical system using mirrors, including a fold mirror and an aspherical main mirror. These mirrors direct and adjust the light path so that the image reaches the windshield at the correct angle.

The windshield works as an optical combiner by reflecting the light toward the driver's eyes. The driver does not see the image on the physical windshield itself. Instead, the reflected light makes the image appear as a virtual image in front of the vehicle, at a specific projection distance (VID). The eye box refers to the area where the driver's eyes need to be positioned in order to see the virtual image clearly. If the driver's eyes are outside this area, the projected image may become partly or fully invisible (Schroeter, n.d.).

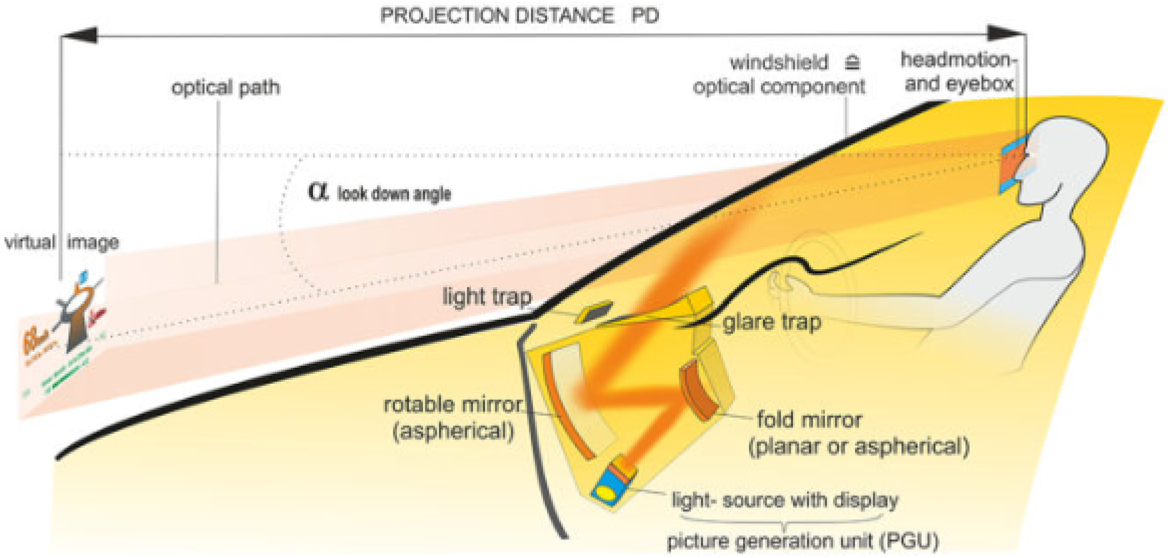
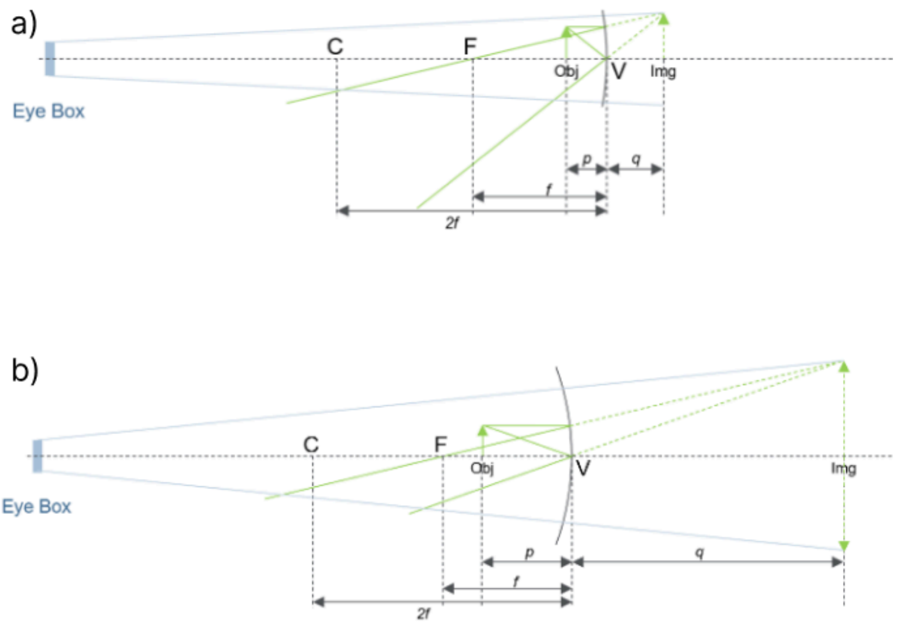


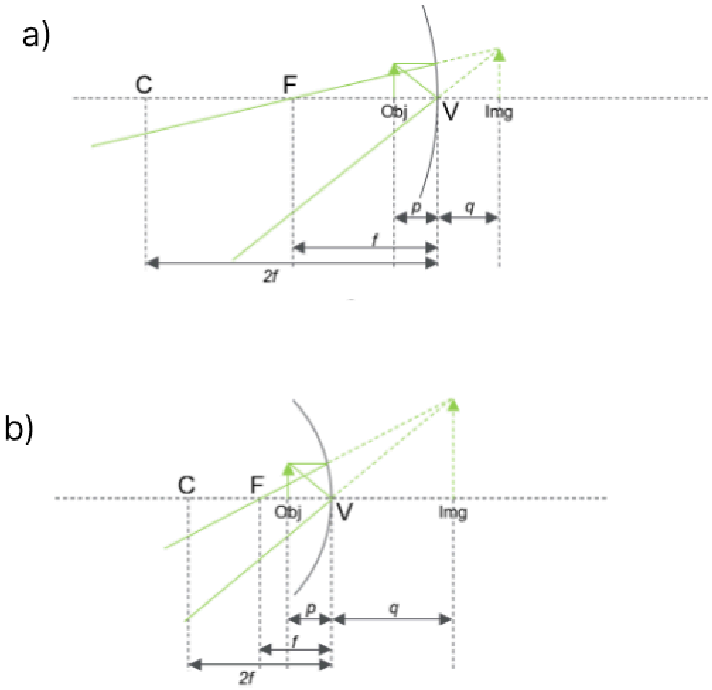
Figure 3.3: HUD projection principle (Schroeter, n.d.).

The VID can be increased in different ways, for example by increasing the optical path between the projector and the mirror (Figure 3.4), or by decreasing the radius in the aspheric main mirror (Figure 3.5). This causes the virtual image to appear further away from the driver and also results in a larger FoV. In an AR-HUD, a VID of about 10 metres is required in order to make navigation graphics such as arrows or lane guidance be perceived as if they are located on the road ahead. (D. S. Hermann, Personal Communication, February 13, 2026).



Source:
D. S. Hermann

Figure 3.4: The effect on FoV and VID of increasing the distance between the PGU and aspheric main mirror: a) Starting point, b) p (projector) is increased, leading to increase of q (VID) as well as of the magnification q/p (FoV). Illustrated by Supervisor David Hermann at VCC.



Source:
D. S. Hermann

Figure 3.5: The effect on FoV and VID of decreasing the radius of curvature of the aspheric main mirror, a) Starting point, b) f (mirror focal length) is decreased, leading to an increase of q (VID) as well as of the magnification q/p (FoV). Illustrated by Supervisor David Hermann at VCC.

3.6 Visual Attention

Visual attention is a fundamental cognitive process that enables individuals to selectively process relevant information in visually complex environments while filtering out irrelevant stimuli. In the context of driving, visual attention plays a critical role in maintaining safety, as drivers must continuously monitor dynamic elements such as other vehicles, pedestrians, traffic signals and road design. Kahneman (1973) conceptualizes attention as a limited cognitive resource that must be distributed across competing tasks. A commonly used metaphor describes visual attention as a “spotlight” that can be directed toward specific regions of the visual field (Posner & Cohen, 1984). Importantly, the direction of attention does not always match with eye gaze; drivers may attend to peripheral or anticipated events without directly fixating on them (Posner 1980).

Visual attention operates through both top-down (goal-directed) and bottom-up (stimulus-driven) mechanisms (Posner, 1980; Corbetta & Shulman, 2002). Top-down attention is goal-driven and guided by the driver’s intentions, such as following navigation instructions or searching for road signs. Bottom-up attention is stimulus-driven and automatically captured by salient visual events, such as sudden movement, bright colors or flashing warnings. In AR-HUD systems, poorly designed visual elements risk unintentionally capturing bottom-up attention and diverting focus from critical road information.

In this thesis, visual attention will be measured using eye-tracking metrics, including fixation duration, gaze dwell time, glance frequency and gaze transitions between the road, HUD and other in-vehicle displays. These measures are widely used in automotive HMI research to assess attentional allocation and visual distraction (Punde et al., 2017; Le & Shi, 2025). By comparing gaze behavior across AR-HUD and non-HUD conditions, the study aims to evaluate how different display technologies influence drivers’ visual attention distribution in real-world driving.

3.7 Eye-Tracking in HUD & AR-HUD Systems

Eye‑tracking technology was increasingly integrated into automotive HUD systems to address perceptual challenges such as parallax error, where the perceived position of virtual content shifts due to changes in the driver’s head or eye position. By tracking eye gaze and head position, HUD systems can dynamically adjust projected imagery to maintain correct alignment with the real‑world scene (Gabbard et al., 1999).

Automotive designers often implement eye-tracking to minimize parallax effects and ensure that AR overlays remain accurately registered with road elements across different driver postures. In addition, eye-tracking enables detailed analysis of driver attention distribution, visual scanning behavior, and interaction with HUD content. Studies using eye-tracking have shown that HUDs and AR-HUDs influence where and how long drivers look, providing valuable insights into visual attention and workload (Le & Shi, 2025).

3.8 Cognitive Load

Cognitive load refers to the amount of mental effort required to perform a task and the extent to which working memory resources are utilized (Sweller, 1988). Human cognitive capacity is limited, and when task demands exceed available resources, performance may degrade, leading to slower reactions, increased error rates and reduced safety in driving.
According to Cognitive Load Theory, cognitive load can be divided into three types (Sweller et al., 1998):

- Intrinsic load - which is inherent to the task itself, such as the complexity of the driving environment.
- Extraneous load - which arises from how information is presented and can be influenced by interface and interaction design.
- Germane load - which reflects cognitive resources devoted to learning and schema formation.

In the context of automotive HUD systems, poorly designed visualizations may increase extraneous cognitive load by presenting unnecessary, cluttered, or poorly timed information that competes with the driving task. Conversely, well-designed AR-HUDs may reduce cognitive effort by presenting information in a spatially meaningful and intuitive manner, thereby supporting faster comprehension and more efficient decision-making (Gabbard et al., 2014; Lopez & Moacdieh, 2025).

3.9 Situation Awareness

Situation awareness involves an individual's ability to perceive elements in the environment, comprehend their meaning, which elements are important and predict future events (Endsley, 1995). In dynamic and safety-critical domains such as driving, high levels of situation awareness are essential for effective decision-making and hazard avoidance (Endsley, 2004).

Endsley’s three-level model of Situation Awareness provides a widely accepted theoretical framework:

Level 1 - Perception: Detection of the relevant elements in the environment, such as other vehicles, traffic signs, pedestrians and road conditions.

Level 2 - Comprehension: Understanding the significance of these elements and how they relate to current goals, for example, recognizing that a braking light from the vehicle ahead indicates a potential hazard.

Level 3 - Projection: Anticipating future states or outcomes of the environment, such as predicting that a vehicle signaling a turn will slow down and change lanes.

Each level builds upon the information from the previous one, progressively enhancing situation awareness. Driving requires continuous integration across all three levels and affects our ability to make split-second decisions. Failures at any level, such as missed visual cues or misinterpretation of traffic situations, can lead to delayed reactions or unsafe decisions. Advanced in-vehicle display systems, including AR-HUDs, have the potential to support situation awareness by presenting information in a contextually relevant and spatially aligned manner.

4. Methodology & Process

The methodology combined prototype development, real-world user testing and mixed-method data collection. The project included both the technical implementation of an AR-HUD prototype and the evaluation of the prototype in a real driving context. Quantitative data was collected through eye-tracking, raw NASA-TLX and a SART-inspired questionnaire. Qualitative data was collected through semi-structured interviews and observations.

4.1 Research Design

The user study was designed as a within-subject study, where each participant experienced both test conditions (Nielsen Norman Group, 2023). This design was chosen because it allowed a direct comparison between the AR-HUD and non-HUD conditions within the same participant, rather than comparing two separate participant groups. This made it easier to identify differences caused by the display condition itself, instead of individual differences such as age, driving habits, confidence or previous experience with HUD systems. A within-subject design was also considered time-efficient and suitable for the scope of the study.

The study was structured as an A/B test. An A/B test is a comparative study design where two or more conditions are tested against each other to identify differences in user behaviour or experience (Nielsen Norman Group, 2024). Each participant drove two predefined real-world routes in a Volvo EX90: one route with AR-HUD navigation support and one route without AR-HUD. In the AR-HUD condition, navigation was shown both in the CSD and in the AR-HUD. In the non-HUD condition, navigation was only shown in the CSD. A real-world driving context was chosen because the experience of an AR-HUD depends strongly on the driving environment. Road layout, traffic flow, speed, exits, roundabouts and turns can all influence how the system is perceived and used.

The routes were selected to include varied navigation situations, such as roundabouts, highway sections, exits, entrances, right turns and left turns. This was important because the AR-HUD prototype focused on navigation support, and the routes therefore needed to include situations where navigation cues could be meaningfully displayed and evaluated. The route selection was also influenced by previous HUD-related thesis work at Volvo Cars, where a similar route structure had been used (Le & Shi, 2025).

A limitation of within-subject studies is that participants may become more familiar with the task during the first condition, which can influence how they perform or experience the second condition. To reduce this risk, the order of the conditions was counterbalanced. Half of the participants started with the AR-HUD condition, while the other half started with the non-HUD condition. This helped reduce learning effects, route familiarity and increased comfort with the test situation, leading to more reliable results (Nielsen Norman Group, 2024). Each full test session lasted approximately 50 minutes.

4.2 Prototype Development

In this project, prototyping was necessary because the AR-HUD interaction had to be experienced in a real vehicle and in relation to the real driving environment. The prototype development was conducted in two main phases. The first phase focused on developing the technical system required to run the AR-HUD prototype. The second phase focused on creating the visual content that would be displayed through the AR-HUD.

4.2.1 Technical System Integration

The aim was to create a prototype that could support the test situation without requiring a fully automated navigation system. The focus was therefore not to build a production-ready AR-HUD, but to create a realistic enough prototype for evaluating the interaction and visual design.

At the beginning of the project, the vehicle already contained an installed AR-HUD system that an external company had worked with. This system contained a “picture box” which allowed static images to be shown in the AR-HUD. The external company gave instructions on how to start the AR-HUD by running a provided script on a connected laptop. However, this company was no longer working directly with VCC at the time of the thesis, which made the support around the system limited.

The initial phase focused on starting the AR-HUD and understanding how the existing system functioned. This phase involved several unexpected technical issues. The available script did not start the AR-HUD as expected, which meant that the system could not be used directly at the beginning of the project.

Another unexpected issue was that the original video cable needed for the AR-HUD system was missing, which meant that time was spent on identifying and finding the correct video cable. Since the support was limited, this involved searching in different areas at VCC, contacting people through Teams, checking different workshops and storage areas.

A considerable amount of time was spent troubleshooting the existing setup, partly because the system was complex and partly because access to technical support was limited. Eventually, the correct cable was found and a new script was created to restart and activate the AR-HUD. This made it possible to get the system running and start with the development of the prototype.

After the AR-HUD had been successfully started, the next step was to move beyond the limitations of the original "picture box". To be able to display dynamic content in the AR-HUD, the "picture box" was removed and a **Linux computer** was integrated into the system. The idea was to run the prototype interface in Figma through a web browser in full-screen mode. Everything shown on the full-screen browser window would be shown in the AR-HUD. This made it possible to present dynamic content and control the visualisations more flexibly.

A **monitor** was also connected to the system. Since only the driver can see what AR-HUD content is shown in the windshield, the monitor was used to mirror the same content. The Linux computer therefore displayed the same content in the AR-HUD and the monitor. This allowed the researchers to follow what was being displayed during the test sessions and adjust the content when needed.

Several additional components were needed to make the system work. A **multi-hub** was used to connect different cables and devices, such as USB, HDMI and micro-USB connections. A **keyboard** and **mouse** were connected to control the Linux computer. A **circuit board** from Analog Devices was also included in the setup. This board was used as a part of the connection between the computer and the AR-HUD. A separate **laptop** was connected to the multi-hub and was used to run the code that started the AR-HUD. The same code also provided a graphical user interface, which made it possible to adjust settings such as AR-HUD position (height wise) and brightness (depending on weather conditions).

The final system consisted of several components, as illustrated in Figure 4.1. The power source (integrated into the car) supplied the monitor, Linux computer and multi-hub. The Linux computer sent the visual content though HDMI to the monitor and to the circuit board. The circuit board then sent a video signal to the AR-HUD through a GMSL video cable. The multi-hub worked as a communication between USB-A, micro-USB and UART connections. The AR-HUD could also be turned **on and off** separately through a button integrated into the car and connected to the power source.

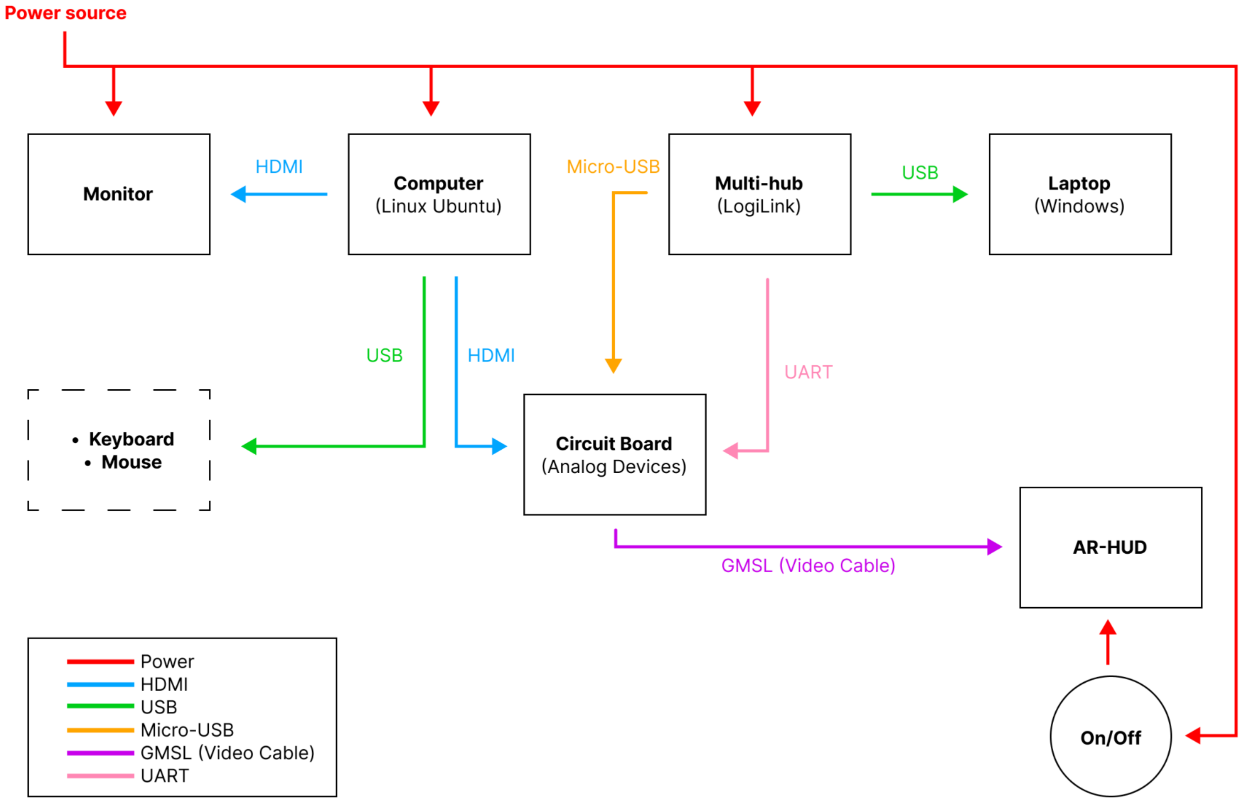


Figure 4.1: Overview of the technical AR-HUD prototype system and its connected components.

