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THE IMPACT OF AGE ON DRIVERS' PERCEPTION AND DECISION-MAKING: AN EXPLORATORY STUDY OF CAMERA MONITORING SYSTEMS

Supervisor
Prof.
Irene Sperandio

Co-Supervisor
Prof.
Kjell Brunnström

Student
Gabriele Pifferi

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Gabriele Pifferi
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ACADEMIC SUPERVISOR: Prof. Irene Sperandio
INDUSTRIAL SUPERVISOR: Prof. Kjell Brunnström

MSc in HUMAN-COMPUTER INTERACTION
Department of Psychology and Cognitive Science
Department of Information Engineering and Computer Science
University of Trento

RI.
SE

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Abstract

The automotive industry continues to hold a central role in transportation and is constantly undergoing multiple innovations. Among these, Camera Monitor Systems (CMS) have emerged as a digital alternative to conventional side-view mirrors, offering advantages such as improved aerodynamics and enhanced visibility in poor weather or low-light conditions. However, challenges related to depth perception remain, as replacing mirrors with screens reduces the availability of depth cues. This thesis investigates how CMS configuration, specifically Camera Position and Field of View, affects distance judgment and safety-related decision making during driving. In addition, a previously unexplored aspect is investigated here: whether user characteristics affect interaction with the system and performance when using it. In particular, age is investigated, given its implications for visual perception and changes in driving behaviour Thirty drivers of varied ages were recruited and completed two simulated driving tasks. The first was a distance estimation task, in which they reported the distance of a following vehicle from their car. The second was a Last Safe Gap task, in which they indicated the latest safe moment at which they would change lanes before being overtaken. Results showed that both Camera Position and Field of View significantly affected drivers' performance. Wider Field of Views and lower Camera Positions generally reduced distance underestimation errors (happening when reporting a chasing vehicle being closer than it actually is) as well as the Time to Contact values selected when reporting the Last Safe Gap for lane changes. Notably, age emerged as a significant factor, with older participants performing with greater accuracy in distance judgment and more conservative gaps in LSG selection compared to their younger counterparts. These findings demonstrate that CMS performance is shaped not only by system configuration but also by user characteristics. Accounting for such variability is essential for designing and optimising CMS that support safe and effective use across the driving population.

Introduction

The automotive sector continues to play a central role in people's lives, remaining one of the main means of transport for people and goods. In Europe, the number of vehicles on the road is steadily increasing, with passenger cars accounting for approximately 80% of all traffic (ACEA, 2024; European Commission, 2024). Given their importance in today's society, continuous efforts are made to enhance vehicle safety and comfort, aiming to ensure a secure and enjoyable experience for automotive users. For instance, Advanced Driver-Assistance Systems (ADAS) and In-Vehicle Information Systems (IVIS) have been introduced, aiming to assist drivers during normal driving tasks, but also helping or even taking over during potentially hazardous situations.

Among the many technologies in use, the Camera Monitor System (CMS), a digital alternative to conventional side-view mirrors, is already being implemented in some passenger and commercial vehicles. However, research is still ongoing to determine to what extent this technology can replace conventional mirrors and how users interact with it. To date, most studies have focused on evaluating the system's technical performance. Furthermore, user-centred research happening in this field often tends to treat participants as a homogeneous group, without giving much attention to differences between user subgroups and how these may influence interaction with the technology. Although demographic data are usually collected during studies, most of them do not explore how these factors can affect user experience, both in task performance and subjective impression. Among the many differences that can be present, age appears to be a critical factor at this time: as most countries' population ages, so does the driving population.

This thesis investigates the user experience and perception with CMS. It focuses on whether and to what extent age influences drivers' ability to perceive approaching vehicles

when using this system, as well as their feelings and attitudes toward CMS and its potential Field of View (FOV) and Camera height Position configurations. This work aims to advance the existing body of knowledge on CMS by deepening the understanding of human factors that may interact with its use. In doing so, this research intends to inform the design and development of more effective CMS systems.

The following sections will provide an overview of the CMS technology, outlining its advantages and limitations in comparison to conventional side-view mirrors. Particular attention will be given to differences in visual perception between the two systems and the specific visual cues each provides. Finally, the relevance of demographic factors, particularly age, in CMS-related research will be discussed, highlighting the importance of considering such differences in this field.

Camera Monitor Systems (CMS)

Although the first studies on human–machine interaction with CMS date back to 2002 (Flannagan et al., 2002), the United Nations Regulation No. 46 (2015) was the first to officially allow its introduction as a replacement for traditional side-view mirrors (technically referred to as Class III mirrors) in both passenger cars and commercial vehicles. This regulation is based on the technical specifications outlined in the ISO 16505:2015 standard (2015), which has since been updated by ISO 16505:2019 (2019). The standard defines safety, ergonomic, and performance requirements for CMS. A typical CMS consists of three main components: (1) a camera mounted on the exterior of the vehicle that captures the rear view; (2) an Electronic Control Unit (ECU) that processes the incoming video stream and may apply be used to apply image enhancements; and (3) a display inside the vehicle that presents the resulting image to the driver (see Figure 1).

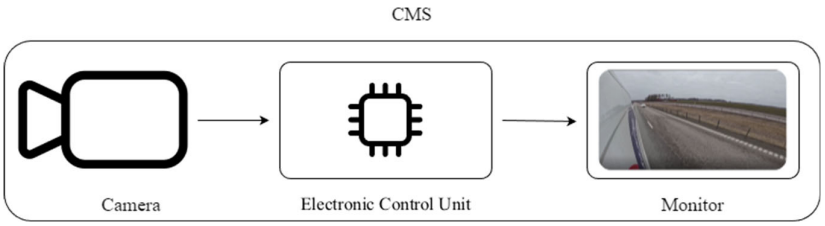

Figure 1. Schematic representation of CMS components.