4.2.2 Visual Content

Blender and Figma were used to create the visual content and prototype flow.

4.2.2.1 Blender

Blender is a 3D modelling and animation software. It can be used to create three-dimensional objects, animations and rendered video sequences (Blender Foundation, n.d.). In this project, Blender was relevant because the AR-HUD navigation content needed movement, direction and depth.

Blender was used for creating animated navigation arrows. The aim was to design arrows that could appear as if they were placed on the road surface in front of the vehicle. This was important because the AR-HUD concept was based on navigation cues that should feel connected to the driving environment. Their movement, perspective, placement and colour were adjusted through several iterations.

Most of the work in Blender was done on an HP laptop at the Volvo Cars office. Blender was also installed on the Linux computer connected to the AR-HUD system. This made it possible to test how the arrows appeared directly in the AR-HUD. Testing the animations in the vehicle was important because the visual impression changed when the content was projected through the windshield. The arrows were adjusted so that they appeared aligned with the road environment and were visible without becoming too dominant. After the animations had been refined, they were exported as video files and added to Figma.

4.2.2.2 Figma

Figma is a digital design and prototyping tool used for creating user interfaces, frames and interactive flows (Figma, n.d.). It is commonly used in interaction design because it allows designers to quickly create and test interface layouts without building a fully functional software system.

Figma was used to design the AR-HUD symbols, visual layout and prototype flow. The prototype was structured with several frames, where each frame represented a specific navigation situation or visual state. This combination of Figma and Blender made it possible to create a prototype that included both static symbols and animated arrows. By running the frames in full-screen mode, the visual content could be shown in the AR-HUD through the connected Linux computer.

During the user tests, Figma was opened in a browser on the Linux computer and displayed in full-screen mode. The content shown in Figma was sent to the AR-HUD and mirrored on the monitor. This made it possible to control what the participant saw in the AR-HUD during the drive.
The Figma prototype was controlled manually using the connected keyboard. This allowed the researchers to switch between frames or trigger specific visualisations at the right moment. In this way, Figma became part of the Wizard of Oz setup, where the AR-HUD content was manually controlled. But for the user, it would seem that the prototype responds naturally to the driving situation.

4.3 Wizard of Oz

Wizard of Oz is a prototyping method where a system appears to function automatically, while some parts are manually controlled by a researcher. This method is often used when a system concept needs to be evaluated before full technical automation has been developed (Paul & Rosala, 2024).

In this project, the method was suitable because the AR-HUD prototype needed to respond to driving situations, but the system was not connected to live navigation data. Manual control made it possible to simulate dynamic behaviour without building a fully automated AR-HUD system. Since the prototype was not fully automated, a researcher needed to trigger the correct Figma frames and animations during the drive. The aim was for the participant to experience the AR-HUD as if it responded naturally to the route and navigation situation.

4.4 Test Driving Competitor Cars

In this project, competitor vehicles with AR-HUD systems were tested. The purpose of the test drives was to explore existing AR-HUD solutions and identify which visual elements felt helpful, clear or distracting during driving.

Two competitor cars were test driven: an Audi Q6 e-tron and a Porsche Macan Turbo. During the test drives, attention was given to how navigation cues were displayed, how symbols were positioned and how the AR-HUD supported the driving task. Insights from the test drives influenced the prototype design. For example, dashed lane lines were added between the lane arrows to make the road connection clearer. This made the symbols easier to interpret as road-related guidance.

4.5 Prototype Testing With Volvo's UX Team

The prototype was tested together with four members of Volvo Cars' UX team. The test involved driving the planned routes while using the AR-HUD prototype. During the drive, the visualisations, timing and overall experience were observed. The purpose was to receive feedback from people with relevant design experience and to check whether the prototype worked in the vehicle.

The feedback led to a few design refinements. Initially, lane symbols and roundabout symbols were placed in different parts of the AR-HUD view. After the test, the symbols were moved to the lower left area so that the information was collected in one place. The symbols were also made slightly smaller to reduce visual dominance. After these refinements, the prototype was considered ready for the main user study.

4.6 Data Collection Methods

The study used several data collection methods to capture different aspects of the driving experience. There were 20 users who participated in the study. Eye-tracking was used to collect objective data on visual attention. Raw NASA-TLX and a SART-inspired questionnaire were used to collect subjective ratings of workload and situation awareness. Surveys, observations and interviews were used to gather background information and qualitative insights.

4.6.1 Survey

In this study, a survey was used to gather background information that could help interpret the results. It was created in Google Forms and included questions about driving experience, driving habits, previous experience with HUD and AR-HUD systems, and use of navigation tools such as Google Maps. The responses were later used to describe the participant group and to understand whether previous experience with driving, HUD systems or navigation tools may have influenced the results.

4.6.2 Eye-Tracking & iMotions

The software iMotions is used for collecting, synchronising and analysing data from sensors such as eye-tracking cameras, scene cameras and video recordings (iMotions, n.d.). In this study, iMotions was used to support the collection of gaze data during real-world driving. The data could provide insight into visual attention by showing where participants look and for how long. This was important for the study because one of the aims was to compare how participants distributed their visual attention between the road, the AR-HUD and other in-vehicle displays.

A predefined world model had already been created and connected to iMotions for the relevant Areas of Interest (AOIs), including the road, mirrors, DIM, CSD and AR-HUD. This world model made it possible to connect the recorded gaze data to specific areas in the vehicle and driving environment during analysis, as illustrated in Figure 4.2.

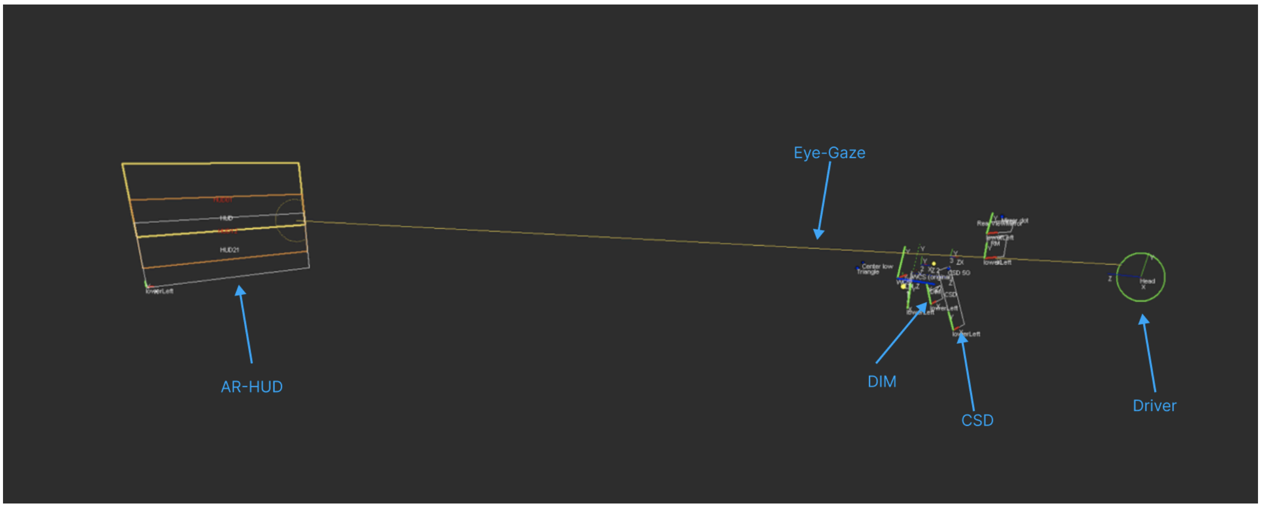


Figure 4.2: World Model of the AOI:s.

Before each test session, scene camera, environment camera and GPS were connected to the eye-tracking system (see Figure 4.3).

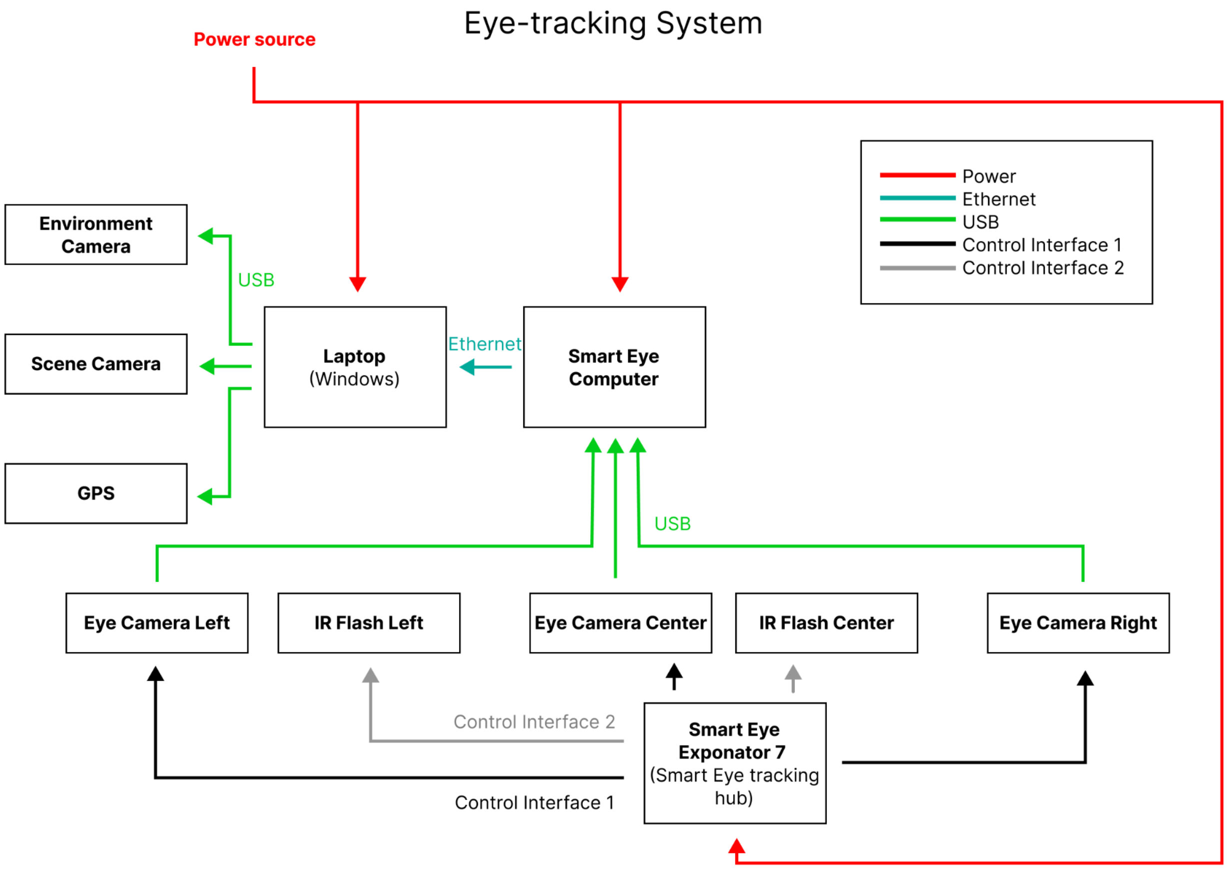


Figure 4.3: Eye-tracking system.

Before each route, a gaze calibration was performed. The participant was asked to look at four calibration points (see Figure 4.4), one at a time, while the researcher calibrated the eye-tracking system in iMotions. This was done to improve the accuracy of the gaze data and ensure that the system could track the participant's gaze direction during the drive.

Figure 4.4: Overview of the four calibration points.

After calibration, the recording was started in iMotions. Eye-tracking data and video were collected during both driving routes. Since each participant completed both the AR-HUD and non-HUD conditions, the recordings were organised by participant, route and condition. There were 40 recordings in total, two for each participant, since each of the 20 participants completed both the AR-HUD and non-HUD conditions. See chapter 4.9.3 for analysis of the iMotions data.

4.6.3 NASA Task Load Index (NASA-TLX)

Cognitive load in this study will be measured using the NASA Task Load Index (NASA-TLX), a widely used multidimensional subjective assessment tool. It is used to measure how demanding a task is perceived to be. The full NASA-TLX includes dimensions such as mental demand, physical demand, temporal demand, performance, effort and frustration (Hart & Staveland, 1988). In the full NASA-TLX, each dimension is first rated (from 0-100) and then weighted based on its perceived importance. The overall workload score is calculated as a weighted average, where the six dimensions are weighted through pairwise comparisons, resulting in a total weight of 15, as shown in Equation (1):

$$NASA\text{-}TLX = \frac{\sum_{i=1}^{6} rating_i \times weight_i}{15} \tag{1}$$

NASA-TLX has been extensively validated in HMI research and driving and provides a reliable indication of perceived workload. By comparing NASA-TLX scores across AR-HUD and non-HUD conditions, the study aims to assess whether these display technologies increase or reduce cognitive load relative to conventional driving.

In this study, workload was relevant because an AR-HUD may either reduce or increase the mental effort required during navigation. A clear and well-timed AR-HUD could reduce workload by making navigation easier to understand. A poorly designed AR-HUD could instead increase workload by adding visual clutter or distracting information.

The original plan was to use the full NASA-TLX after each route to compare perceived workload between the AR-HUD and non-HUD conditions. However, the pilot test showed that the full version took too long to complete and created unnecessary effort for the participant. Therefore, the *raw NASA-TLX* was used instead (see Appendix A). In the raw NASA-TLX, the weighting step is removed. The final score is instead calculated as the mean of the six dimension ratings, as shown in Equation (2):

$$Raw\ NASA\text{-}TLX = \frac{\sum_{i=1}^{6} rating_i}{6} \tag{2}$$

4.6.4 Situation Awareness Rating Technique (SART)

Situation Awareness Rating Technique (SART), is a subjective measurement method that captures perceived attentional demand, understanding of the situation, and available mental resources (Taylor, 2017). SART has been shown to align well with Endsley’s theoretical model and is commonly used in transportation and human factors research (Endsley, 1995; Salmon et al., 2006). By combining SART with objective eye-tracking data, the study aims to provide a more comprehensive understanding of how AR-HUD systems influence drivers’ situation awareness in real-world driving conditions.

A SART-inspired questionnaire was used after each route (see Appendix B) to compare participants’ perceived situation awareness between the AR-HUD and non-HUD conditions.

Since the original SART is relatively general, it was adapted to better fit the driving context of this study. The questions were therefore adjusted to focus more specifically on aspects relevant to real-world driving.

The SART score was calculated by combining the three dimensions: understanding, demand and supply. A higher SART score indicates better perceived situation awareness. The total situation awareness score is commonly calculated by subtracting demand from the sum of understanding and supply, as shown in Equation (3):

$$SART = Understanding + Supply - Demand \tag{3}$$

4.6.5 Semi-Structured Interviews

In semi-structured interviews, the researcher follows a prepared interview guide consisting of predefined themes, while allowing participants the freedom to express their answers in their own way (Denscombe, 2009). Follow-up questions are asked when needed to further explore and deepen participants' responses. The questions do not need to be asked in a fixed order and can be adapted during the course of the interview (Bryman, 2012). This interview approach is chosen because it encourages participants to freely express and reflect on their thoughts and ideas about the topic (Denscombe, 2009). As the study aimed to explore participants' opinions and experiences, semi-structured interviews were considered the most suitable method.

Following recommendations by Wadsworth (2020), the interviews are based on a consistent set of questions to support comparability during analysis. The interview questions focused on perceived differences between the two conditions, clarity of the visualisations, distraction, safety, workload and general user experience. The purpose was to gain a deeper understanding of how participants experienced the AR-HUD compared to the non-HUD condition.

The interviews were held either in English (see Appendix C) or Swedish (see Appendix D), depending on the participant's preference. This allowed the conversation to feel more natural and made it easier for participants to express their thoughts. The interviews followed a prepared guide, but follow-up questions were asked when needed. This made it possible to explore specific comments or reactions in more detail.

4.6.6 Observations

In this study, observations were used as a complementary method to understand how participants interacted with the system during the drive. This included noting uncertainty, spontaneous comments, visible reactions to the AR-HUD content and situations where the participant asked for clarification or support. During the drive, one researcher observed the participant and took notes. Participants were also encouraged to think aloud when they noticed something important. These comments were written down and later used for the Thematic Analysis.

4.7 Pilot Study

A pilot study is conducted before the main user study to ensure reliability and to refine the question design (Bryman, 2012). Here, the pilot study was planned to test the full user study procedure and equipment. This included the AR-HUD prototype, the technical setup, the eye-tracking calibration, the driving routes, the questionnaires and the interview guide. The pilot was also used to assess whether the duration of the session was reasonable and whether the participant could complete the tasks without unnecessary stress or confusion.

The pilot test showed that the full NASA-TLX took too long to complete. The participant started to answer less carefully and expressed frustration, which indicated that the questionnaire added unnecessary workload after the driving task. Based on this, the full NASA-TLX was replaced with raw NASA-TLX, which excludes the weighting procedure. This change reduced the time needed to complete the questionnaire while still allowing perceived workload to be measured.

In addition, the post-survey was reduced from two parts to one, as several questions were either unnecessary or already answered in the interview questions. During the pilot, the researcher became more efficient for the procedure of the user tests, which further reduced the overall session time. As a result, the total duration of the study decreased from approximately 1 hour and 10 minutes to 45-50 minutes.

4.8 Participant Recruitment

Participant recruitment was based on convenience sampling. Convenience sampling means that participants are recruited because they are accessible and suitable for the study context (Golzar et al., 2022). This approach is practical in applied design research, especially when the study involves specific equipment, safety requirements or access to a particular organisation. A limitation of convenience sampling is that the results may not be fully generalisable to all drivers. However, it was considered appropriate for this study because the test involved a prototype vehicle and had to follow internal safety and approval procedures at Volvo Cars.

Participants were recruited through Teams group chats and email communication within Volvo Cars. A short description of the study was shared together with a link to a scheduling tool, where employees could book a time slot. 20 Volvo Cars employees were recruited. This simplified approval procedures and supported safety, as the study involved driving a prototype vehicle in real traffic. More information about the participants will be discussed under section 6.2.1.

4.9 Data Analysis Methods

The analysis combined quantitative and qualitative data. The quantitative data included raw NASA-TLX scores, SART-inspired questionnaire responses and eye-tracking data. The qualitative data included interview responses and observations.

Using several types of data made it possible to study the AR-HUD from different perspectives. The aim was not only to measure whether differences existed between the two conditions, but also to understand how participants experienced those differences.

4.9.1 Triangulation

Triangulation means that several methods or data sources are combined to study the same phenomenon. This can strengthen the analysis because the findings are not based on one type of data only. If different data sources point in the same direction, the interpretation becomes more robust. If they differ, the contrast can provide a more nuanced understanding (Noble & Heale, 2019; Denscombe, 2009). Therefore, both quantitative and qualitative methods were used in this study.

The results from eye-tracking, raw NASA-TLX, SART inspired questionnaire, interviews and observations were compared during the analysis. For example, questionnaire results were interpreted together with interview comments and observed behaviours. This made it possible to identify whether participants’ subjective experiences aligned with the objective gaze data and qualitative findings.

4.9.2 Thematic Analysis

To analyse the semi-structured interviews and observations, a thematic analysis approach was employed. Thematic analysis is a widely used qualitative method, providing qualitative insights into participants’ experiences, perceptions, and opinions (Bryman, 2012; Braun & Clarke, 2006). The process involves identifying patterns in data through systematic coding and development of themes.

Thematic analysis was used for analysing the semi-structured interviews. The aim was to identify recurring themes in how participants experienced the AR-HUD and how they compared it to the non-HUD condition. The approach followed Braun and Clarke’s (2006) six-step process. First, the material from the user tests was read through to become familiar with the data. This included interview notes and observation notes. Second, initial codes were created by selecting comments and observations that were considered relevant or noteworthy. In this study, noteworthy data referred to material that related to the research question, such as visual attention, driving behaviour, situation awareness, perceived workload or the experience of using the AR-HUD. Third, all codes were collected in one place to make the material easier to compare. Fourth, patterns were identified across the codes and similar codes were grouped into preliminary themes. Fifth, the themes were reviewed and refined through an iterative process involving repeated reading, comparison and discussion. Finally, the themes were named and written up as part of the analysis, where they were used to explain the participants’ experiences in relation to the research question. Results of thematic analysis can be found under chapter 6.5.

4.9.3 Analysis of iMotions Data

The eye-tracking recordings saved in iMotions were exported as CSV files for further processing. The exported eye-tracking data was sent to RISE, where researchers involved in the SCREENS II project, of which this thesis is also a part, carried out the main analysis of the collected gaze data due to their expertise in eye-tracking and Smart Eye systems. The exported data was analysed in Python 3.13 using pandas, NumPy, SciPy and Matplotlib. This made it possible to structure, clean and calculate gaze-related measures for each participant and condition.

For each condition recording, the data was first cropped to include only the on-road driving segment. This was done to ensure that the analysis only included the part of the recording where the participant was actively driving.

Seven AOIs were included in the analysis: left mirror, rearview mirror, right mirror, DIM, CSD, AR-HUD and No-AOI. No-AOI was used when the gaze sample did not belong to any of the defined areas.

A glance was defined as a continuous sequence of samples within the same AOI. Short tracker dropouts shorter than 100 ms were handled through a gap-fill step, but only when the dropout was surrounded by the same AOI on both sides. This reduced the effect of brief tracking losses without changing larger gaze shifts. After this step, runs shorter than 150 ms were removed, since they were considered too short to represent meaningful fixations and were treated as below-fixation noise.

Three dependent measures were then calculated for each AOI. The first was *dwell time*, expressed as the percentage of the recording spent looking at each AOI. The second was *glance rate*, calculated as the number of glances per minute. The third was mean *glance duration*, measured in milliseconds. Together, these measures were used to compare how visual attention was distributed between the AR-HUD and non-HUD conditions.

5. User Test Procedure

During the procedure, one researcher sat in the passenger seat and one researcher in the back seat. Each researcher had their own role and areas of responsibility. The researcher in the front was handling the AR-HUD content, while the researcher in the back was handling the eye-tracking system, gaze calibration and writing down notes during the two routes. Figure 5.1 shows an overview of the full user test procedure.

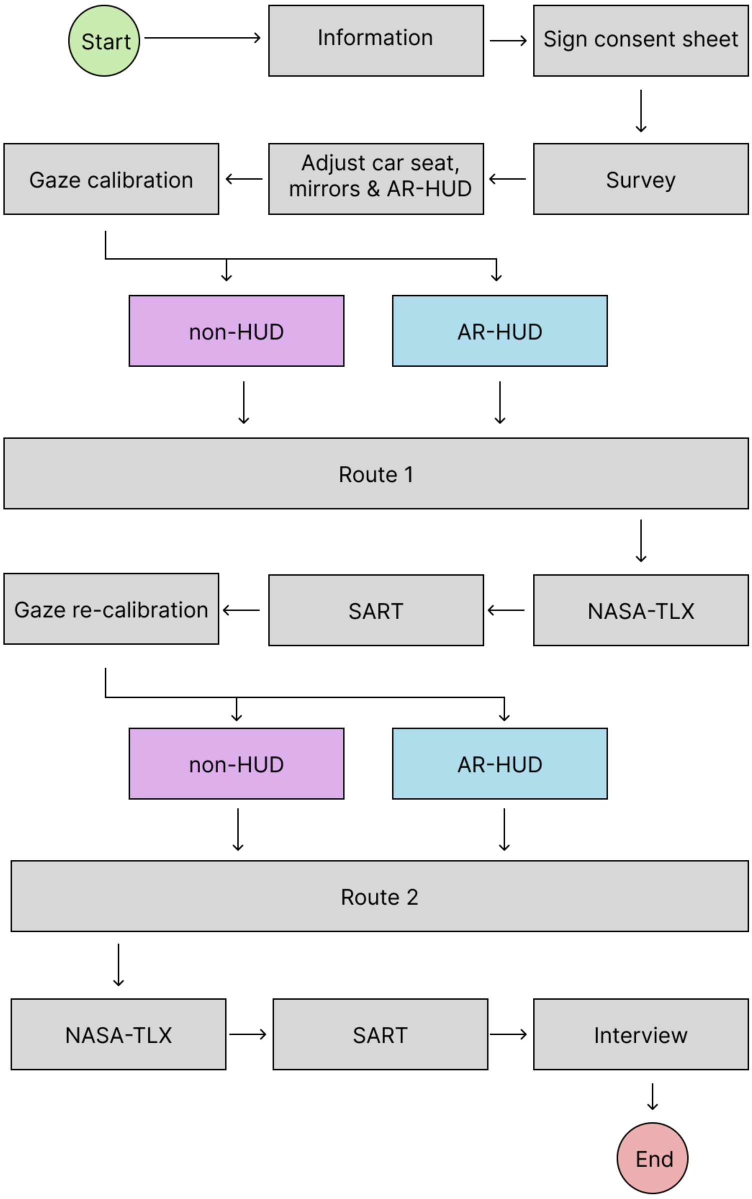


Figure 5.1: Flowchart of the user test procedure

Information

Each session began with an introduction where the participant received information about the test and its overall procedure. The researchers highlighted that they would drive a prototype car and also explained the eye-tracking system shortly.

Consent Sheet

After the introduction, the participant was given a consent form (see Appendix E) to read and sign. The consent form explained how the data would be collected and used. It also stated that participation was voluntary and the participant could withdraw from the study at any time.

Survey

After signing the consent form, the participant completed a digital survey in Google Forms (see Appendix F). The survey collected background information that was relevant for interpreting the results. This included information about the participant’s driving experience, driving habits and previous experience with HUD and AR-HUD systems.

The survey also included a question about how often the participant used navigation such as Google Maps while driving. This was included because previous experience with navigation systems could influence how easily the participant understood the navigation in the CSD and AR-HUD during the test.

Adjustments

Before the driving task started, the participant was asked to adjust the driver’s seat and mirrors. The AR-HUD was then adjusted. The researchers activated a white frame in the AR-HUD and asked the participant if they could see the whole white frame or if it was cut off in the top/bottom. If it was cut off, the height would be adjusted (by the researcher) through the laptop that was connected to the AR-HUD system.

This step was done because the visibility and perceived placement of the AR-HUD content can vary depending on the participant’s seating position and height. Adjusting the system before the test helped ensure that the participant could clearly see the AR-HUD content during the driving condition with AR-HUD.

Gaze Calibration

After the adjustments, the eye-tracking system was calibrated. The participant was asked to look at four calibration points, one at a time. The researcher in the back then calibrated the eye-gaze with the help of iMotions. This was done to ensure that the eye-tracking cameras could accurately detect the participant's gaze direction during the drive. When the calibration was completed, the recording in iMotions was started, which meant that the participant could start driving route 1.

Route 1

Depending on the counterbalanced order, the participant drove the first route either with the AR-HUD or without the AR-HUD. During the drive, the researcher in the passenger seat provided guidance if needed, for example if the participant was about to miss an exit. When the AR-HUD condition was active, the researcher also controlled the AR-HUD content using the Wizard of OZ setup with a keyboard. This meant that the researcher manually controlled the timing and presentation of the content during the drive. The other researcher observed the participant's behaviour and wrote down notes.

Route 1 (see Figure 5.2) started at *PVH, Volvo Jakobs v, 418 78 Göteborg* and ended at *Maxi ICA Stormarknad Torslanda, Gamla Flygplatsvägen 60, 423 37 Torslanda*.

Figure 5.2: Overview of Route 1 (Google Maps. 2026)

Questionnaires after Route 1

At the end of the first route, the participant was asked to park the car. The participant then answered two questionnaires. Firstly, the raw NASA-TLX questionnaire, and then the SART inspired questionnaire. Both questionnaires were completed directly after the route so that the participant's experience of the condition was still fresh.

Gaze Re-Calibration

Before starting the second route, the eye-tracking system was recalibrated. This was done to ensure that the eye-tracking cameras still had accurate gaze values after the first drive. Recalibration was necessary to start a new recording for the second condition.

Route 2

After recalibration, the second route began. The participant now drove under the opposite condition from the first route. This meant that participants who had started with the AR-HUD condition now drove without the AR-HUD, while participants who had started without the AR-HUD now drove with the AR-HUD. The same general procedure was followed during the second route.

Route 2 (see Figure 5.3) started at *Maxi ICA Stormarknad Torslanda, Gamla Flygplatsvägen 60, 423 37 Torslanda* and ended at *PVH, Volvo Jakobs v, 418 78 Göteborg*.

Figure 5.3: Overview of Route 2 (Google maps, 2026)

Questionnaires after Route 2

After the second route, the participant again completed the raw NASA-TLX questionnaire and the SART-inspired questionnaire.

Interview

The session ended with a short semi-structured interview. The interview included open questions about the participant’s driving experience across the two routes and the two display conditions. The interview also gave the participant an opportunity to express opinions about the AR-HUD prototype, including what was helpful, distracting and what could be improved.

6. Results & Analysis

This section presents results of the prototype visualisations and results from the user study, including survey data, questionnaire data, eye-tracking metrics, and qualitative interview findings. The results are structured according to the different data sources and are later used as a basis for the discussion and interpretation in the following chapter.

6.1 Final Prototype Visualisations

The final AR-HUD prototype was designed with a consistent visual structure to make the navigation information easy to understand while driving. The design combined static symbols and dynamic animated arrows. The static symbols were placed in the lower left corner of the AR-HUD view and were used to give early guidance before an upcoming manoeuvre. This included lane guidance, exit information and roundabout symbols. By placing these symbols consistently in the same area, the driver could quickly learn where to look for upcoming navigation information.

The static symbols were created in Figma and were intended to support planning. They appeared before the action needed to be taken, allowing the driver to prepare for lane changes, exits or roundabouts in advance. For example, the lane guidance symbols showed which lane should be followed, while the roundabout symbols included a number indicating which exit to take.

The dynamic arrows were created in Blender and were used as action-oriented guidance. These arrows were placed more centrally in the AR-HUD view and appeared visually aligned with the road. While the static symbols helped the driver understand what was coming next, the animated arrows indicated what action should be taken in the moment, for example, where to turn, change lane or exit.

Colour was also used consistently to separate available information from recommended action. In the static symbols, white was used to show the available road or lane options, while blue indicated the lane or direction the driver should follow. This made it possible to show both the road structure and the intended route within the same symbol. For the dynamic animations, all arrows were shown in a cyan-blue colour.

Below, examples of the final AR-HUD visualisations are presented across different driving scenarios. For a short overview of both routes, including highlights and navigation scenarios, as well as the full video material from both routes, see Appendix G.

6.1.1 Left Turn

The left turn visualisation used an animated arrow (see Figure 6.1). The arrow indicated the direction of the upcoming turn and was positioned centrally. In this case, no additional lane guidance symbol was needed, since the only action was the turn itself.

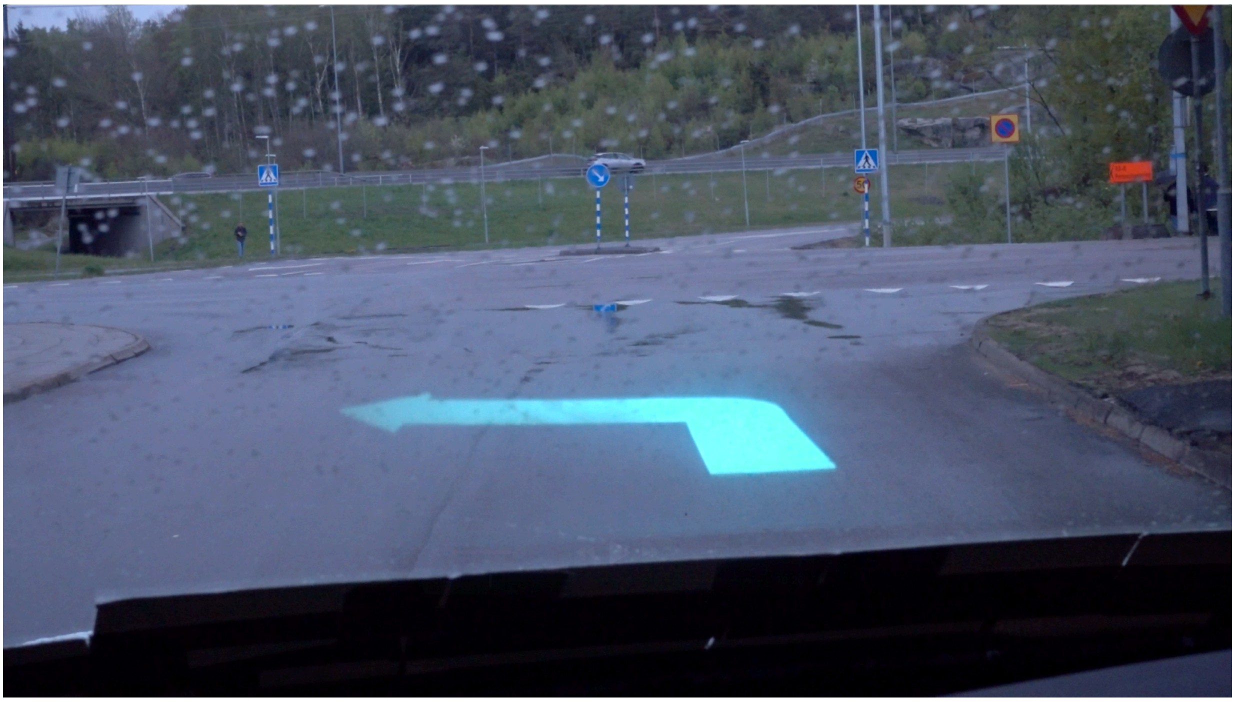


Figure 6.1: AR-HUD visualisation for a left turn

6.1.2 Exit & Lane Change

The exit visualisation combined static lane guidance in the lower left corner with a dynamic arrow in the centre of the AR-HUD view (see Figure 6.2). The lane guidance showed that the far-right lane was the relevant exit lane, while the animated arrow showed the action the driver should take. This allowed the driver to first prepare for the correct lane and then follow the arrow when approaching the exit.

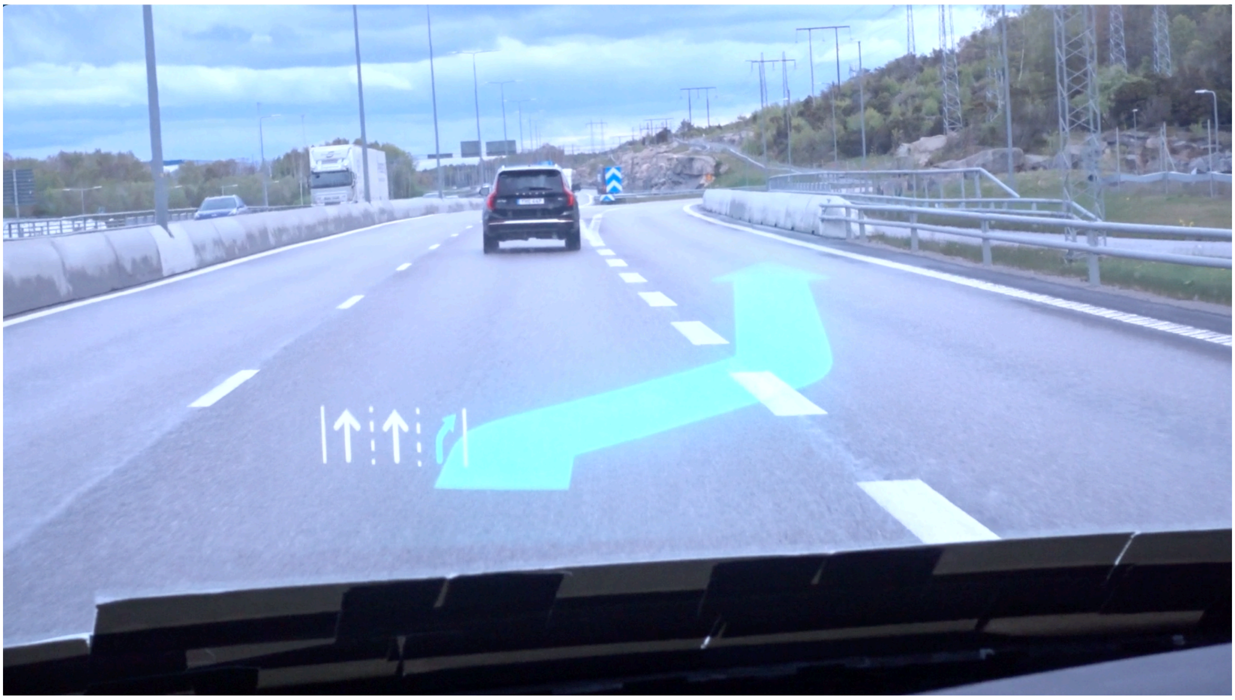


Figure 6.2: AR-HUD visualisation for changing lanes and taking an exit.

6.1.3 Third Exit in Roundabout

Figure 6.3 shows a roundabout situation where the driver should take the third exit. The lane guidance below the symbol helps the driver understand which lane to use before entering the roundabout. The roundabout symbol includes the number three, indicating that the third exit is the correct one.

After the driver has passed the second exit, the animated cyan-blue arrow appears in the centre of the AR-HUD view. The arrow acts as a confirmation that the driver should now leave the roundabout. In this way, the static symbols support planning before entering the roundabout, while the animated arrow supports the action at the moment when the exit should be taken.

Figure 6.3: AR-HUD visualisation for taking the third exit in a roundabout.

6.1.4 Roundabout with Bus Lane

Figure 6.4 shows a situation before entering a roundabout, where the driver should take the first exit. In many driving situations, the right lane would normally be used when taking the first exit. However, in this case, the right lane was a bus lane and should therefore not be used.

The static lane guidance in the lower left corner showed the available lane structure and indicated that the driver should stay in the left lane. The roundabout symbol above it showed that the first exit should be taken. Together, these symbols helped the driver understand both the correct lane choice and the upcoming roundabout action before reaching the roundabout.