According to the United Nations Regulation No. 46 (2015), Class III mirrors (side-view mirrors) must provide the driver a minimum horizontal view angle of about 12°. Most cars in Europe meet this requirement and extend the FOV by an additional 10°–15° through the use of aspherical mirror sections, resulting in a combined horizontal FOV of up to 35°. This coverage can be further increased by a combination of head and upper body movements, which are particularly helpful in specific driving situations such as when merging onto a highway. Conventional mirrors also preserve stereoscopic vision and binocular depth cues. In contrast, CMS do not reflect the environment as conventional mirrors do, but instead present a fixed camera view on a display that cannot be adjusted through driver movement (see Figure 2).

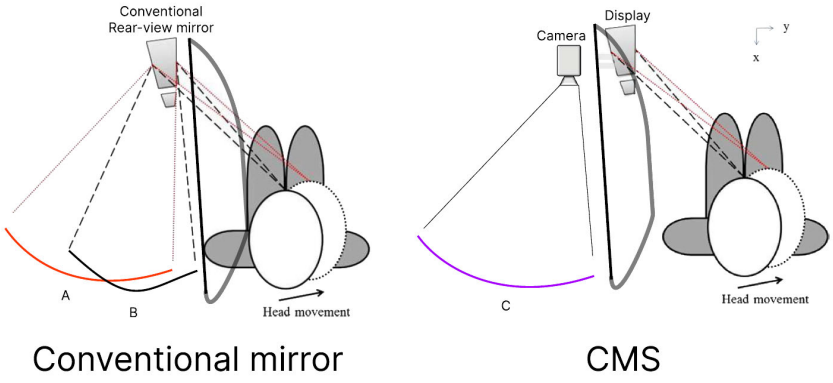

Figure 2. Representation of the Field of View offered by a conventional mirror (A & B) versus a Camera-Monitor System (C). Adapted from Terzis (2016).

As a result, CMS inherently eliminate binocular depth cues and rely solely on monocular information, making it necessary to provide a broader baseline FOV during system design to compensate for these inherent limitations.

Advantages of CMS

The introduction of CMS brings benefits both on an individual level and on a broader scale. From a design and engineering perspective, its adoption can improve the vehicle's aerodynamics, while also reducing overall weight and diminishing soiling (accumulation of dirt, debris or water). These improvements, in turn, can contribute to lower fuel consumption and CO_2 emissions (Terzis, 2016b).

Additionally, transitioning to CMS may help reduce discrepancies in current mirror designs and regulations across different regions. For instance, the United States requires the use of flat mirrors on the driver's side, which provide an accurate representation of distance but offer a limited FOV. In contrast, European regulations favour convex aspherical mirrors, which offer a wider FOV but distort distance perception, making objects appear farther away than they actually are (Hahnel & Hecht, 2012). By replacing conventional mirrors with digital systems, CMS enables the use of the same hardware across markets, with region-specific adaptations made at the software level if necessary(e.g., modifying the displayed FOV through the ECU).

Beyond manufacturing advantages, CMS also offers practical benefits for drivers and other road users in everyday scenarios. By employing wide-angle cameras, CMS significantly expands the FOV available at a glance, thereby reducing blind spots and the risk of collisions with otherwise unseen road users, a concern particularly relevant for trucks and other heavy vehicles. These, in fact, account for 18% of fatalities on European roads (European Commission, 2023a; Tomasch & Smit, 2023), and most accidents involving vulnerable road users (e.g., pedestrians, cyclists, motorcyclists) are attributed to limited visibility (Schindler

et al., 2022). Additionally, image processing performed by the ECU helps reduce glare from sunlight or headlights and enhances visibility in low-light conditions, such as during night driving (Schmidt et al., 2016; Terzis, 2016a). Relocating the display inside the cabin can ease the physical demand associated with head and eye movements (Beck et al., 2021). This, together with the use of cameras with smaller exposed surfaces compared to exterior mirrors, makes the system less susceptible to rain, dirt, and debris, offering a clearer view of the surrounding area.

Challenges of CMS

Despite providing several advantages, CMS presents intrinsic limitations due to its digital nature, which differs significantly from that of conventional rearview mirrors. CMS relies on additional hardware components (i.e., cameras, electronic control units, and displays), which lead to higher manufacturing costs and an increased risk of malfunction due to the system's complexity. The implementation of CMS also requires manufacturers to invest in research and design modifications to the vehicle's interior to understand how and where best to integrate displays within the cabin (Beck et al., 2021; Schmidt et al., 2016).

From the driver's perspective, CMS does not directly reflect the environment, as a traditional mirror does. Instead, it presents a digital video feed whose characteristics such as clarity and responsiveness can be influenced by the camera's capture capabilities, the monitor's resolution and size, or the system's video processing speed. Furthermore, because the image is displayed on a fixed monitor, drivers cannot adjust their FOV through head movements, as they can with a conventional mirror (see Figure 2).

These differences in how visual information is presented also alter how depth and distance are perceived, factors critical to safe driving. CMS only provides monocular depth cues, as each eye receives the same image from the monitor. In contrast, conventional mirrors

offer both monocular and binocular depth cues, thereby providing more information about the distance of objects (Schmidt et al., 2016). To understand these implications, it is essential to consider how human visual perception works and to examine in more detail the possible cues presented by each system.

Visual Perception and Depth Cues

Human visual perception is the ability to interpret and make sense of the information captured by the visual system. This process relies on multiple signals and cues to interpret spatial layout, motion, depth, and other object visual features. As Wolfe et al. (2021, p. 168) explain, “our visual experience is a reconstruction of the world based on two distorted inputs: the two distinct retinal images”. The slight difference between the images projected onto each retina, known as binocular disparity, forms the basis for stereopsis, the perception of depth from binocular vision (see below for more details). Nonetheless, perception of the third dimension is also possible with purely monocular (one-eyed) vision, although it is generally less rich and effective than binocular vision. Both monocular and binocular vision rely on various cues available in the visual environment, allowing the brain to reconstruct the third dimension and interpret how objects are positioned within it and in relation to one another.

Depth cues can be classified as primary, those that depend on the properties and physiology of the visual system, and secondary, those that depend on image features external to the observer. Accommodation, binocular disparity, and convergence are considered primary depth cues, whereas pictorial cues fall under secondary depth cues. In the following section, for each depth cue described a corresponding figure visually illustrates its mechanism and functioning.

Monocular Cues

Accommodation. The eye's lens changes shape to focus on objects at different distances: it becomes rounder for nearby objects and flatter for distant ones. Although accommodation is a primary cue, it is relatively weak, being effective only within a limited range from approximately 10 cm to about 5 meters. Beyond this distance, the lens is fully flattened and no longer provides additional depth information (Wolfe et al., 2021).

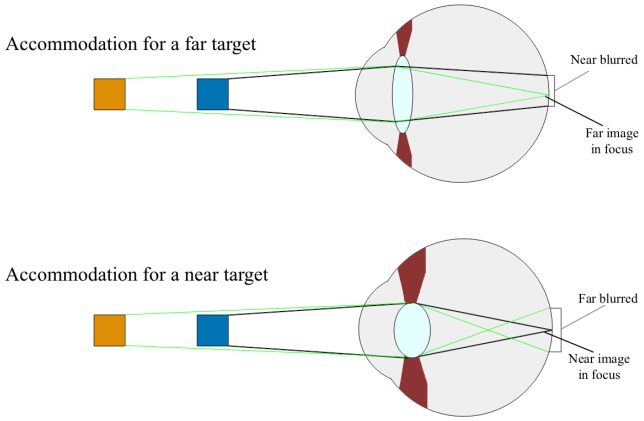

Figure 3. Illustration of the depth cue accommodation.

The ciliary muscles contract or relax to change the curvature of the lens, making it thicker for nearby targets and thinner for distant ones, thereby adjusting the focal distance to maintain a clear image.

Texture Gradient. Repeating elements or patterns receding in depth will appear smaller, denser, and less detailed as their distance from the observer increases.

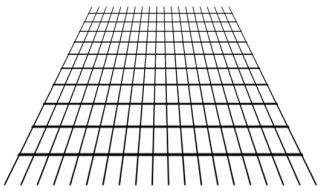

Figure 4. Illustration of the depth cue texture gradient.

Occlusion. When one object partially covers another, the blocked object is perceived as being farther away. This depth cue is non-metrical, thus allowing the viewer to understand the relative ordering of occluders and occluded objects, but not offering information about the actual distance separating them in the third dimension—something that metrical depth cues can convey.

Figure 5. Illustration of the depth cue occlusion.

The blue square is perceived as farther than the yellow triangle. The visual system interprets the overlapping configuration as the triangle partially occluding the square, thereby inferring that the triangle occupies a position closer to the observer.

Relative Size. If similar objects are presented in the same scenario and known or assumed to be of the same size, the smaller one is perceived as more distant.

Figure 6. Illustration of the depth cue relative size.

The smaller car is perceived as more distant than the larger car. When objects are assumed to be of similar physical size, the visual system interprets smaller retinal images as corresponding to greater distance from the observer.

Relative Height. Objects assumed to rest on the ground plane and positioned higher in the visual field are typically perceived as being farther away than those placed lower.

Furthermore, if two objects are the same size but differ in relative height, the one positioned higher in the visual field is often perceived as larger. This is because the visual system interprets higher placement as greater distance and infers that an object must be physically larger to produce the same retinal image size. These cues provide limited relative metrical depth information, allowing the observer to estimate how close one object is to a second compared with the distance between the second and a third.

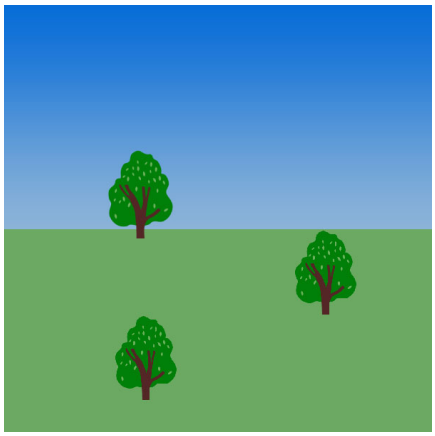

Figure 7. Illustration of the depth cue relative height.

Three identical trees are shown at different vertical positions within the visual field. Because they are assumed to lie on the same ground plane, the tree positioned higher in the image is perceived as farther away than those placed lower. Although all trees are identical, the higher one may also appear larger, as the visual system infers that an object producing the same retinal image size at a greater distance must be physically bigger.