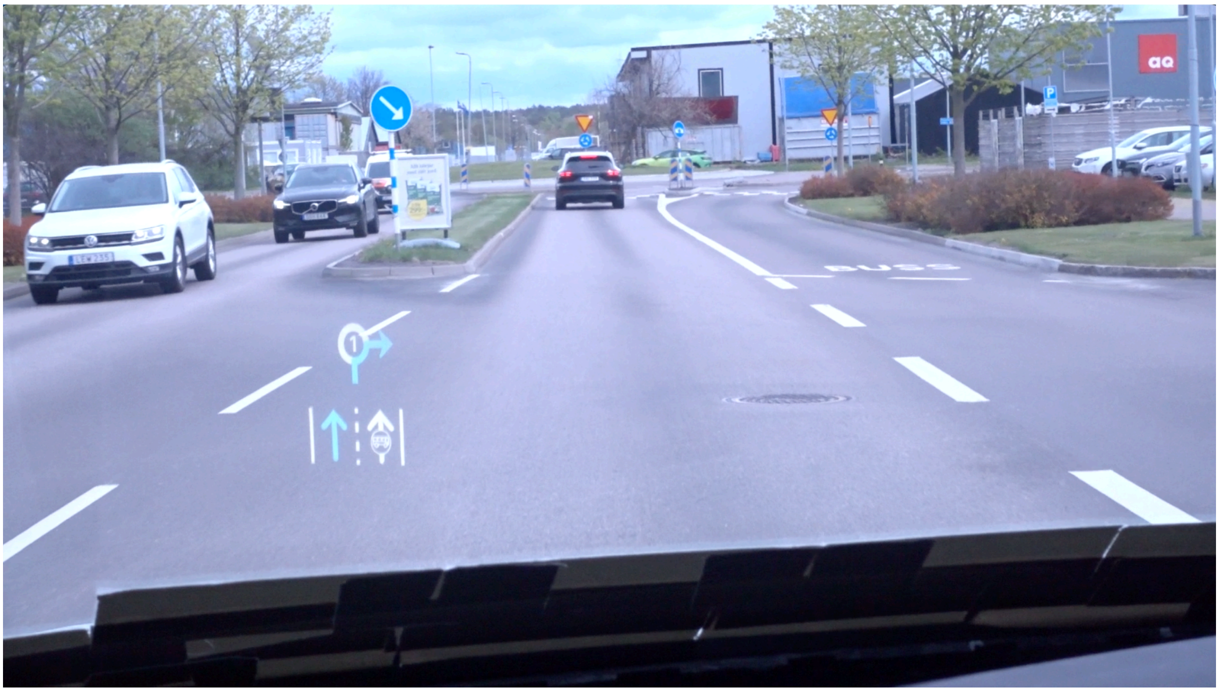


Figure 6.4: AR-HUD visualisation for taking the first exit in a roundabout where the right lane is a bus lane.

6.2 Result from Survey

This section presents the results from the survey conducted before the user study. The survey collected demographic information, driving habits, previous experience with HUD and AR-HUD systems, vision conditions, and use of navigation tools to provide context for the participant group.

6.2.1 Participants

A total of 21 participants took part in the user study; however, one participant was excluded from the analysis due to incomplete data collection, resulting in a final sample of 20 participants. The gender distribution consisted of 14 males and 6 females. The participants' ages ranged from 25 to 61 years, as shown in Figure 6.5, with the majority being over 35 years old. The most common age was 45 years, represented by three participants, followed by participants aged 25 and 30 years, with two participants in each age group.

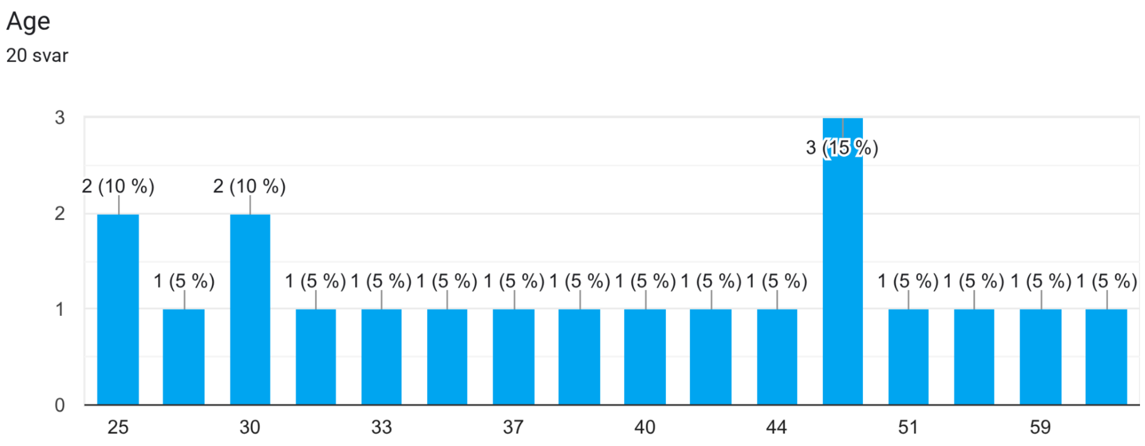


Figure 6.5: Distribution of participant ages.

6.2.2 Driving Experience

The participants were widely spread between different departments at Volvo, and the majority had had their driving license for more than 10+ years. However, the majority of the participants, 7 people, only drove 0-2 hours per week, then 4 people each drove 6-10 hours, 3-5 and 11-20 hours per week. Only one drove 11-20 hours per week. See Figure 6.6.

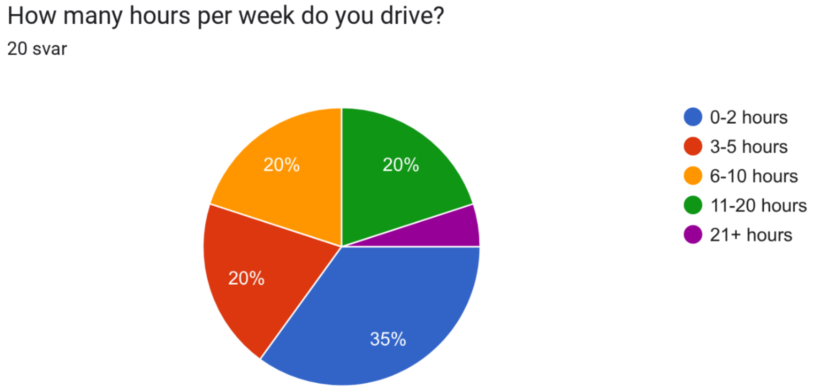


Figure 6.6: Distribution of driving hours per week.

6.2.3 HUD and AR-HUD Experience

The majority of the participants have previous experience with HUD; 12 people and 7 people had experience with AR-HUD, and 6 had no experience with any of them. See Figure 6.7.

Why the results show more answers in total than 20 is because 5 people answered that they had experience with both HUD and AR-HUD. Also, almost everyone doesn't have a HUD currently in their car; only 4 have it in their car now. Out of those 4 people, three of them use it 0-5 hours per week, and only one uses it 21+ hours per week.

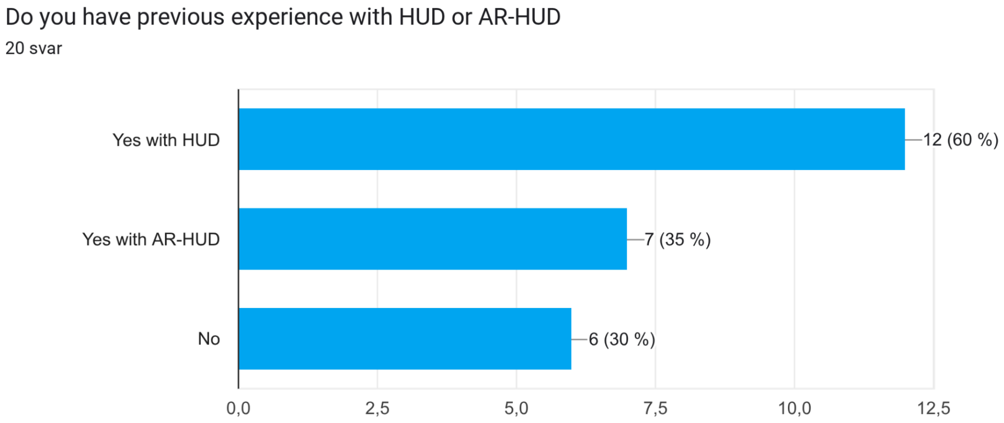


Figure 6.7: Distribution of previous experience with HUD and/or AR-HUD.

6.2.4 Vision and Use of Navigation

For vision, the majority had normal vision (uncorrected vision), 10 people, 6 use glasses to correct their vision and 3 people use contact lenses. Only one has done correction surgery and one whose vision is not fully corrected to normal. For navigation tools such as Google maps, it was quite divided, 7 people use it every time they drive, and an equal amount of people use it a few times a month. 6 people use it a few times a week, and one use it a few times a week, see Figure 6.8.

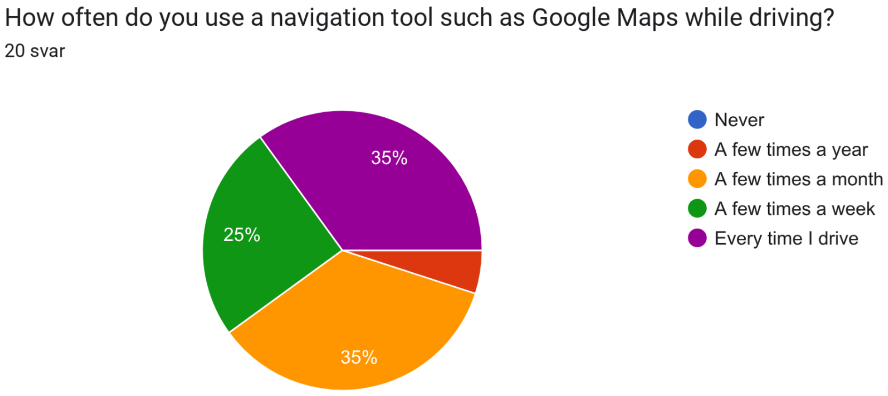


Figure 6.8: Distribution of use of navigation tools while driving.

6.3 Result from Nasa TLX & SART Questionnaire

This section presents the results from the NASA-TLX and SART questionnaires used to evaluate perceived workload and situation awareness during the user study. The results compare the AR-HUD and non-HUD conditions and provide both overall scores and key dimensions.

6.3.1 Raw NASA TLX Result

The average overall score of raw NASA-TLX with the AR-HUD condition (M = 17,67), compared to (M = 28.92) in the non-HUD condition. This shows the NASA-TLX scores were reduced by 38,9 % in the AR-HUD condition compared to non-HUD, indicating that participants experienced lower perceived workload. See Figure 6.9.

In addition, the standard deviation was lower in the AR-HUD condition (SD = 10.89) compared to the non-HUD condition (SD = 13.79), suggesting reduced variability in perceived workload across participants. This suggests that the AR-HUD not only reduced overall workload but also provided a more consistent user experience when using the AR-HUD system.

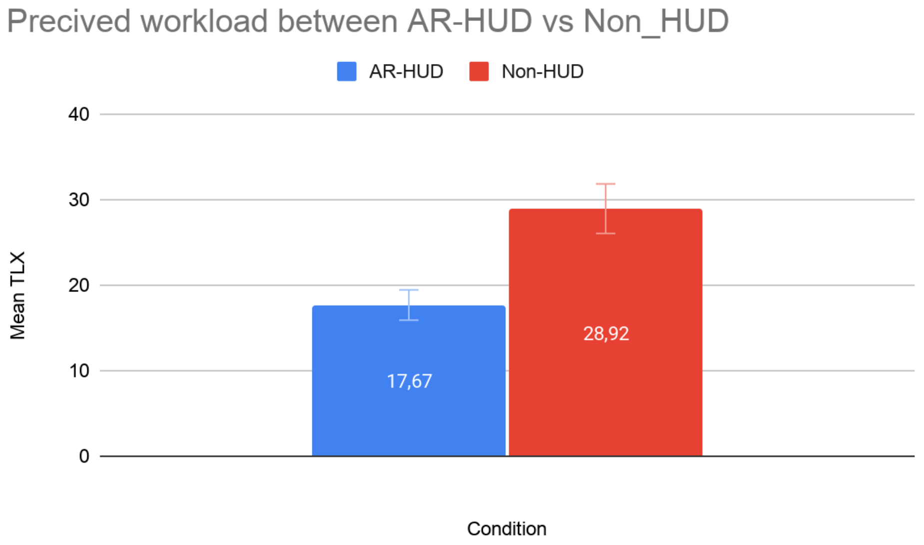


Figure 6.9: Comparison of mean overall NASA-TLX scores and standard deviations between AR-HUD and non-HUD conditions.

Among the individual NASA-TLX dimensions, the largest differences were observed in Mental Demand and Frustration. Participants reported considerably lower mental demand in the AR-HUD condition (M = 19.5) compared to the non-HUD condition (M = 41.5). Similarly, effort scores were also reduced when using the AR-HUD system, (M = 22,25) with AR-HUD compared to (M = 29,75) non-HUD condition. The frustration levels were also lower under the AR-HUD condition (M = 14.0) compared to the non-HUD condition (M = 26.50). See Figure 6.10.

These findings suggest that the AR-HUD system reduced cognitive workload and improved the overall driving experience during navigation tasks.

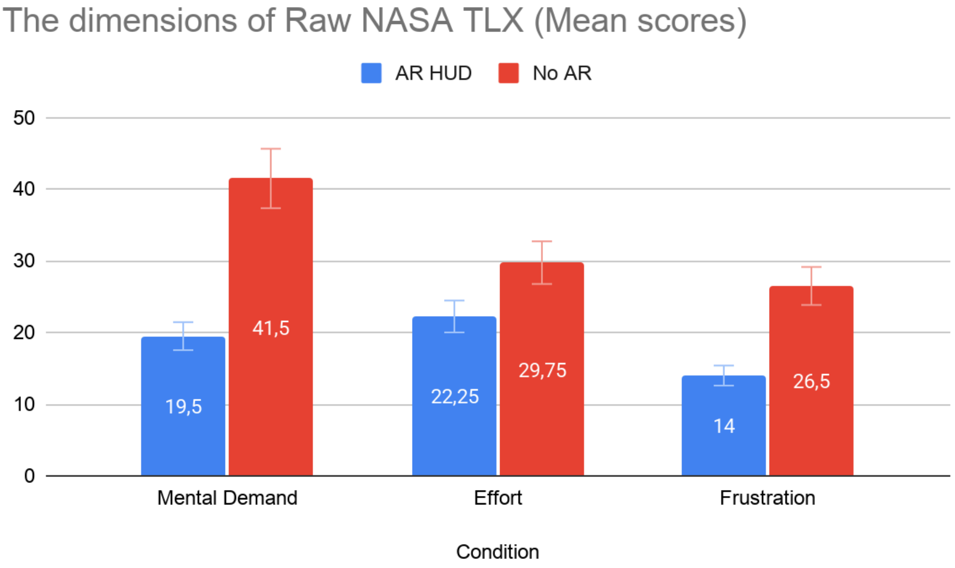


Figure 6.10: Three dimensions from Raw Nasa TLX questionnaire.

6.3.2 SART Result

The average overall SART score with AR-HUD condition was 24 compared to 23.7 in the non-HUD condition. See Figure 6.11. This corresponds to an approximate 1.3% increase in situation awareness under the AR-HUD condition, suggesting a marginal improvement in participants' perceived awareness of the driving environment.

The variability in SART scores was lower in the AR-HUD condition (SD = 4.17) compared to the non-HUD condition (SD = 5.66), indicating more consistent situation awareness ratings among participants when using the AR-HUD system.

Compared to NASA-TLX, the SART scores showed lower overall variability. This may be related to differences in questionnaire structure and scale design, as NASA-TLX uses a broader 0–100 rating scale, whereas SART uses a smaller Likert-based scale. Additionally, two participants misunderstood one of the NASA TLX questions, which may have affected the results slightly as well.

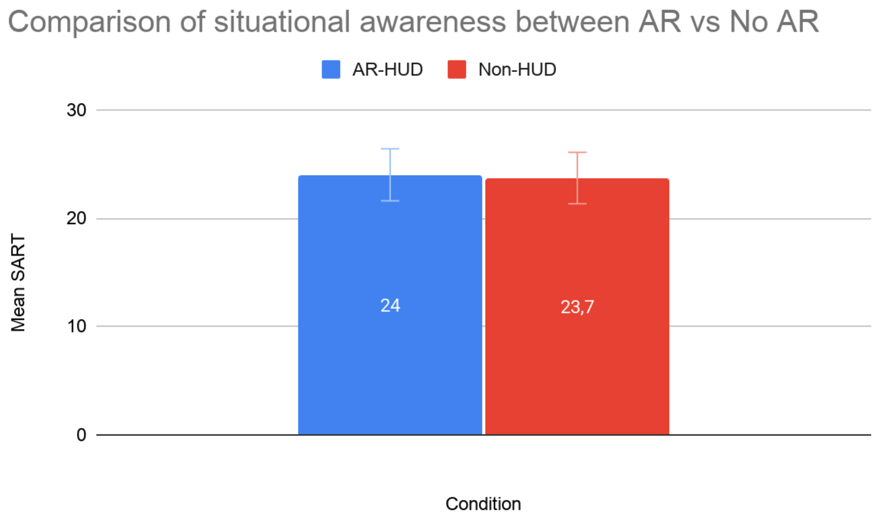


Figure 6.11: Comparison of mean overall SART scores and standard deviations between AR-HUD and non-HUD conditions.

However, although the overall SART scores showed only a small difference between the conditions, analysing the individual SART dimensions revealed clearer differences. See Figure 6.12. The AR-HUD condition resulted in higher Understanding scores (M = 14.05) compared to the non-HUD condition (M = 12.7), while Demand scores were lower in the AR-HUD condition (M = 6.6) than in the non-HUD condition (M = 8.05). Supply scores were slightly lower in the AR-HUD condition (M = 16.4) compared to the non-HUD condition (M = 19.05), but remained relatively balanced between conditions. According to the SART calculation described in Section 4.6.4, higher Understanding together with lower Demand contributes to improved situation awareness. Therefore, despite the relatively small overall SART difference, the dimensional analysis suggests that the AR-HUD supported better perceived situation awareness while reducing attentional demand during driving.

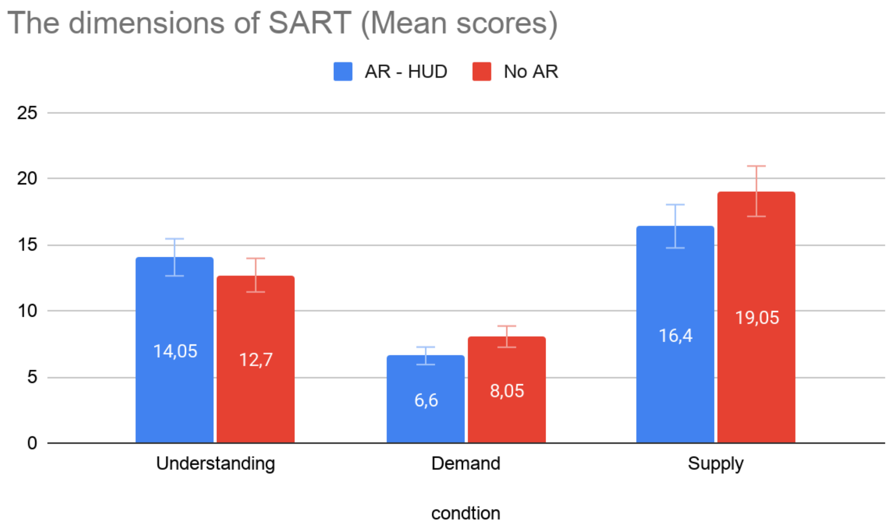


Figure 6.12: Comparison between the three dimensions of SART.

6.3.3 Route Comparison

A comparison between Route 1 and Route 2 uncovered some variation in both NASA-TLX and SART scores across the different conditions. Under the AR-HUD condition, the mean NASA-TLX score for Route 1 was 24.8 and for Route 2 was 17.83. Similarly, under the non-HUD condition, NASA-TLX scores were 32.58 on Route 1 and 23.4 on Route 2. Similarly, the SART scores showed only small variations between the routes. In the AR-HUD condition, the mean SART score decreased from 24.8 on Route 1 to 22.9 on Route 2, while the non-HUD condition increased slightly from 23.4 on Route 1 to 24.0 on Route 2.

Although several participants subjectively described Route 2 as more demanding during interviews, the workload scores generally was lower on the second route regardless of condition. This may indicate the presence of a learning or familiarization effect rather than differences caused solely by route complexity.

Overall, despite some variation between routes and potential learning effects, the AR-HUD condition consistently resulted in lower NASA-TLX scores compared to the non-HUD condition across both routes. This suggests that the AR-HUD reduced perceived workload independently of route order. The relatively small differences in SART scores additionally suggest that perceived situation awareness remained comparatively stable regardless of route order.