Familiar Size. Through experience with our surroundings and familiarity with object size, observers can infer distance by comparing an object's retinal size with the stored representation of its real size. This cue belongs to the category of absolute metrical cues, as our knowledge of the actual size of an object, together with its visual angle on the retina, would (theoretically) allow the observer to calculate its exact distance from the eye. Nevertheless, the human visual perception system does not estimate this information with sufficient precision to provide truly reliable distance measurements.

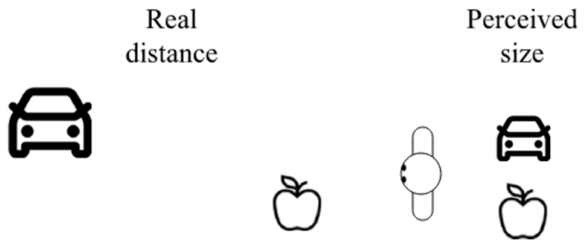

Figure 8. Illustration of the depth cue familiar size.

On the left the real size and distance two objects are depicted: the car is much larger but farther from the observer, while the apple is smaller but much closer. On the right, both objects are depicted as having the same apparent retinal size from the observer's viewpoint. However, the observer uses their knowledge of the actual sizes of the two objects to infer that the car must be farther away, demonstrating how familiar size helps estimate absolute distance in the visual scene.

Aerial Perspective. The implicit understanding of light being scattered by the atmosphere allows the observer to perceive distant objects as fainter, lower in contrast, and bluish, thereby enabling an estimation of their distance.

Figure 9. Illustration of the depth cue aerial perspective.

As buildings and mountains become farther from the observer's point of view, they appear bluish and lower in contrast due to atmospheric scattering, aiding distance estimation. Figure adapted from Yim (2020).

Linear Perspective. Parallel lines appear to converge towards a vanishing point as they recede into the distance.

Figure 10. Illustration of the depth cue linear perspective.

Parallel railroad tracks appear to converge toward a vanishing point as they recede into the distance, enhancing the perception of depth. Figure adapted from Harvey (2019).

Motion Parallax. When the observer moves, nearby objects appear to shift more rapidly across the visual field compared to distant ones, allowing not only to locate objects in space but also to perceive their relative position. This kind of information is obtained by a single eye from two different positions at separate times, similar to the depth information gathered simultaneously by two eyes in binocular stereopsis. This depth cue works only if the viewer moves relative to the object or vice versa, as movement is the key component that allows for the perception of such a difference in the objects.

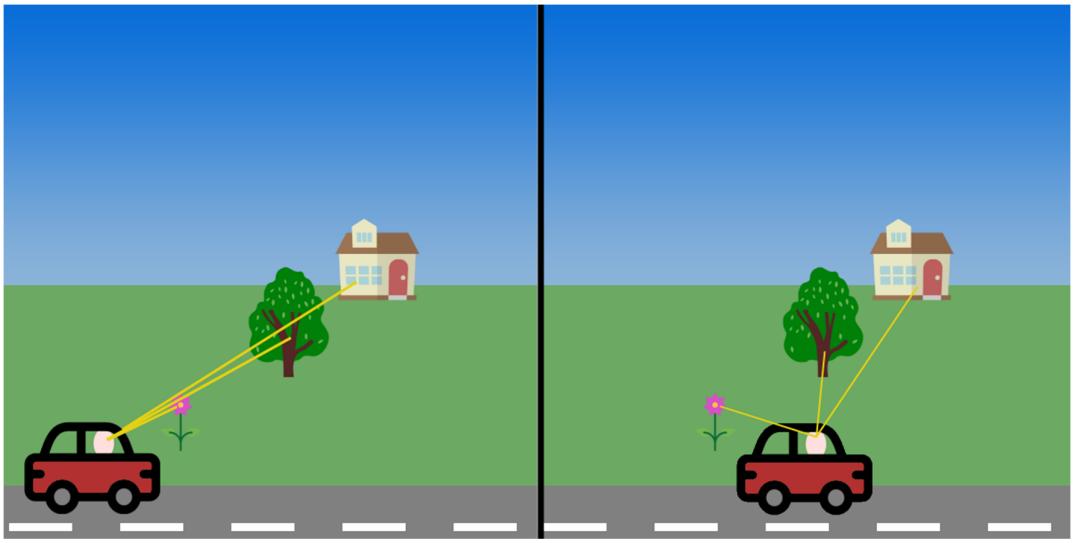

Figure 11. Illustration of the depth cue Motion parallax.

Two observer positions show how nearby objects shift more across the visual field than distant ones when the observer moves. The yellow lines represent sight lines from the moving car to objects at different distances. The flower, being closest, exhibits the largest angular displacement between the two viewpoints, while the tree and house show progressively smaller displacements as the distance increases. This difference in apparent motion illustrates how motion parallax provides information about relative depth.

Shadow and Shading. Objects that are farther from a light source tend to appear dimmer, thereby creating a sense of distance. Shadows cast by objects also convey information about their position relative to the environment: an object that is closer to the light source and farther from the surface onto which the shadow is cast will produce a broader shadow. Additionally, variations in shading across an object's surface provide information about its three-dimensional shape and the relative depth of different parts of the scene.

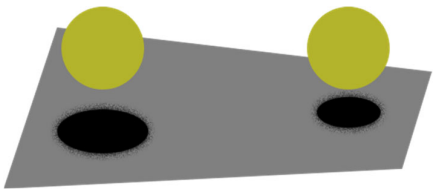

Figure 12. Illustration of the depth cue shadow.