Table 6.1: Presents the comparison between the two routes.

Condition	Route	Mean SART	Mean TLX
AR-HUD	Route 1	24,8	17,83
AR-HUD	Route 2	22,9	17,5
Non-HUD	Route 1	23,4	32,58
Non-HUD	Route 2	24	25,25

6.4 Result from Eye-Tracking Data

The eye-tracking results were analysed based on AOIs defined in the vehicle environment. The most relevant AOIs for this study were the AR-HUD, DIM, CSD and No-AOI. Left Mirror, Right Mirror and Rearview Mirror were also included in the analysis to separate them from No-AOI. No-AOI therefore refers to gaze samples that were not assigned to any of the predefined AOIs, and most likely mainly represented gaze through the windshield.

Figure 6.13 presents the AOI hit breakdown per drive. The figure gives an overview of how participants' visual attention was distributed across the defined AOIs during both AR-HUD and non-HUD conditions. Overall, the results show that participants looked less at the CSD when the AR-HUD was active. This indicates that the AR-HUD reduced the need to look down at the central display during navigation. The DIM also showed a slight reduction in visual attention in the AR-HUD condition. At the same time, gaze toward the AR-HUD area was slightly higher when AR-HUD content was active, which suggests that participants used the AR-HUD as part of their navigation support.

No-AOI accounted for a large part of the recordings in both conditions. This is expected in a real-world driving study, since drivers continuously look at areas in the road environment that are not always captured by the predefined AOIs. The No-AOI values were slightly higher in the AR-HUD condition, which may indicate that participants spent more time looking toward the general road environment when AR-HUD support was available. However, this should be interpreted carefully, since No-AOI includes all gaze samples outside the defined AOIs and is therefore less specific than the display-related AOIs.

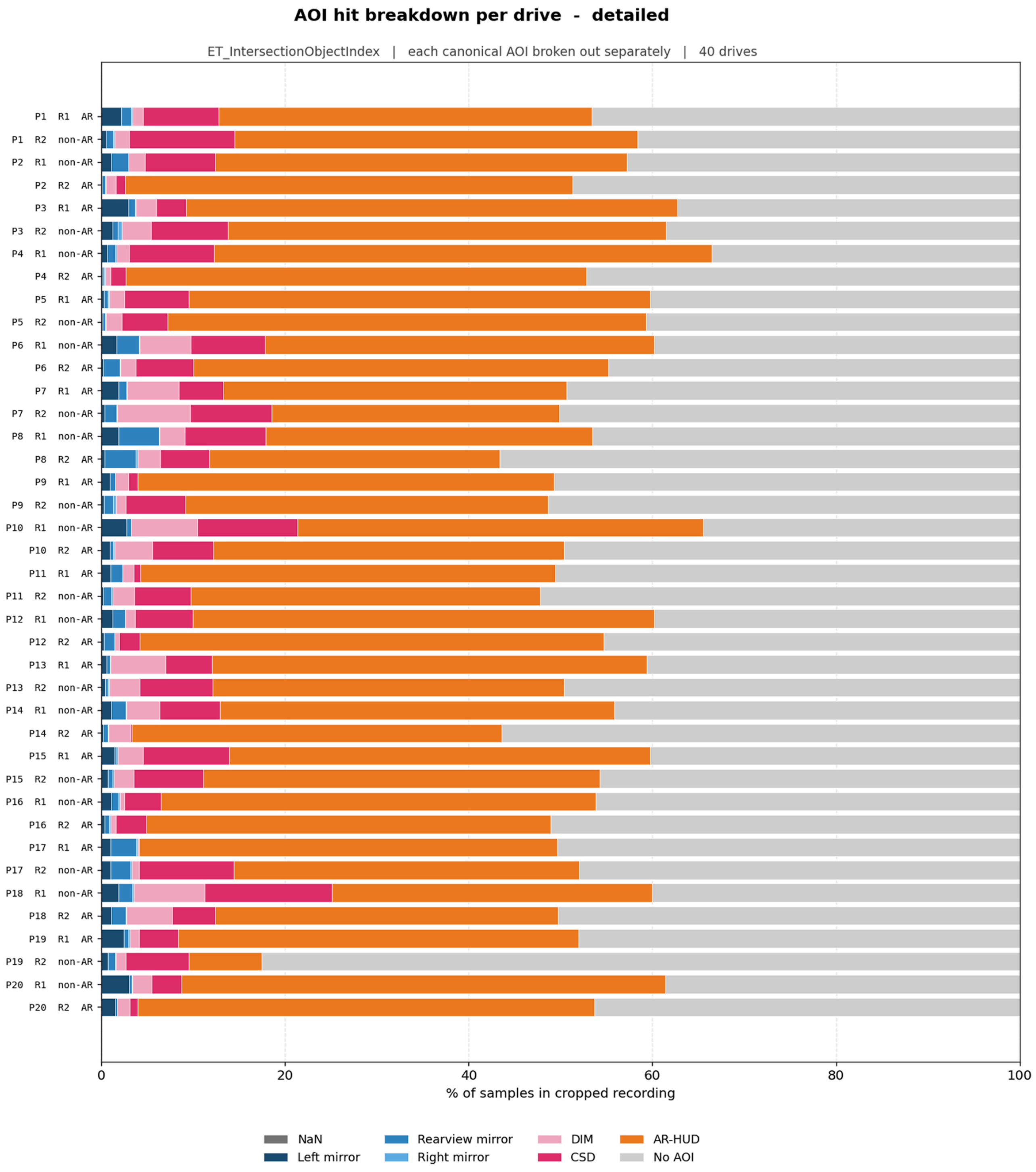


Figure 6.13: AOI hit breakdown per drive.

6.4.1 Dwell Time

Dwell time refers to the percentage of the recording that participants spent looking at a specific AOI. It shows how much of the total driving time was visually directed toward each area (see Figure 6.14).

For dwell time, the clearest difference was found for the CSD. In the AR-HUD condition, participants spent on average **3.8%** of the recording looking at the CSD, compared to **8.0%** in the non-HUD condition. This corresponds to a reduction of approximately 52.5%, which may suggest that the AR-HUD had a clear effect on reducing visual attention toward the CSD.

The DIM also showed a lower dwell time in the AR-HUD condition, with **2.1%** compared to **3.0%** in the non-HUD condition. This indicates a small reduction in attention toward the DIM.

The AR-HUD AOI had a slightly higher dwell time in the AR-HUD condition, with **45.8%** compared to **42.4%** in the non-HUD condition. This suggests that participants spent somewhat more time looking toward the AR-HUD area when visual content was presented there.

No-AOI also increased slightly in the AR-HUD condition, from **36.6%** in the non-HUD condition to **39.2%** in the AR-HUD condition. This may suggest that participants spent more time looking toward the broader road environment when the AR-HUD was active.

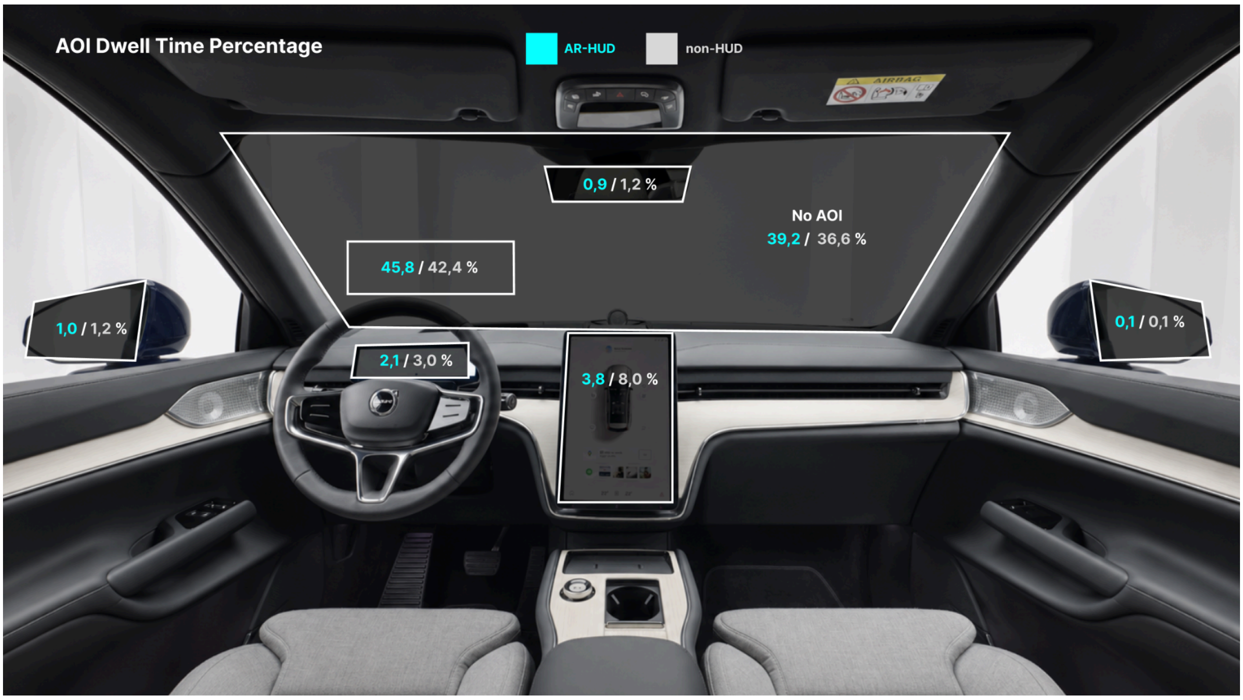


Figure 6.14: AOI Dwell time percentage.

The AOI Dwell time percentage for each individual participant and drive is presented in Appendix H.

6.4.2 Glance Rate

Glance rate refers to how often participants looked at a specific AOI, measured as the number of glances per minute. A glance was defined as one continuous sequence of gaze samples within the same AOI. This means that if a participant looked at the AR-HUD continuously for one minute, it would count as one glance, resulting in a glance rate of one glance per minute. Several shorter looks toward the same AOI within one minute would result in a higher glance rate.

The glance rate results show a clear reduction in how often participants looked at the CSD when the AR-HUD was active (see Figure 6.15). In the AR-HUD condition, participants looked at the CSD on average **3.5 times per minute**, compared to **6.8 times per minute** in the non-HUD condition. This may indicate that the AR-HUD reduced the frequency of glances toward the central display.

The DIM also showed a lower glance rate in the AR-HUD condition, with **3.2 glances per minute** compared to **4.1 glances per minute** in the non-HUD condition. This suggests that participants checked the driver display slightly less often when AR-HUD support was available.

For the AR-HUD AOI, the glance rate was slightly higher in the AR-HUD condition, with **29.9 glances per minute** compared to **27.7 glances per minute** in the non-HUD condition. This suggests that participants returned their gaze to the AR-HUD area somewhat more often when the AR-HUD was active.

No-AOI had a higher glance rate in the AR-HUD condition, with **31.1 glances per minute** compared to **28.5 glances per minute** in the non-HUD condition. Since No-AOI includes gaze outside the defined display areas, this may indicate that participants shifted their gaze more often within the general driving environment when using the AR-HUD.

Figure 6.15: AOI Glance Rate (count per minute).

The AOI Glance Rate for each individual participant and drive is presented in Appendix I.

6.4.3 Glance Duration

Glance duration refers to the average length of each glance within a specific AOI, measured in milliseconds. While dwell time shows the total proportion of time spent looking at an AOI, and glance rate shows how often participants looked there, glance duration shows how long each individual glance lasted on average.

The AR-HUD AOI had the longest mean glance duration among the display-related AOIs (see Figure 6.16). In the AR-HUD condition, the mean glance duration for the AR-HUD AOI was **947.7 ms**, compared to **931.4 ms** in the non-HUD condition. This shows that glances toward the AR-HUD area lasted just under one second on average in both conditions.

For the CSD, mean glance duration was lower in the AR-HUD condition, with **629.0 ms** compared to **701.5 ms** in the non-HUD condition. This suggests that participants not only looked at the CSD less often when the AR-HUD was active, but their glances toward it were also shorter on average.

The DIM showed a similar pattern. Mean glance duration was **381.3 ms** in the AR-HUD condition and **414.2 ms** in the non-HUD condition. This indicates slightly shorter glances toward the driver display when the AR-HUD was active.

For No-AOI, mean glance duration was similar across conditions, with **767.4 ms** in the AR-HUD condition and **775.8 ms** in the non-HUD condition. This suggests that the average length of glances outside the defined AOIs remained stable across the two conditions.

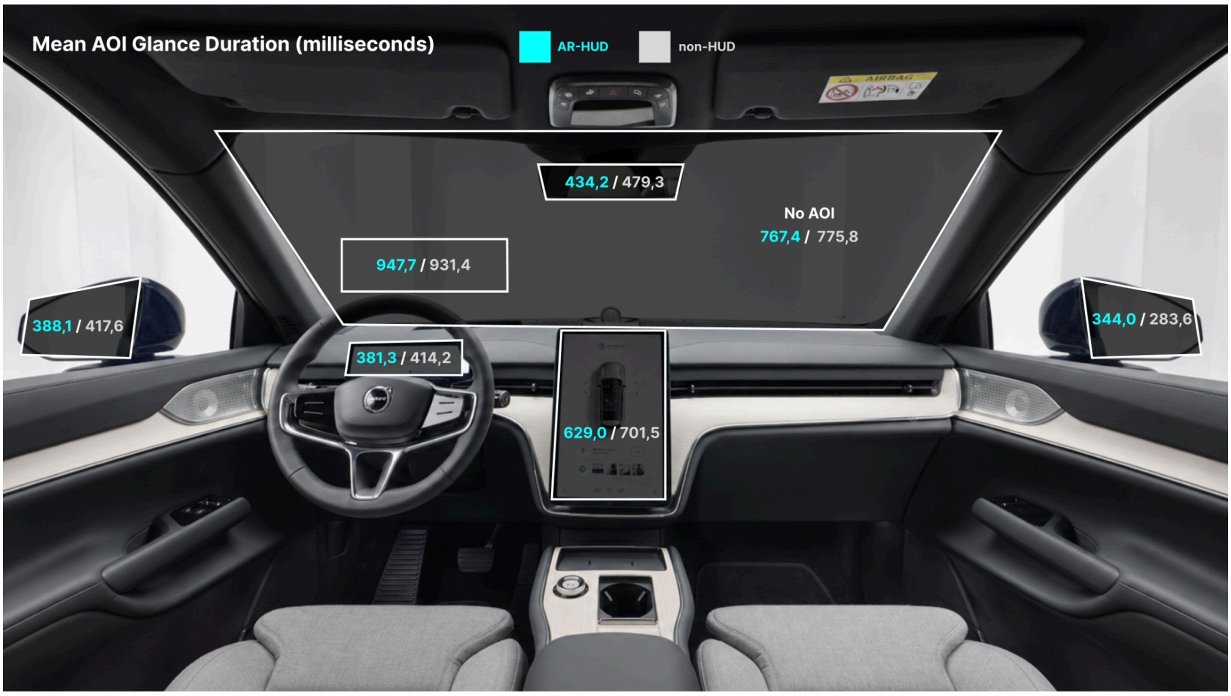


Figure 6.16: Mean AOI Glance Duration (milliseconds).

The Mean AOI Glance Duration for each individual participant and drive is presented in Appendix J.

Overall, the eye-tracking results suggest that the AR-HUD reduced visual attention toward the CSD, both in terms of total dwell time and number of glances per minute. This indicates that participants relied less on the CSD for navigation when AR-HUD support was available. The AR-HUD condition also showed slightly higher attention toward the AR-HUD area and No-AOI, suggesting that participants' gaze remained more oriented toward the forward driving environment.

6.5 Thematic Analysis of Interview Findings

A thematic analysis was conducted from the semi structured interview responses to identify patterns and themes related to driver behaviour, workload, situation awareness and overall user experience when comparing the AR-HUD and non-HUD conditions.

The analysis resulted in five primary themes:

- Theme 1: Reduced visual distraction and cognitive load,
- Theme 2: Increased navigation confidence and guidance
- Theme 3: Initial confusion and learning effect
- Theme 4: Situation awareness and road focus
- Theme 5: Design improvements.

6.5.1 Theme 1: Reduced Visual Distraction & Cognitive Load

One of the most recurring themes among the participants was that the AR-HUD reduced the need to look away from the road toward the CSD. Participants repeatedly described the AR-HUD condition as more intuitive, less distracting and less mentally demanding compared to the non-HUD condition.

Several participants explained that the navigation cues presented directly in the forward field of view helped them maintain focus on the road while still understanding upcoming navigation instructions. This was particularly noticeable in situations involving lane changes, exits, and roundabouts, where participants otherwise needed to repeatedly shift attention between the road and the CSD.

> "It was much smoother that it came up when you should turn instead of looking down there." (Participant 17)

Similarly, Participant 1 explained:

> "It was much much better with the AR-HUD, especially with the big arrows and then it took the focus off the CSD."

Participants also described the AR-HUD as reducing cognitive effort and simplifying the driving task. Several participants explained that they no longer needed to divide their attention between the road and the navigation display to the same extent as during the non-HUD condition.

Participant 6 explained:

> “Sometimes when you have navigation on the CSD, you need to focus on both road and CSD. But with AR-HUD you can just look at the road and not waste time.”

Likewise, Participant 17 described the AR-HUD as:

> “Much easier, easy to understand, you didn’t need to think as much” (Participant 17)

Some participants additionally reported that the AR-HUD changed how frequently they checked other displays inside the vehicle. Instead of repeatedly glancing toward the CSD or DIM for navigation confirmation, participants felt more confident relying on the information projected in the forward field of view.

Participant 9 explained:

> “First it was very clear, the arrows usually show on time. I didn't look at DIM and CSD. It was the first time I drove where I didn't have to look at them.”

Similarly, Participant 7 stated:

> “Don't need to check it (CSD) like I usually do.”

Overall, participants perceived the AR-HUD as reducing visual distraction and lowering cognitive workload during navigation tasks. These qualitative findings also align with the NASA-TLX results, where the AR-HUD condition showed lower Mental Demand and Effort scores compared to the non-HUD condition.

6.5.2 Theme 2: Increased Navigation Confidence & Guidance

Another recurring theme was increased confidence while navigating with the AR-HUD system. Participants frequently described feeling more certain about lane positioning, exits, and upcoming turns.

Participant 15 explained:

> "It increased my confidence about when I should turn right."

Participants particularly appreciated the lane guidance and contextual information presented in complex traffic situations such as roundabouts and multi-lane roads with bus lanes.

Participant 7 stated:

> "How nice with the bus symbol! I like it."

Similarly, Participant 14 explained:

> "Very handy that it also shows a bus lane, it's not always easy to note that in normal cases"

Participant 17 additionally described the lane guidance as especially helpful in more demanding traffic situations:

> "It was useful to see which lane to stay in. Now I should stay in the middle lane, three lanes, it's very clear."

Several participants also described the AR-HUD as easier to follow and more intuitive compared to relying solely on the CSD.

Participant 7 stated:

> "I found it easy to follow, you definitely know which lane to take. I found it easier to drive with an AR HUD."

Participants additionally reported that the AR-HUD reduced uncertainty and supported safer navigation decisions. In several non-HUD driving sessions, participants required verbal navigation assistance from the researchers regarding lane changes and exits, which occurred less frequently during the AR-HUD condition.

Participant 8 expressed uncertainty and said:

> "Should I go straight ahead?"

Similarly, Participant 17 stated:

> “I felt much more confident about where I was going, and didn't have to look at CSD to understand where I was going next. I felt safer on the road.”

Several participants also described the AR-HUD condition as less stressful and easier to follow compared to relying solely on the CSD. Participant 13 explained:

> “Without it, I missed the exit. Without it I was a little more stressed.”