Even if the two spheres are identical in size and aligned at the same height, the one on the left appears farther from the surface because its shadow is larger and more separated from it, whereas the sphere on the right appears closer to the surface because its shadow is smaller and nearer.

Binocular Cues

Convergence and Divergence. Depth perception relies, in part, on how ample the vergence angle is between each eye's line of sight. The more eyes rotate inwards (converge), the larger the angle, the closer the estimated fixated object. Although offering useful information on depth judgment, this cue, like accommodation, is effective for close objects up to 2-3 meters (Wolfe et al., 2021). The angle changes rapidly at close distance but then diminishes significantly at a farther point, where the eyes become as diverged as possible and no more information can be gathered from it.

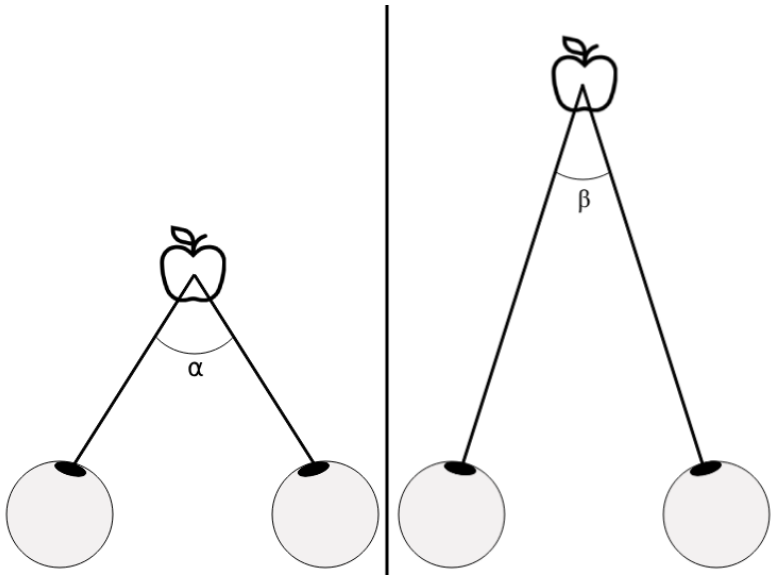

Figure 13. Illustration of vergence angle.

The vergence angle between the eyes varies with the distance of an object from the observer. On the left, when the object is close, both eyes rotate inward (converge) to fixate it, resulting in a larger vergence angle (α). When the object is farther away, the required convergence decreases, producing a smaller vergence angle (β).

Binocular disparity. Each eye receives a slightly different image due to horizontal separation (interocular distance). The visual system combines these two perspectives to create stereopsis and uses such differences to estimate depth and distance. When disparities are small, depth estimation is precise and quantitative, thus giving an accurate estimate of relative depth. As disparity increases, stereopsis ceases to provide precise metrics and instead offers only qualitative information, such as understanding if an object is located in front or behind another, without specifying the exact distance. Ultimately, stereopsis breaks down when the images differ either too much or too little from each other, namely when objects are too close or too far from the observer.

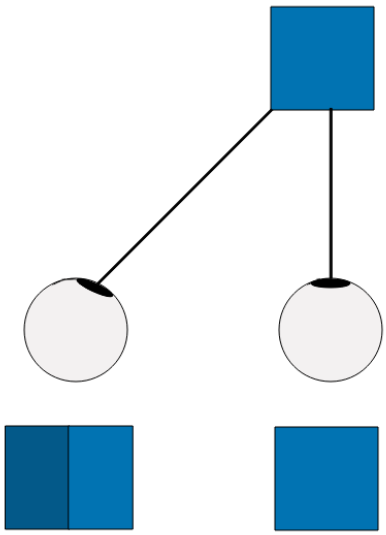

Figure 14. Illustration of Binocular disparity.

The diagram shows how each eye receives a slightly different horizontal view of the same object due to their physical separation. The resulting images (bottom shapes) include a shifted region, representing the disparity that the visual system compares and fuses to create stereopsis and estimate depth. Greater disparity corresponds to closer objects, and less disparity to distant ones.

Ageing

Ageing and Vision

As discussed earlier, the perception of depth and distance relies on a variety of visual cues, some of which are altered or completely absent when viewing through CMS compared to conventional mirrors.

However, visual perception is not only determined by the hardware used in the vehicle to present information, but also by the driver's perceptual and cognitive capabilities when interacting with the system. Ageing is associated with a gradual decline in several sensory, perceptual, and cognitive functions that are critical for safe and efficient driving (Fillit et al., 2017; Hunter et al., 2016; Roberts & Allen, 2016), making it important to consider how these changes may influence drivers' experience.

From a physiological perspective, studies have shown that after the age of 20, a progressive decline in retinal photoreceptors occurs, contributing to reduced visual acuity in older adults (Fillit et al., 2017). Furthermore, the time required for lens relaxation and accommodation increases progressively with age, peaking around 50 years (Fillit et al., 2017). In parallel, oculomotor function declines, with saccades becoming slower, less precise, and exhibiting longer inter-movement delays. The overall angle covered by eye movement and gaze, particularly in the vertical direction, declines with age, and reaction times are also negatively affected (Fillit et al., 2017). These changes can impair the ability to rapidly scan and interpret peripheral and dynamic visual information, tasks that are essential when driving.