Participants additionally reported that the AR-HUD helped them plan driving actions earlier and navigate more efficiently. Participant 14 explained:

> “With (AR) you get info and have time to check the surroundings.”

Likewise, Participant 6 explained that the system improved planning during navigation:

> “Much simpler, easier to understand, didn’t have to think too much.”

Many participants also emphasized that the AR-HUD and CSD complemented each other well. While the AR-HUD supported immediate driving actions, what action to take now and lane positioning, the CSD provided a broader overview of the route ahead.

Participant 4 summarized this distinction by stating:

> “AR-HUD is right now in traffic. CSD is further ahead.”

> “I think that AR-HUD still conveys a type of clarity, for example which lane to be in. Conveys what to do at the moment. When the animations come, focus on the driving. CSD okay, yes, I'll make a turn in 6 km maybe. CSD further ahead in traffic. AR-HUD right now in traffic. CSD may not have it with which lane to be in.” (Participant 4)

Similarly, Participant 2 explained:

> “In CSD you actually get a map with where you are going, whereas AR-HUD is just step-by-step navigation.”

Overall, participants perceived the AR-HUD as improving navigation comprehension, reducing uncertainty and supporting a more relaxed and confident driving experience.

6.5.3 Theme 3: Initial Confusion & Learning Effects

Although the AR-HUD condition was generally perceived positively, several participants initially experienced uncertainty when first interacting with the system. This was particularly noticeable among participants unfamiliar with AR-HUD technology.

Participants initially struggled to understand why navigation cues only appeared when necessary and why no guidance was displayed during certain driving segments.

Participant 7 explained:

> "You have to get used to when it disappears and when it comes back."

Similarly, Participant 16 explained:

> "Initially I was not clear when the AR direction was coming."

Several participants also described the roundabout visualizations and numerical indicators as initially confusing before they understood how the system functioned.

Participant 7 asked:

> "Does 1 mean I should take the first exit?"

However, most participants adapted quickly after a short familiarization period and later described the same features as useful and intuitive. Participant 10 stated:

Participant 14 explained:

> "Now I guess I'm going straight ahead, second exit, a 2a is very nice, very clear where I'm going."

Similarly, Participant 14 later described the roundabout information as:

> "The number in the roundabout symbol was very clear, not as clear in GPS (CSD navigation)."

Participant 20 also explained that participants adapted quickly during the drive:

> “I think at first I was a bit uncertain, it took me a couple of seconds to realize, but it was very clear.”

Some participants additionally suggested that a minimal “straight ahead” indication could further reduce uncertainty when no guidance was displayed or when there was an exit they could take. Nevertheless, most participants understood the interaction logic after a short period of time.

These findings suggest that short-term adaptation and familiarity may play an important role in how drivers perceive and interact with AR-HUD systems during early use.

6.5.4 Theme 4: Situation Awareness & Road Focus

Participants frequently described the AR-HUD condition as supporting greater focus on the surrounding driving environment. Many participants stated that they could concentrate more on traffic, road conditions, and surroundings rather than repeatedly checking the navigation display..

Participant 8 explained:

> “I could concentrate more on driving and the surroundings instead of focusing on the map.”

Similarly, Participant 14 stated:

> “With AR I could focus much more on the road and surroundings, I didn't have to look down”

Participant 12 additionally described the AR-HUD as:

> “A good eye-catcher, no need to change focus, right in the field of view.”

Several participants described the visual placement of the AR-HUD as contributing to a more natural visual behaviour while driving. Participant 15 explained:

> “It’s the right height and depth.”

Participants also reported that the AR-HUD allowed them to maintain attention toward the road environment while still feeling confident that navigation support would appear when needed.

Participant 8 explained:

> “It was like I could focus better on my surroundings and driving. I knew help was coming.”

Some participants additionally described that the AR-HUD reduced the need for gaze shifts toward the CSD, which they perceived as supporting smoother and more controlled driving behaviour.

However, a few participants also noted that poorly timed or unexpected visualizations could briefly draw attention away from the surrounding environment. Some participants further mentioned that excessive or prolonged visualizations could risk becoming distracting if too much information was displayed simultaneously.

Despite these concerns, the majority of participants perceived the AR-HUD as supporting more road-focused driving behaviour and improved situational awareness compared to the non-HUD condition.

6.5.5 Theme 5: Design Improvements

Participants also provided several suggestions for improving the AR-HUD system. One of the most recurring requests was additional contextual driving information such as speed, speed limits, ADAS information and traffic-light indicators.

Participant 14 stated:

> “The only thing that would have been so great was the speed.”

Several participants also suggested that the inclusion of future ADAS-related information could further reduce the need to look down toward other displays inside the vehicle.

Another recurring topic concerned the positioning and timing of the visualizations. Some participants felt that certain lane guidance elements appeared too far to the left or appeared either too early or too late during navigation.

Participant 15 explained:

> “Three arrows telling me where to go, it’s quite on the left side. It can be hard to see it. It would be nice to have it in the front (middle)”

Similarly, participant 21 stated:

> “The symbols are a bit too left, the position is a bit weird.”

Some participants also described the spatial positioning of the lane markings as slightly unnatural, which occasionally reduced the perceived realism of the visualizations. Participant 21 explained:

> “The lane markings were sometimes a bit confusing because of their positioning. They did not always feel naturally integrated with the driving environment, although the information itself was very useful.”

Timing was repeatedly described as an important aspect of the user experience.

Participant 4 stated:

> “Timing is the most important thing.”

Some participants explained that the guidance occasionally appeared too early or too late depending on traffic situations and individual driving style. Participants additionally emphasized that the visualizations should only appear when necessary to avoid information overload.

Participant 2 explained:

> “I don't think they should have graphics on all the time, but just in time.”

Similarly, Participant 4 stated:

> “If it always shows the same so you need to change lanes, then you might miss it. There must be a clear difference.”

Some participants also suggested that additional contextual information regarding upcoming lane changes or distances could further reduce the need to rely on the CSD.

Participant 4 explained:

> "If you have a symbol that shows a few km ahead, I wouldn't have checked the CSD at all."

Participants also expressed differing opinions regarding the animated arrows. Some participants perceived the animations as immersive, intuitive, and highly supportive, while others considered them slightly distracting or unnecessary in certain situations.

Participant 9 explained:

> "I don't know how much that arrow helps in the roundabout when getting off."

Several participants further suggested that the amount of guidance may need to adapt depending on traffic complexity and driving context. For example, some participants believed that the AR-HUD was particularly beneficial in city driving and dense traffic situations where lane positioning becomes more demanding.

Finally, many participants described the combination of AR-HUD and CSD as beneficial, where the AR-HUD supported immediate driving actions while the CSD provided overview information about the route ahead and overall journey planning.

Overall, participants generally perceived the AR-HUD system positively while also identifying opportunities for improved timing, positioning, customization, and contextual driving information.

6.5.6 Summary of themes

The thematic analysis revealed that participants generally perceived the AR-HUD system as intuitive, supportive, and less cognitively demanding compared to the non-HUD condition. The most prominent themes included reduced visual distraction, increased navigation confidence, and improved road-focused attention. Participants particularly appreciated the lane guidance, contextual navigation information, and the reduced need to repeatedly check the CSD during driving.

However, some participants initially experienced uncertainty regarding how and when the AR visualizations appeared, suggesting that familiarity and learning may play an important role in future AR-HUD implementations. Participants also identified several opportunities for future improvements, including additional contextual information, improved timing, and increased customization of the when and what it displays in the interface.

Overall, the qualitative findings support the quantitative NASA-TLX results and mostly support the SART and eye-tracking findings as well, strengthening the overall interpretation through methodological triangulation.

7. Discussion

This chapter will present a brief summary of the results, followed by a discussion of the results and a discussion of the methods. The chapter connects the results with previous research, theories and own reflections. The discussion of the results is structured according to the three research questions and concludes by answering the overall research question. Finally, the implications of the study and suggestions for future research are presented.

7.1 Summary of the Result

The purpose of this study was to investigate how AR-HUD systems influence driver behaviour, perceived workload, situation awareness, and user experience during real-world navigation tasks compared to non-HUD conditions. The results indicate that the AR-HUD generally supported more road-focused driving behaviour, reduced perceived workload and improved navigation confidence compared to the non-HUD condition, where the participants had to rely solely on the CSD navigation. Eye-tracking data showed reduced visual attention toward the CSD, where dwell time decreased from 8.0% to 3.8% and glance rate decreased from 6.8 to 3.5 glances per minute during the AR-HUD condition. The NASA-TLX results further showed a 38.9% reduction in overall perceived workload in the AR-HUD condition, while the largest improvements were observed in mental demand, effort, and frustration. Although the overall SART differences were relatively small, the dimensional analysis indicated higher understanding and lower attentional demand when using the AR-HUD. The qualitative findings supported the quantitative results, as participants consistently described the AR-HUD as intuitive, less distracting, and easier to follow, especially during complex driving situations such as lane changes, exits, and roundabouts.

7.2 Method

To strengthen the credibility of the findings, the study applied methodological triangulation by combining quantitative and qualitative methods, including eye-tracking, questionnaires and semi-structured interviews. According to Denscombe (2009), triangulation can improve the accuracy and completeness of research findings by examining the same phenomenon from multiple perspectives. By integrating these methods, researchers can benefit from their different strengths, which has contributed to a broader and more reliable understanding of how AR-HUD systems influenced driver behaviour, perceived workload, situation awareness and user experience.

However, several methodological limitations should be considered when interpreting the findings. The user study included a relatively small sample size of 20 participants, which limits the statistical power and generalisability of the results. In addition, most participants were recruited within Volvo Cars through a convenience sampling, meaning that a larger and more diverse participant group may have produced different findings. While this approach was chosen due to time and resource constraints, it may limit the representativeness of the sample, and therefore the results should be interpreted with caution when generalising to a broader population. Some participants also had prior experience with HUD or AR-HUD systems, which may have influenced their expectations and introduced bias in their responses. To partially mitigate this, participants with varying levels of experience and from different departments were included.

Furthermore, the study was conducted using only two predefined driving routes during relatively short driving sessions of approximately 10 minutes each. As a result, this may have limited the ability to capture long-term behavioural changes, adaptation effects, and variations in driver behaviour over time. The selected routes and driving conditions may not reflect the full complexity of real-world driving. Including longer driving sessions and a broader range of driving environments, such as urban traffic, highways, and adverse weather conditions, could potentially have strengthened the reliability of the findings and produced different behavioural patterns.

Another important methodological consideration concerns the eye-tracking system. Since participants were aware that their gaze behaviour was being recorded, this may have influenced their behaviour during the study. Participants may consciously or unconsciously have adjusted their attention toward the road or the AR-HUD. Furthermore, eye-tracking calibration quality varied slightly between participants. Although all calibrations met the predefined acceptance threshold below 5° of error, some participants achieved substantially better calibration scores than others. Variations in calibration quality may therefore have influenced the accuracy of the gaze data and AOI classifications. Factors such as seating position, eyesight, reflections and head movement may also have affected eye-tracking accuracy during the driving sessions.

A pilot study was conducted before the main study to identify procedural issues and improve reliability and overall study design. The pilot test revealed that the full NASA-TLX questionnaire was too time-consuming and created unnecessary frustration after the driving task. Therefore, the full NASA-TLX was replaced with raw NASA-TLX to reduce participant workload while still enabling subjective workload to be measured.

Thematic analysis was used to analyse the qualitative data because it is a flexible and widely used method for identifying patterns in participants' experiences and perceptions. However, thematic analysis is influenced by researcher interpretation and judgement, which may affect reliability and objectivity (Bryman, 2012). There is also a risk that complex qualitative experiences become simplified into broader themes, potentially leading to a loss of nuance. Although an inductive approach was used, it is difficult to completely avoid pre-assumptions during interpretation.

Despite these limitations, conducting the study in a real-world driving environment rather than in a simulator may increase the ecological validity and transferability of the findings. At the same time, it also introduces uncontrolled variables such as varying traffic situations, weather conditions and individual driving differences, which may have influenced the results.

7.3 Result

This section discusses the findings in relation to the three domains in the research question: (1) visual attention distribution, (2) perceived workload, and (3) situation awareness. The results are interpreted across quantitative and qualitative data sources, including eye-tracking metrics, NASA-TLX, SART, and interview findings.

7.3.1 Visual Attention Distribution

The eye-tracking results demonstrate a clear shift in visual attention distribution when using the AR-HUD compared to the non-HUD condition. Participants significantly reduced their visual attention toward the CSD, as shown by both dwell time (8.0% to 3.8%) and glance rate (6.8 to 3.5). These findings may indicate that participants relied less on the CSD for navigation when AR-HUD support was available.

At the same time, visual attention toward the AR-HUD area increased slightly, suggesting that participants adapted their gaze behaviour to integrate the AR-HUD into their natural visual scanning strategy. The No-AOI category also increased slightly during the AR-HUD condition, which may indicate more attention toward the surrounding road environment rather than in-vehicle displays. Although No-AOI includes all gaze outside predefined areas and should therefore be interpreted cautiously, the findings still support a more road-focused visual behaviour when using the AR-HUD.

These findings are supported by the qualitative data, where participants consistently reported a reduced need to look down at the CSD and described the AR-HUD as allowing them to maintain focus on the road. Several participants also stated that the AR-HUD made navigation easier to follow during complex driving situations such as lane changes, exits, and roundabouts. These findings align with previous research suggesting that HUD systems can reduce visual distraction by presenting information closer to the driver's field of view. Overall, the results indicate that AR-HUD shifts visual attention from HDD:s to the forward driving scene, which may support more continuous environmental monitoring and reduced visual distraction.

7.3.2 Perceived Workload

One of the prominent findings in this study was the reduction in perceived workload during the AR-HUD condition. The NASA-TLX results showed lower overall workload scores compared to the non-HUD condition (17.67 vs 28.92), corresponding to a 38.9% reduction. The largest differences were observed in Mental Demand, Effort and Frustration. This indicates that the AR-HUD reduced the cognitive resources required for navigation-related tasks during driving.

The qualitative interview findings further support this interpretation, as participants consistently described the AR-HUD as easier to follow, more intuitive, and less distracting than the CSD. Many reported reduced stress during navigation, since they no longer needed to divide attention between multiple displays. This was particularly evident in situations requiring quick decisions, such as lane changes and exits, where the AR-HUD provided clearer and more immediate guidance. Several participants also noted that lane positioning and exit information were less intuitive in the CSD alone, sometimes requiring additional guidance from the researcher during the task. In general, participants often preferred a combination using the AR-HUD for immediate actions and CSD for longer-term route planning.

The reduction in workload was also reflected in the eye-tracking results. Since participants looked less frequently toward the CSD during the AR-HUD condition, the need for repeated attentional switching appeared to decrease. This may have contributed to lower cognitive demand during driving. These findings are consistent with previous AR-HUD research suggesting that HUDs can reduce visual demand and support faster interpretation of navigation information.

Although some learning effects between routes may have influenced the results, NASA-TLX scores remained consistently lower in the AR-HUD condition across both routes. The counterbalanced study design helped reduce systematic order effects, although some reduction in workload during the second route may still reflect increased familiarity with the driving task and the AR-HUD interface.

Overall, the results indicate that the AR-HUD primarily contributed to reduced workload by simplifying navigation tasks and reducing the need for repeated visual attention shifts toward secondary displays.

7.3.3 Situation Awareness

The results indicate that the AR-HUD contributed to slightly improved situation awareness compared to the non-HUD condition (24.0 vs. 23.7), although the differences in the overall SART scores were relatively small. The largest improvements were instead observed in perceived workload. This suggests that the AR-HUD primarily supported driving by reducing cognitive demand rather than dramatically increasing overall situation awareness.

The relatively small differences in overall situation awareness may partly be explained by the driving context. The routes used in the study primarily consisted of rural and highway environments with moderate traffic complexity, although they included a few more demanding elements such as exits and roundabouts. This may have limited the potential differences between conditions. In more complex urban environments, where attentional demands are higher, larger differences in situation awareness may have emerged. In addition, some participants were already familiar with parts of the route due to their everyday driving, which may have further reduced the sensitivity of the measure.

However, when analysing the SART dimensions separately, the AR-HUD condition showed higher Understanding scores (14,05 vs 12,7) together with lower Demand scores (6,6 vs 8,05) and Supply remained relatively similar (16,4 vs 19,05). This pattern suggests that participants experienced the navigation information as easier to interpret while at the same time experiencing lower attentional demand. The interview findings support this interpretation, as several participants described that the AR-HUD allowed them to focus more on surrounding traffic and road conditions while still feeling confident about where to drive.

An interesting observation was that the familiarity-related scores in SART were slightly lower for the AR-HUD condition. This may reflect participants' limited previous experience with AR-HUD systems rather than weaknesses in the interface itself. Several participants initially expressed uncertainty regarding when visualisations would appear or disappear, particularly during the beginning of the drive. However, most participants adapted relatively quickly and later described the system as intuitive and easy to understand.

The findings also suggest that contextual navigation information played an important role in supporting situation awareness. Participants frequently highlighted lane guidance, bus lane visualisations and roundabout support as particularly valuable features. One scenario discussed during the interviews was the exit before the large roundabout on Route 2, where participants had limited time to position themselves correctly due to the bus lane. In this situation, several participants described the AR-HUD guidance as especially helpful, although some also suggested that clearer or earlier communication could further improve the experience with distance information to change lanes.

Overall, the findings suggest that the AR-HUD supported situation awareness primarily by helping drivers maintain focus on the road environment while reducing uncertainty during navigation tasks.

7.3.4 Design Implications & Qualitative Reflections

The qualitative findings revealed that participants generally perceived the AR-HUD system as supportive, intuitive and beneficial for navigation-related driving tasks. Across the interviews, participants consistently described the AR-HUD as reducing distraction, improving navigation confidence and supporting more road-focused driving behaviour. These findings aligned closely with the quantitative results from the NASA-TLX, SART and eye-tracking analysis.

One important finding concerned the timing and contextual presentation of navigation information. Participants appreciated that the AR-HUD displayed guidance only when needed rather than continuously presenting visual elements. This reduced unnecessary visual clutter and helped maintain focus on the road. At the same time, some participants initially became uncertain when no visualisations were visible, particularly during the beginning of the drive. This suggests that future AR-HUD systems should provide clearer onboarding and more predictable interaction behaviour, especially for first-time users.

The interviews also highlighted the value of contextual navigation guidance. Features such as lane guidance, bus lane visualisations and animated arrows were repeatedly described as particularly useful in complex traffic situations, including exits, lane changes and roundabouts. Participants frequently stated that the AR-HUD made it easier to understand where to position the vehicle and reduced uncertainty during navigation decisions. These findings suggest that AR-HUD systems may provide the greatest benefit in situations requiring rapid interpretation and decision-making.

Several participants additionally commented on the visual design and placement of interface elements. The colours and visual clarity were generally appreciated, although some participants suggested that certain symbols should be positioned more centrally instead of toward the left side of the display. Since AR-HUD systems rely heavily on spatial alignment with the real-world environment, positioning, calibration and field of view appear to be important usability factors. Differences in participant height, seating position and eyesight may also have influenced how the visualisations were perceived.

The findings further suggest that AR-HUD systems should carefully balance visibility and information density. While participants appreciated clear and noticeable guidance, excessive or badly timed visualisations may risk becoming distracting or overwhelming. Some participants also preferred different levels of guidance depending on the driving situation, indicating that future systems may benefit from adaptive or customizable interfaces.

The findings therefore suggest several concrete implications for future AR-HUD design:

- AR-HUD visualisations should appear contextually and “just in time” to avoid unnecessary distraction and visual clutter.
- Navigation guidance should prioritize complex driving situations such as lane changes, exits and roundabouts where rapid decision-making is required.
- Spatial alignment and positioning of visual elements are critical for usability, intuitiveness and perceived realism.
- Onboarding and interaction predictability are important, especially for first-time AR-HUD users unfamiliar with the system behaviour.
- AR-HUD systems should carefully balance visibility and information density to avoid overwhelming the driver.
- Future AR-HUD interfaces may benefit from adaptive or customizable levels of guidance depending on user preference and driving context.

Overall, the qualitative findings support the quantitative results and indicate that AR-HUD systems have strong potential to improve navigation-related driving experiences by reducing distraction, simplifying interpretation of navigation information and supporting greater focus on the driving environment.

7.5 Future Development

Future development of the AR-HUD prototype could focus on both design improvements and broader testing conditions. From a design perspective, feedback from the user study indicated that the static symbols should be placed in the center instead of in the lower left corner. Participants mention this suggestion as it would make the information easier to notice and be similar to their previous experience with regular HUD and reduce the need for drivers to shift their gaze away from the central road view. Future iterations could therefore explore alternative placements of symbols.

Future studies should also test the AR-HUD system in more demanding driving environments. This study was conducted on predefined routes with either sunny or partly cloudy weather. Further research could investigate how the system performs in dense city traffic, where the driving situation is often more complex and stressful. Different weather conditions, such as heavy rain, snow or fog, should also be explored, since these factors may affect both driver workload and how clearly AR-HUD visualisations are perceived. Also different times of the day, daylight and nightlight driving which may significantly affect AR-HUD readability, perceived brightness, and contrast against the road environment. Future studies should therefore investigate how AR-HUD performance and driver workload vary across day/night cycles and under different visibility conditions.

Another important direction for future development is to connect the AR-HUD more directly to the vehicle's internal systems. Access to vehicle data such as speed, ADAS information, GPS, and sensor input would make it possible to develop more advanced and context-aware AR-HUD content. For example, future designs could include visualisations for blind spot information, vehicles ahead, speed adaptation or warnings based on the surrounding traffic situation. Also to have similar to today turn by turn to indicate how long they should be in that lane.

Future studies should also investigate AR-HUD systems under more demanding and varied driving conditions. This study was conducted on predefined routes during relatively stable weather conditions. Further research could explore how AR-HUD systems perform in dense city traffic, highway driving, heavy rain, snow, fog or low-visibility environments. Daytime and nighttime driving should also be investigated further, since brightness, contrast and readability may significantly affect the user experience.

Long-term studies would additionally provide a better understanding of how familiarity and adaptation influence driver behaviour, perceived workload and trust in the system over time. Several participants initially experienced uncertainty regarding how and when visualisations appeared, but adapted relatively quickly during the drive. Future research could therefore investigate how user experience changes after longer-term AR-HUD use. Additionally, including a larger and more diverse sample size would also improve the generalisability of the findings.

Finally, future research could combine eye-tracking data with additional physiological measurements, such as heart rate variability or other workload-related measures. This could provide a more comprehensive understanding of how AR-HUD systems influence driver attention, workload and overall driving experience in real-world conditions.

7.6 Data & Privacy

Data and privacy were important considerations in the user study, as several types of participant data were collected. Before taking part in the study, all participants received information about the purpose of the study, what data would be collected and how the data would be handled. They were then asked to sign a consent form (see Appendix E) before the test began. Participation was voluntary and participants were informed that they could withdraw at any time without giving a reason.

The collected data included eye-tracking recordings, video material, questionnaire responses and interview data. Since the eye-tracking system and in-vehicle cameras could record parts of the participant’s face, head and upper body, participants were informed that facial data could appear in the recordings. However, facial data was not used for analysis and no facial footage was published or shared publicly.

All collected data was handled confidentially and stored securely, including paper-based material, local storage on a restricted-access computer and secure cloud services. Access to non-anonymized data was restricted to the researchers conducting the study. For analysis and reporting, the data was anonymized and no personal data was published. The data handling followed GDPR requirements according to the European Parliament & Council of the European Union (2016). It also followed ethical principles outlined in the Declaration of Helsinki according to the World Medical Association (2024).

7.7 Usage of Artificial Intelligence

Artificial intelligence (AI) tools were used in this project as a supportive resource during technical development, troubleshooting and language refinement, but not for generating study results or analytical content.

In the initial phase of the project, several technical challenges arose when setting up and running the AR-HUD system. The system required execution of a provided script on a connected laptop supplied by an external company; however, limited documentation and restricted technical support made the setup process challenging. In this context, AI tools were used to assist with debugging code issues and interpreting potential causes of system errors. AI was also used as a supplementary resource when identifying compatible hardware components, such as finding the correct video cable and their specifications, in cases where internal documentation was insufficient.

AI tools were also used during the development of AR visual elements. Specifically, when using Blender AI assisted finding and understanding the tools that were needed when creating the visualisations.

Finally, AI tools were used for language support, including grammar and spelling correction. All conceptual decisions and analysis were conducted by the authors, and AI was not used to generate research findings or interpret results. Instead, it functioned solely as a supplementary tool to support technical implementation and improve clarity of written language.

8. Conclusion

The purpose of this study was to answer the following research question:

How does driver behaviour differ between AR-HUD and non-HUD conditions in terms of (1) visual attention distribution, (2) perceived workload, and (3) situation awareness during real-world automotive driving?

The answer to the research question is that driver behaviour differed mainly through reduced visual attention toward the CSD, lower perceived workload and slightly improved navigation-related situation awareness in the AR-HUD condition. When using the AR-HUD, participants spent less time looking down at the CSD, which suggests reduced reliance on secondary displays and more road-focused visual behaviour during navigation.

The findings also indicate that the AR-HUD generally reduced perceived workload, particularly regarding mental demand, effort and frustration. This suggests that the AR-HUD made navigation feel easier to understand and follow compared to the non-HUD condition. The qualitative findings supported this, as participants consistently described the AR-HUD as intuitive, supportive and easier to use during navigation tasks.

In terms of situation awareness, the improvements were relatively small. However, the results suggest that the AR-HUD supported participants' understanding of navigation information and increased their navigation confidence, especially in more complex traffic situations. Participants particularly appreciated the contextual lane guidance and real-time directional support.

The study also identified several important design considerations for future AR-HUD systems, including timing of visualisations, placement, information density and the importance of user familiarisation.

Overall, the study shows that AR-HUD navigation support can contribute to more efficient and road-focused navigation behaviour compared to a non-HUD condition. At the same time, the findings highlight that the effectiveness of AR-HUD systems depends on careful design and further validation in real-world driving contexts.

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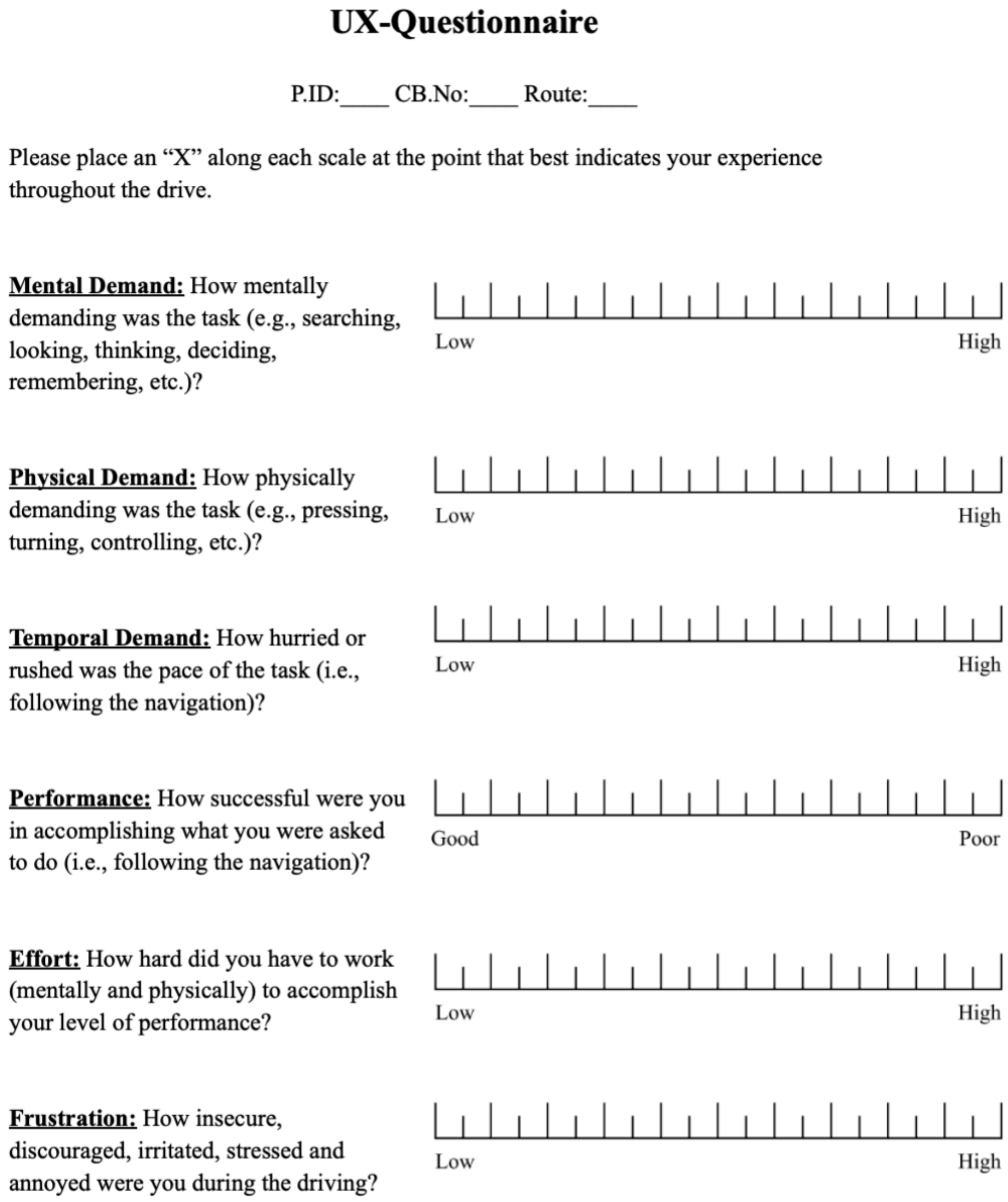
Appendix

A Raw NASA - TLX



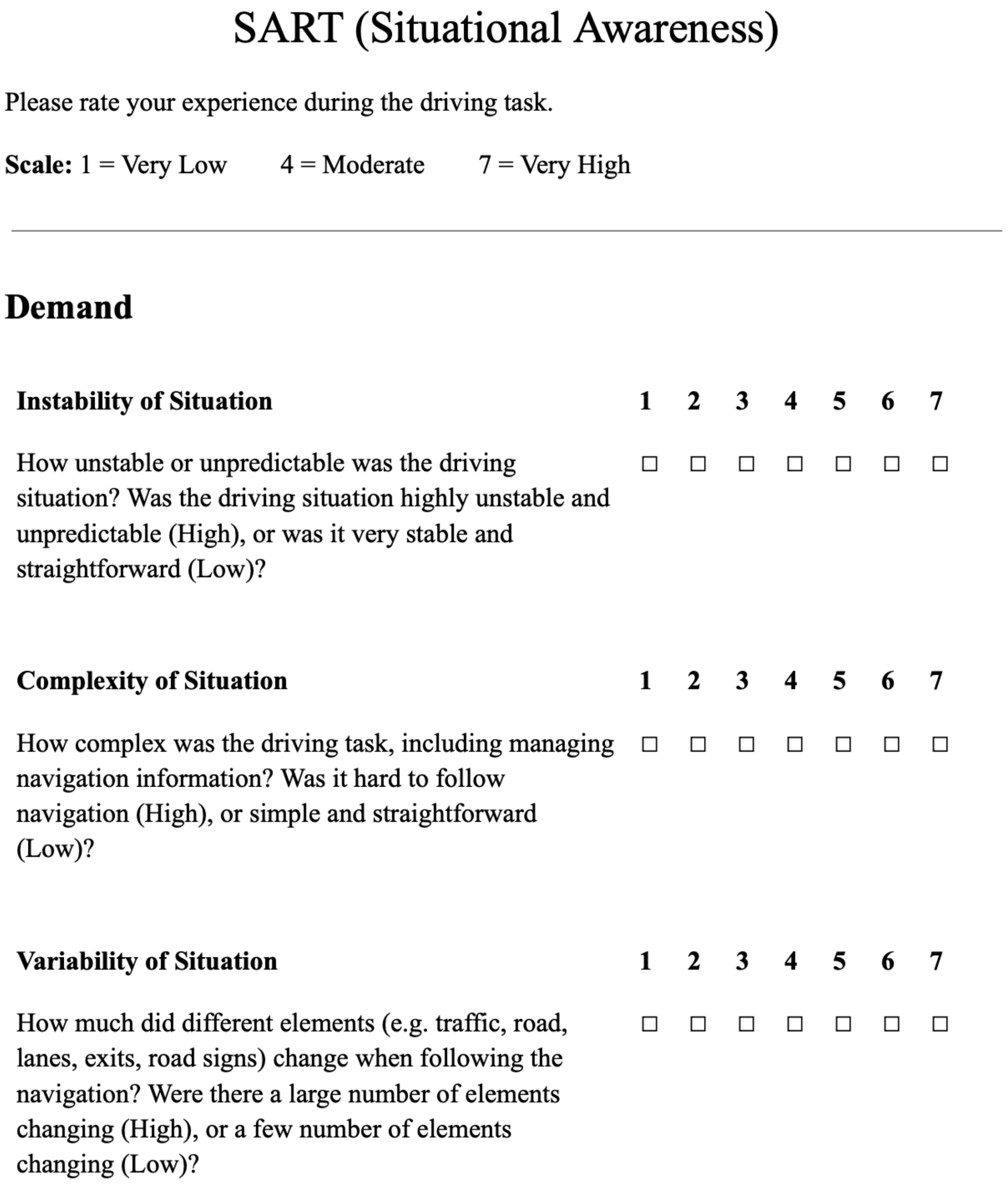
UX-Questionnaire

P.ID:____ CB.No:____ Route:____

Please place an “X” along each scale at the point that best indicates your experience throughout the drive.

Mental Demand: How mentally demanding was the task (e.g., searching, looking, thinking, deciding, remembering, etc.)?	Low	High
Physical Demand: How physically demanding was the task (e.g., pressing, turning, controlling, etc.)?	Low	High
Temporal Demand: How hurried or rushed was the pace of the task (i.e., following the navigation)?	Low	High
Performance: How successful were you in accomplishing what you were asked to do (i.e., following the navigation)?	Good	Poor
Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?	Low	High
Frustration: How insecure, discouraged, irritated, stressed and annoyed were you during the driving?	Low	High

B SART Inspired Questionnaire



SART (Situational Awareness)

Please rate your experience during the driving task.

Scale: 1 = Very Low 4 = Moderate 7 = Very High

Demand

Instability of Situation	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How unstable or unpredictable was the driving situation? Was the driving situation highly unstable and unpredictable (High), or was it very stable and straightforward (Low)?	☐	☐	☐	☐	☐	☐	☐

Complexity of Situation	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How complex was the driving task, including managing navigation information? Was it hard to follow navigation (High), or simple and straightforward (Low)?	☐	☐	☐	☐	☐	☐	☐

Variability of Situation	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How much did different elements (e.g. traffic, road, lanes, exits, road signs) change when following the navigation? Were there a large number of elements changing (High), or a few number of elements changing (Low)?	☐	☐	☐	☐	☐	☐	☐

Supply

Arousal	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How alert and attentive did you feel while keeping track of both the road and navigation information? Were you alert and ready for activity (High), or did you have a low degree of alertness (Low)?	☐	☐	☐	☐	☐	☐	☐

Concentration of Attention	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How much did you need to concentrate on multiple aspects of information (e.g. road, traffic and display/navigation)? Were you concentrating on many aspects of the situation (High), or focused on only one (Low)?	☐	☐	☐	☐	☐	☐	☐

Division of Attention	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How much was your attention divided in the driving situation? Did you divide your attention much between driving and navigation (High) or very little (Low)?	☐	☐	☐	☐	☐	☐	☐

Spare Mental Capacity	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How much mental capacity did you have to spare while driving? Did you have a lot of mental capacity available to handle the driving situation (High), or were you fully occupied with no capacity to spare (Low)?	☐	☐	☐	☐	☐	☐	☐

Understanding

Information Quantity	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How much information did you receive during the drive to understand the driving situation and follow the route? Was it a large amount of information (High) or very little information (Low)?	☐	☐	☐	☐	☐	☐	☐

Information Quality	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How good was the information you have gained about the driving situation and following the route? Was the information provided very useful and easy to interpret (High), or was it not useful at all (Low)?	☐	☐	☐	☐	☐	☐	☐

Familiarity with Situation	**1**	**2**	**3**	**4**	**5**	**6**	**7**
How familiar are you with the driving situation? Did you have a great deal of relevant experience (High) or was it a new situation (Low)?	☐	☐	☐	☐	☐	☐	☐

C Interview Questions English

Interview questions

Overall Experience/driving behaviour

1. How did your overall driving experience differ between the AR-HUD and non-HUD conditions? Did your driving style change?

Navigation

2. Were there any moments where you felt uncertain about what to do next?
3. What kind of information do you check for in each display (during AR-hud condition)?

Situational awareness:

4. Can you describe a moment where you felt particularly aware, or unaware, of your surroundings?

Safety:

5. In which condition did you feel more confident or safe, and why?

User Experience:

6. What did you like most and least about each condition, and why? *(if something was distracting or helpful)*
7. Did the AR-HUD feel intuitive or confusing to use?

Improvements

8. What improvements would you suggest for the AR-HUD system (navigation-wise)?

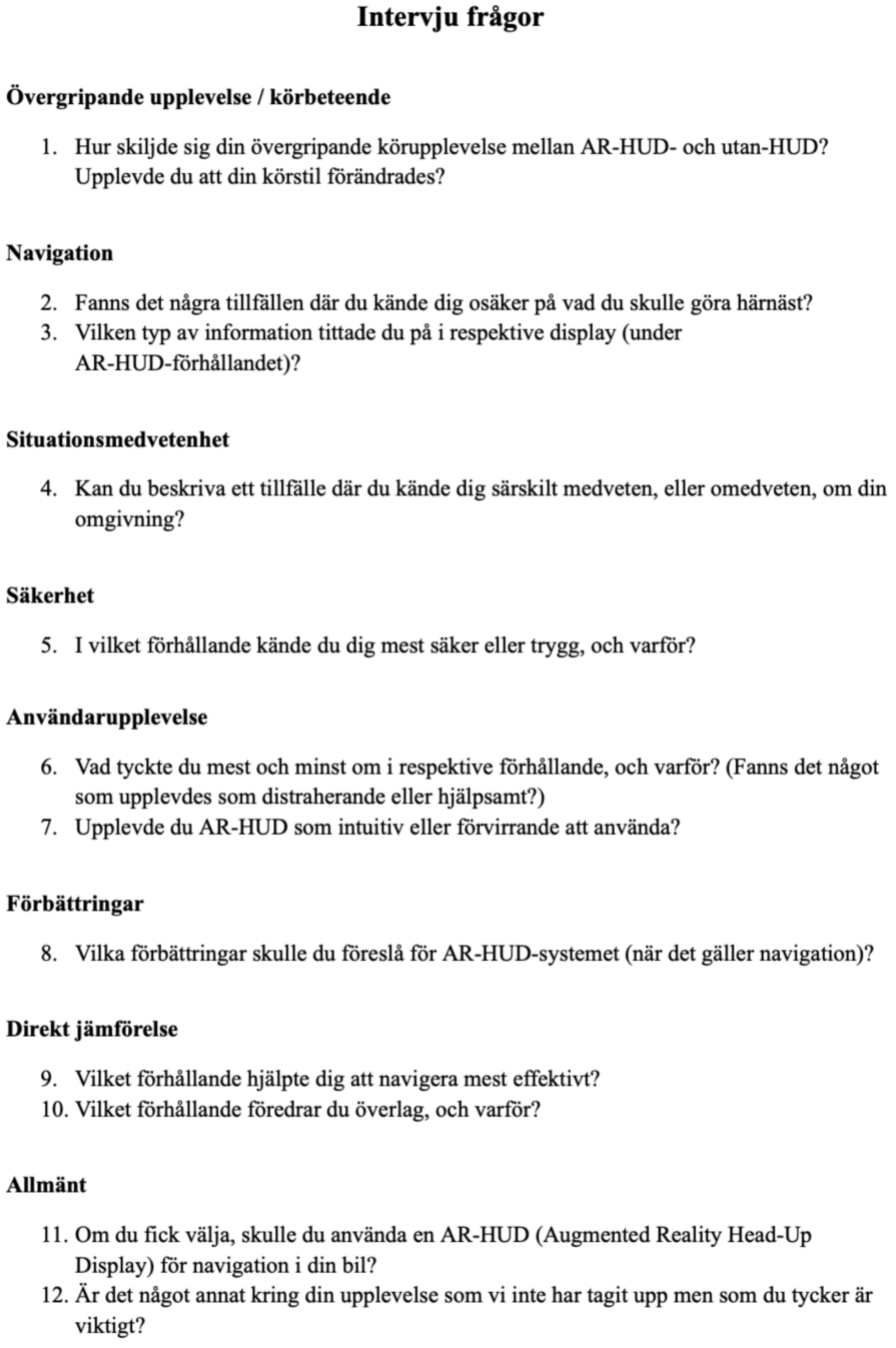
Direct comparison

9. Which condition helped you navigate more efficiently?
10. Which condition would you prefer overall, and why?

General question

11. If given the option, would you use an AR-HUD (Augmented reality Head-Up-Display) for navigation in your car?
12. Is there anything else about your experience that we haven't discussed but you think is important?