In addition, the overall quantity of light that can enter the eye is also influenced by a natural reduction in pupillary size, and potential degenerative conditions that can occur with ageing (i.e., cataracts, glaucoma, or macular degeneration), potentially leading to a reduction in contrast sensitivity and luminance detection. It is estimated that by the age of 60, only one-third of the light that reaches the retina at age 20 is still perceived (Weale, 1961). Moreover,

straylight, which causes unwanted glare, increases with age, making it more difficult to recognise objects against a bright background or under low visibility conditions (i.e., headlights from oncoming vehicles, particularly in dim light). Van Den Berg et al. (2007) reported that while straylight remains relatively constant up to the age of 45, it increases substantially with ageing, doubling by the age of 65 and tripling by the time a person reaches 77.

Ageing and Driving

As the global population ages, the number of older drivers is steadily increasing. This highlights the importance of investigating how age-related factors influence both the development and adoption of in-vehicle technologies, as well as drivers' experiences with them. In Sweden, for instance, more than 80% of people over the age of 65 still hold a valid driving licence, and the numbers remain high even in the 80+ age group, making them close to one-third of active driving licenses (Trafik Analys, 2025; Transportstyrelsen, 2025). Similar trends can be observed across other European countries (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2025; Ministero delle Infrastrutture e dei Trasporti, 2022).

As mentioned above, age-related changes involve functional compromises that require adaptations in lifestyle and in the performance of various activities, including driving. In the following section, a review of current literature will be presented, examining recent research on CMS, studies investigating the impact of ageing on driving performance, as well as older adults' use of in-vehicle technologies. Based on this background, the research gaps have been identified, and the research questions for this thesis are subsequently presented.

Previous research

CMS has, since their introduction as an alternative to conventional mirrors, attracted increasing research attention. While some studies have focused on technical performance, other have explored usability, safety, and the potential functional advantages of CMS over traditional mirrors. Three key themes emerged from the literature review: (1) the positioning of CMS displays inside the cabin and the impact of external camera Field of View (FOV) on driver perception; (2) the possibility to add overlays, such as Augmented Reality (AR), given the digital nature of CMS, and the effects that these can have on drivers' experience; (3) and drivers' acceptance of this technology. In parallel, the literature on ageing and driving was reviewed to examine whether age might influence CMS adoption and use. Although many studies report participants' ages, age is rarely analysed as a factor. This gap in the literature underscores the need to investigate how ageing may affect perception, behaviour, and interaction with CMS.

CMS positioning and Field of View

A central focus in CMS research concerns the spatially disjointed nature of the camera and monitor positions. Beck et al. (2017, 2021) investigated whether changing the monitor placement may affect the driver's physical demands while driving—specifically the extent of eye and head movements required to check the mirrors, as well as their self-reported perceived effort while driving. Their findings suggest that relocating the monitor closer to the driver's line of sight, particularly beside the steering wheel, significantly reduced physical demand. These insights highlight how this design can benefit individuals who frequently check side-view mirrors (i.e., heavy truck drivers) as well as those with physical limitations or mobility restrictions, such as older drivers or individuals with arthritis. Similar results are reported by Mole & Wilkie (2017), who analysed how cognitive load and mirror positioning

affect reaction time in a computer-simulated truck-driving task. More eccentric mirror placements resulted in slower reaction times and increased hazard potential, supporting the recommendation to position CMS monitors closer to the central FOV of the driver. Supporting these findings, Murata & Kohno (2018) found that positioning displays around the centre of a driver or around the steering wheel significantly reduced reaction times compared to traditional side mirrors, with larger displays (8-inch) showing superior performance over smaller ones (6-inch). However, Large et al. (2016) observed that although the use of CMS reduced decision time, shortened head movements, and decreased eyes-off-road time, it also led to higher subjective workload, reduced trust, lower situation awareness, greater distraction, and poorer depth perception when the monitors were positioned within the central console. Taken together, these findings suggest that CMS can offer drivers valuable information about the rearward road scene, but that adaptation may be challenging, particularly when the system differs substantially from conventional mirror setups.

Research has also explored the physical configuration of the CMS external camera, particularly its placement and displayed FOV, analysing how these factors influence driver perception. Thulinsson & Söderlund (2024) have examined drivers' ability to estimate distance and Last Safe Gap (LSG) during an overtaking scenario using simulated CMS. Participants viewed pre-recorded videos featuring various combinations of camera heights and FOVs. The authors demonstrated that camera height had little impact on distance estimation, whereas wider FOVs generally led to more accurate judgments compared to the narrower ones. However, results also showed that such FOVs can introduce a tendency to overestimate available space, leading drivers to accept potentially smaller gaps than would be safe and therefore increasing the risk of accidents. These findings highlight a key design challenge in CMS systems. While wider FOVs help drivers judge distances more accurately and make overtaking easier, they can also lead to overestimation, causing drivers to accept

smaller gaps and thereby increasing risk. In contrast, narrower FOVs may encourage more cautious behaviour but reduce perceptual accuracy and lead to inefficiencies (e.g., not overtaking even when it would be safe to do so).

Complementary evidence comes from Bernhard & Hecht (2022), who reported that distance estimation in CMS is sensitive to camera vertical placement. Comparing distance judgment performance with the camera at three different mounting heights, they found that a lower camera position led to greater overestimation on rearward distances, whereas higher positions produced relative underestimation, with such effects intensifying at closer range.