F Interview Questions Swedish



Intervju frågor

Övergripande upplevelse / körbeteende

1. Hur skiljde sig din övergripande körupplevelse mellan AR-HUD- och utan-HUD? Upplevde du att din körstil förändrades?

Navigation

2. Fanns det några tillfällen där du kände dig osäker på vad du skulle göra härnäst?
3. Vilken typ av information tittade du på i respektive display (under AR-HUD-förhållandet)?

Situationsmedvetenhet

4. Kan du beskriva ett tillfälle där du kände dig särskilt medveten, eller omedveten, om din omgivning?

Säkerhet

5. I vilket förhållande kände du dig mest säker eller trygg, och varför?

Användarupplevelse

6. Vad tyckte du mest och minst om i respektive förhållande, och varför? (Fanns det något som upplevdes som distraherande eller hjälpsamt?)
7. Upplevde du AR-HUD som intuitiv eller förvirrande att använda?

Förbättringar

8. Vilka förbättringar skulle du föreslå för AR-HUD-systemet (när det gäller navigation)?

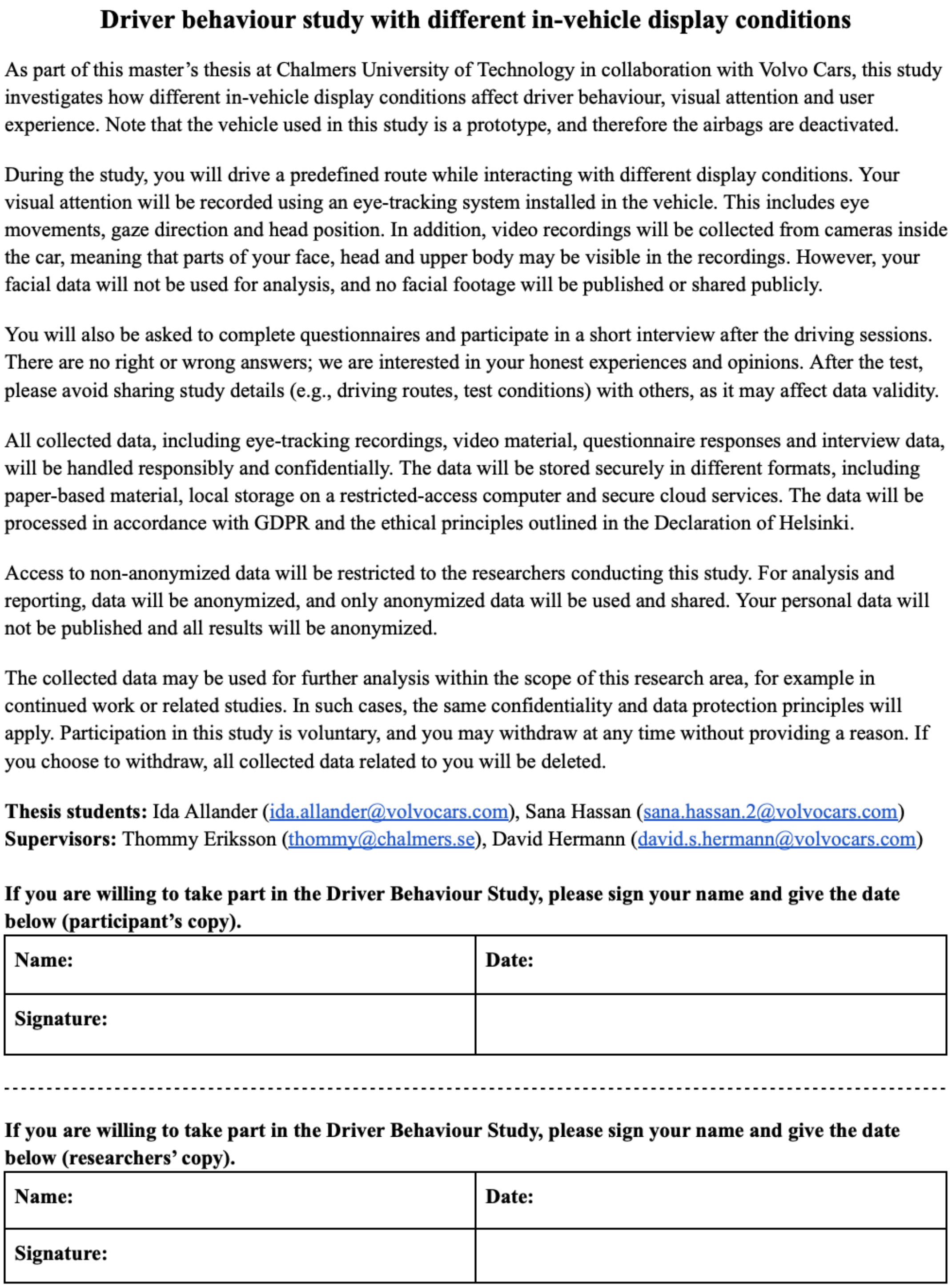
Direkt jämförelse

9. Vilket förhållande hjälpte dig att navigera mest effektivt?
10. Vilket förhållande föredrar du överlag, och varför?

Allmänt

11. Om du fick välja, skulle du använda en AR-HUD (Augmented Reality Head-Up Display) för navigation i din bil?
12. Är det något annat kring din upplevelse som vi inte har tagit upp men som du tycker är viktigt?

E Consent Sheet



Driver behaviour study with different in-vehicle display conditions

As part of this master's thesis at Chalmers University of Technology in collaboration with Volvo Cars, this study investigates how different in-vehicle display conditions affect driver behaviour, visual attention and user experience. Note that the vehicle used in this study is a prototype, and therefore the airbags are deactivated.

During the study, you will drive a predefined route while interacting with different display conditions. Your visual attention will be recorded using an eye-tracking system installed in the vehicle. This includes eye movements, gaze direction and head position. In addition, video recordings will be collected from cameras inside the car, meaning that parts of your face, head and upper body may be visible in the recordings. However, your facial data will not be used for analysis, and no facial footage will be published or shared publicly.

You will also be asked to complete questionnaires and participate in a short interview after the driving sessions. There are no right or wrong answers; we are interested in your honest experiences and opinions. After the test, please avoid sharing study details (e.g., driving routes, test conditions) with others, as it may affect data validity.

All collected data, including eye-tracking recordings, video material, questionnaire responses and interview data, will be handled responsibly and confidentially. The data will be stored securely in different formats, including paper-based material, local storage on a restricted-access computer and secure cloud services. The data will be processed in accordance with GDPR and the ethical principles outlined in the Declaration of Helsinki.

Access to non-anonymized data will be restricted to the researchers conducting this study. For analysis and reporting, data will be anonymized, and only anonymized data will be used and shared. Your personal data will not be published and all results will be anonymized.

The collected data may be used for further analysis within the scope of this research area, for example in continued work or related studies. In such cases, the same confidentiality and data protection principles will apply. Participation in this study is voluntary, and you may withdraw at any time without providing a reason. If you choose to withdraw, all collected data related to you will be deleted.

Thesis students: Ida Allander (ida.allander@volvocars.com), Sana Hassan (sana.hassan.2@volvocars.com)
Supervisors: Thommy Eriksson (thommy@chalmers.se), David Hermann (david.s.hermann@volvocars.com)

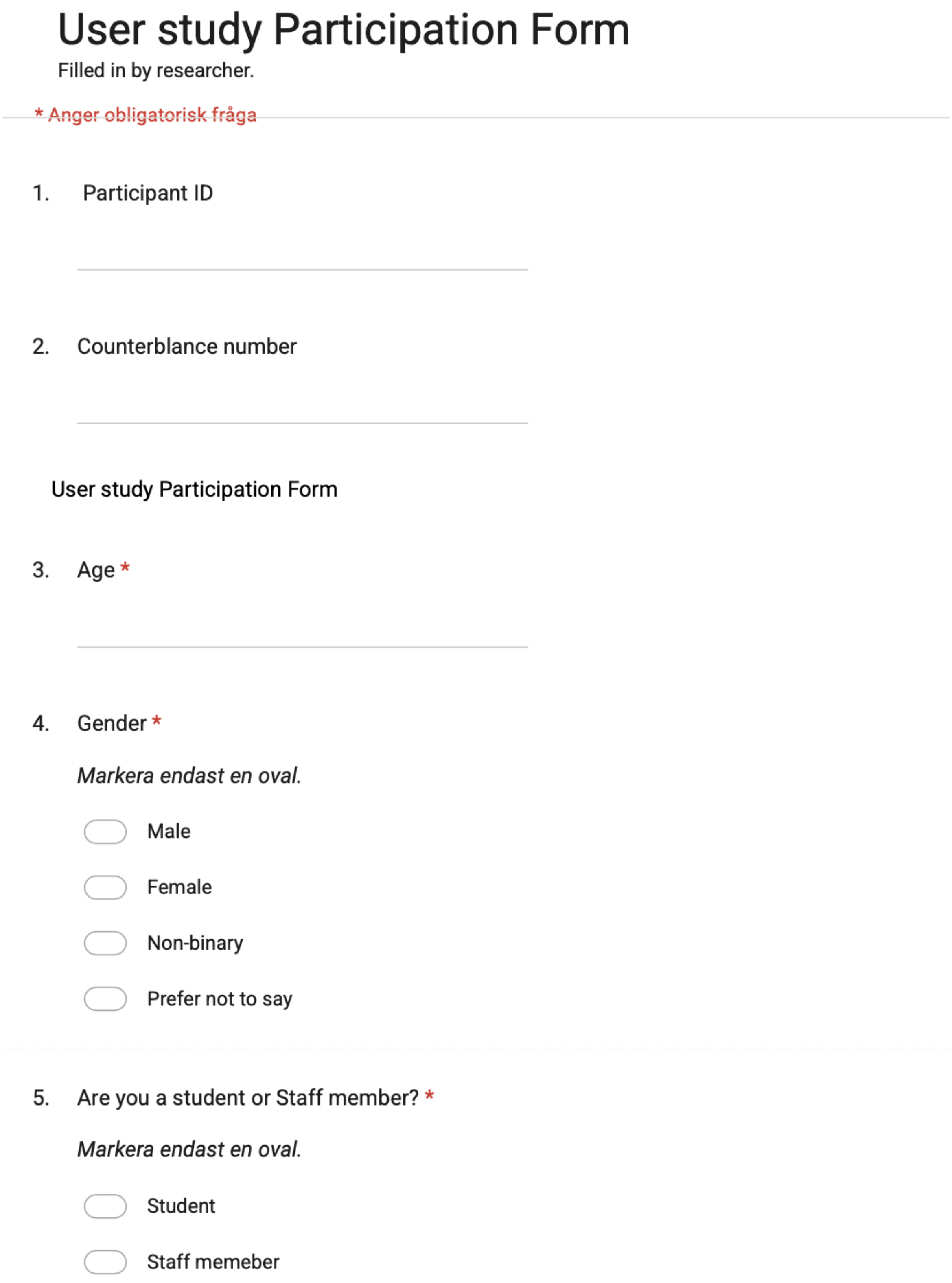
If you are willing to take part in the Driver Behaviour Study, please sign your name and give the date below (participant's copy).

Name:	**Date:**
Signature:	

If you are willing to take part in the Driver Behaviour Study, please sign your name and give the date below (researchers' copy).

Name:	**Date:**
Signature:	

F Survey



User study Participation Form

Filled in by researcher.

* Anger obligatorisk fråga

1. Participant ID

2. Counterblance number

User study Participation Form

3. Age *

4. Gender *

Markera endast en oval.

○ Male
○ Female
○ Non-binary
○ Prefer not to say

5. Are you a student or Staff member? *

Markera endast en oval.

○ Student
○ Staff memeber

6. Which team are you affiliated with? *

____

7. For how many years have you had your driving license? *

Markera endast en oval.

○ less than a year
○ 1-2 years
○ 3-5 years
○ 6-10 years
○ 10+

8. How many hours per week do you drive? *

Markera endast en oval.

○ 0-2 hours
○ 3-5 hours
○ 6-10 hours
○ 11-20 hours
○ 21+ hours

9. Do you have previous experience with HUD or AR-HUD *

Markera alla som gäller.

☐ Yes with HUD
☐ Yes with AR-HUD
☐ No

10. Does your car have a HUD?

Markera endast en oval.

○ Yes
○ No

11. If yes, how often do you use it per week?

Markera endast en oval.

○ 0-5 hours
○ 6-10 hours
○ 11-20 hours
○ 21+ hours

12. What best describes your current vision? *

Markera endast en oval.

○ I have normal (uncorrected) vision
○ I use glasses to correct my vision to normal
○ I use contact lenses to correct my vision to normal
○ I have had vision correction surgery (e.g., LASIK)
○ My vision is not fully corrected to normal
○ I prefer not to say

13. How often do you use a navigation tool such as Google Maps while driving? *

Markera endast en oval.

○ Never
○ A few times a year
○ A few times a month
○ A few times a week
○ Every time I drive

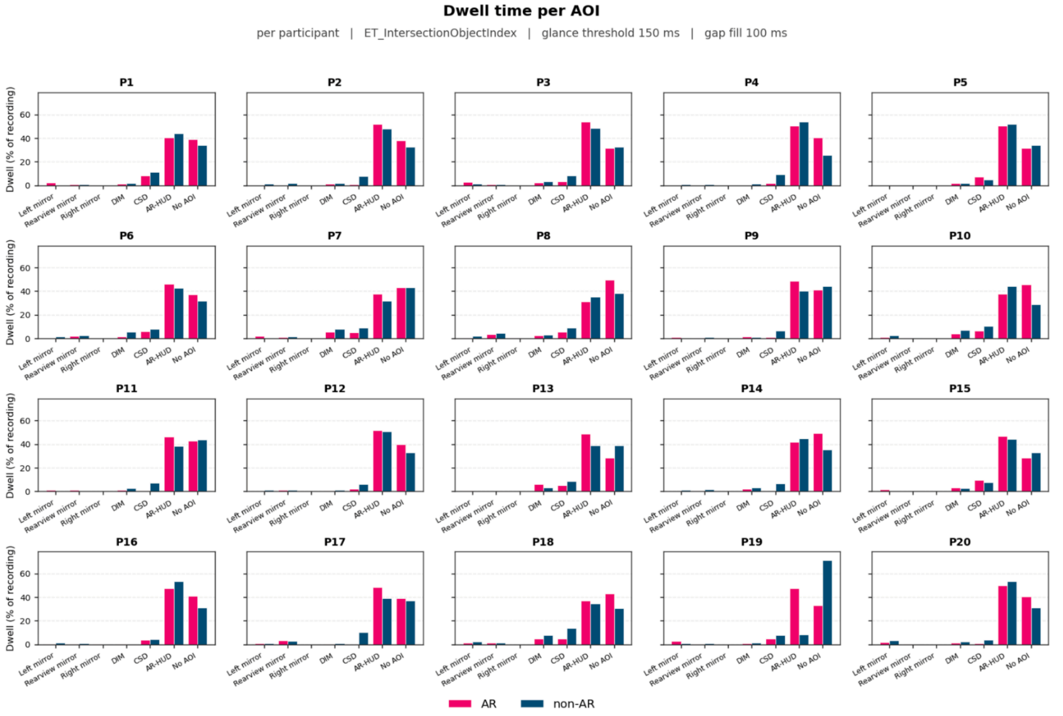
G AR-HUD Visualisations in Route 1 & Route 2

Short overview: 🎬 Presentation video.mp4

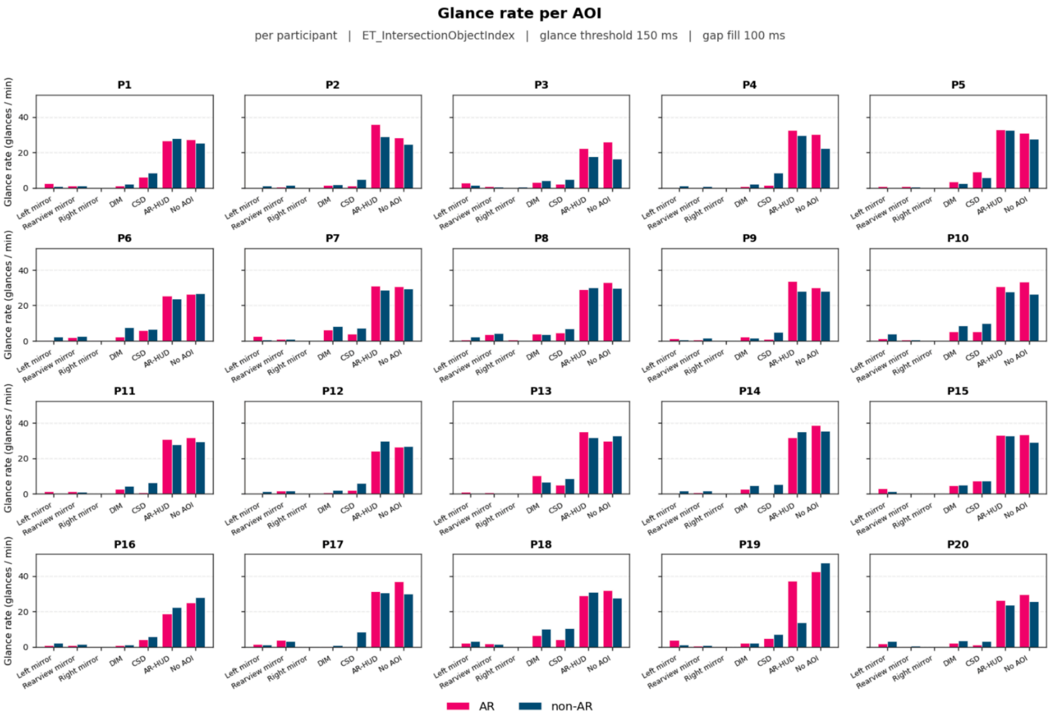
Route 1: 🎬 Route1.MP4

Route 2: 🎬 Route2.MP4

H AOI Dwell Time Percentage for Each Participant



I AOI Glance Rate for Each Participant



J Mean AOI Glance Duration for Each Participant

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