In contrast to the above laboratory-based findings, Mazzae et al. (2023) conducted an on-road study at a closed test track, adopting driving scenarios similar to those used by Beck et al (2021). In their experiment, they not only assessed CMS performance but also compared it to conventional European side-view mirrors under both daylight and nighttime conditions. Participants executed two overtaking manoeuvres, changing lanes to pass a slower car while another approached from behind. Results showed that CMS use led to longer completion times for the entire passing manoeuvre, particularly in daylight, and greater overtaking distance compared to conventional mirrors. Moreover, participants exhibited a greater number of fixations when using CMS displays in daylight and longer average fixation durations in darkness. However, consistent with Beck et al. (2017, 2021), CMS use was associated with smaller head movements during lane change, suggesting a potential ergonomic advantage despite slower task execution.

Augmented Reality

The presence of an Electronic Control Unit (ECU) in CMS-equipped vehicles, capable of processing and enhancing the camera feed before it is displayed to the driver, has induced researchers to investigate how image processing and the integration of Augmented

Reality (AR) might improve drivers' performance and depth perception. AR overlays on the CMS monitor may help compensate for perceptual limitations introduced by both the system and the human senses. Kane et al. (2016) conducted a pilot study comparing three types of visual augmentations to a non-augmented control condition, finding positive effects from one of the proposed options compared to the control. Specifically, the augmentation that highlighted the silhouette of an approaching vehicle using a bounding box was the best-performing condition. Zhang et al. (2024) further investigated the impact of AR on driving performance by comparing conventional mirrors, CMS, and CMS enhanced with AR in a simulated experiment involving four critical scenarios: merging lanes, overtaking, intersections, and roundabouts. Participants exhibited the best performance with CMS enhanced by AR, while results using standard CMS were worse than with conventional mirrors, potentially due to unfamiliarity with the system and the absence of further cues compared to the already known tool. Between the proposed scenarios, a significant improvement was observed in the overtaking and roundabout trials. Interestingly, the use of CMS led to a reduction in shoulder checks, an important safety behaviour for detecting vehicles in blind spots, raising concerns already discussed by Terzis (2016a). While offering wider and clearer FOV, CMS should not completely replace the use of shoulder checks to ensure it is safe to perform lane changes or other actions on the road.

Expanding on these findings, Rosén & Törner (2025) evaluated both previously proposed AR augmentations and new designs derived from user-centred research. Their results demonstrated how the inclusion of visual indicators representing fixed distances significantly enhanced participants' ability to judge the distance of incoming vehicles without causing visual clutter. Furthermore, this augmentation appeared to have a lasting effect, with distance estimation improvement observed even in subsequent trials where overlays were changed or removed.

While these results highlight promising directions for AR-enhanced CMS, it is essential to consider regulatory constraints when applying them on the road. According to United Nations Regulation No. 46 (2015), such augmentations cannot obstruct more than 10% of Class II (side-view) mirrors, and each overlay element must not exceed 2,5% of the surface displaying the FOV.

Acceptance

Overall sentiment towards new technologies being implemented in the automotive field tends to be positive, with both younger and older drivers showing a willingness to adopt such systems (Beggiato & Krems, 2013; Bernhard & Hecht, 2021; Eby et al., 2016; Gish et al., 2017). Older drivers, in particular, reported engaging with these technologies because they found them useful in compensating for age-related and functional changes. They also appreciated the increased comfort, reduced driving workload, and enhanced sense of safety these systems provide for both themselves and other road users (Gish et al., 2017). Focusing specifically on CMS, Bernhard & Hecht (2022) surveyed 364 participants to evaluate their attitude and acceptance of the technology. The data followed the aforementioned trends, with high usage intention reported by the majority of respondents. However, this positive attitude did not fully translate into a concrete willingness to replace now-owned conventional mirrors, particularly when already equipped with blind spot detection technologies. The perceived lack of additional benefit, despite being informed about the advantages of CMS, contributed to this hesitancy. Additionally, cost emerged as a significant barrier: participants were only willing to pay up to €400 for a CMS, whereas market prices at the time of the study were over three times higher.

Effect of Age on Driving

Ageing affects sensory, perceptual, and cognitive functions, which in turn can influence both driving performance and confidence. Older adults (60 years and older) show slower reaction times, more frequent collisions, and greater difficulty maintaining consistent speed and distance from other vehicles compared to younger drivers (18-40 years) (Doroudgar et al., 2017). Furthermore, their presence in fatal car accidents is higher compared to middle-aged drivers, but a decline in the overall rate was observed over the last twenty years (Cicchino & McCartt, 2014; Cox & Cicchino, 2021).

Nonetheless, it is important to clarify that age itself is not the primary risk factor; rather, it is the conditions and changes that may occur with ageing that pose challenges. It is also worth noting that young drivers represent a high-risk group as well, with studies showing they are the highest age group involved in accidents, even when crash risk is adjusted for the number of trips (Regev et al., 2018). Lyon et al. (2020) reported that younger drivers are at risk due to inexperience, sensation seeking, overconfidence, and peer influence, with these factors leading them to engage in risky behaviours such as speeding, tailgating, fatigued or distracted driving (Doroudgar et al., 2017; European Commission, 2023b; Scott-Parker et al., 2013). In contrast, older adults tend to be aware of their abilities and potential decline, often engaging in self-regulation behaviours, including driving for shorter distances, avoiding nighttime driving, congested routes or high-speed roads (Eby et al., 2016; Molnar & Eby, 2008). When it comes to the use of rearview mirrors, older drivers exhibit a lower number of checks of the blind spot when performing a lane change and report that line changes are more difficult than their younger counterparts, performing fewer lane changes overall (Lavallière et al., 2011).

As can be observed from this literature review, CMS research branches in different directions, analysing how its functioning, placement, and interaction can influence the

driver’s experience behind the wheel. Some research also gathers insights about drivers' acceptance and thoughts on this new technology, highlighting which aspects are functional and enhance their experience and what is holding them back from engaging with this system. Nonetheless, age has been only sparsely investigated in the literature. The research reviewed so far reports age in the demographic data collected during the study; however, it is neither further analysed in the results nor are its potential effects on driving performance explored. Some qualitative work has considered age differences in attitudes toward assistive technologies and CMS, yet robust quantitative evidence is lacking. As Beck et al. (2017), building on Terzis et al. (2016b), point out, there is a clear need to investigate how these emerging technologies interact with different user groups, including age and its related changes in perception and behaviour. The present thesis directly addresses this gap by systematically examining the role of age in drivers’ perceptual judgments and decision-making when using CMS.

Current Research

Research Questions & Hypotheses

Building on previous literature as well as preliminary data from Thulinsson & Söderlund (2024), this study aims to further explore the potential interaction between age and driving performance while using a CMS and being presented with different rear-view perspectives. Based on data gathered by Thulinsson & Söderlund (2024) and the experimental design used in their study, we conducted a new replication and extension of the experiment to further investigate the research questions. This allowed us to maintain compatibility and comparability across studies, while adding new measures to better investigate age-related aspects. In doing so, we increased the data set to reach a desirable statistical power. Therefore, two main aims were pursued: (1) to replicate and compare the newly collected results with those reported by Thulinsson & Söderlund (2024); and (2) to investigate the interaction between age and driving performance. More specifically, the research questions and corresponding hypotheses were:

- RQ1: Do the results of the present study replicate the findings of Thulinsson & Söderlund (2024) regarding drivers' performance with different CMS perspectives?

  H1a: FOV will significantly influence Dist performance, with wider FOV (112°) leading to the most accurate distance estimations, and narrower FOV (76° and 40°) resulting in greater underestimation.

  H1b: Camera height position (high vs low) will not produce a significant effect on the Dist task performance.

  H2a: FOV will have a significant effect on the LSG task, with a smaller FOV (40°) resulting in the largest Time-To-Contact, and a larger FOV (112°) leading to the smallest Last Safe Gaps.

H2b: Camera height position (high vs low) will not produce a significant effect on LSG selection.

- RQ2: Does age influence perceived distance when using CMS?

  H3a: Older drivers will show larger errors in distance judgments compared to younger drivers.

  H3b: The age-related difference will be more pronounced with a narrower FOV (40°)

- RQ3: Does age influence LSG judgments?

  H4: Older drivers will select larger safety margins than younger drivers.

Methods

In the following section, the experiment designed to address the aforementioned research questions will be described. First, an overview of the participants is provided, followed by a detailed account of the experimental design of the study and the materials employed.

Using the participants' data gathered by Thulinsson & Söderlund in 2024 ($N = 28$) as a basis, a new iteration of the experiment was conducted. The original methodology and design were retained to ensure compatibility and comparability with the previous results, while additional measures were introduced to explore age-related effects. This allowed us to expand the previously collected data set, thus enhancing statistical power.

Participants

Current Study Sample. 30 volunteer participants (16 males, 13 females, 1 preferred not to disclose), aged between 22 and 62 years (*Mean (M)* = 38.7, *Median (Mdn)* = 34.0, *Standard Deviation (SD)* = 13.1), took part in the current study. This sample size, combined with the previously collected data (see below), approached the recommended size. An a priori

power analysis indicated that a minimum of 68 participants were required to detect a moderate effect size with $\alpha = 0.05$ and power = 0.80 for a $2 \times 2 \times 3 \times 3$ mixed ANOVA. The calculations were performed using G*Power (Faul et al., 2007).

Participants were recruited through the online platform Accindi (accindi.se) and via printed flyers distributed near the RISE (Research Institutes of Sweden) office in Stockholm, Sweden.

All participants held a valid driving license (*Min* = 8 months, *Max* = 41 years, *M* = 15.5 years, *SD* = 12.6). Inclusion criteria required normal or corrected-to-normal vision, fluent English proficiency (spoken and written), possession of a valid driving licence, and no prior participation in CMS-related studies at RISE in Kista. Participants received written informed consent at least 24 hours before their scheduled session and signed the form upon arrival at the research centre. Each received a gift card with a corresponding value of 200 SEK for approximately one hour of participation.

Visual acuity was assessed using a backlit Monoyer chart. All participants achieved binocular vision above the European threshold of 0.5 (European Commission, 2009), with scores ranging between 0.8 and 1.0. One participant recorded 0.4 in the right eye but 1.0 in the left, still meeting the required standard. No participants exhibited colour vision deficiencies, as assessed using the Ishihara Test (2007).

Handedness was evaluated using the Edinburgh Handedness Inventory (EHI; Oldfield, 1971; see Appendix A), revealing 26 right-handed, two left-handed, one mixed left-handed, and one ambidextrous participant. All participants held a Class B driver's license, with three reporting additional licenses (one Class C, one Class D, and one train license). Three participants identified as professional drivers (two car drivers and one bus driver).

Combined Sample. Data from the current study were merged with those collected by Thulinsson and Söderlund (2024), who used a comparable experimental design and

apparatus. The combined dataset comprised 58 participants (35 males, 22 females, 1 preferred not to disclose) aged between 22 and 64 (M = 37.7; Mdn = 31.0; SD = 14.0). All participants held a valid Class B driver's license, with four possessing additional qualifications (one Class C, two Class D, and one train license). Three participants across the dataset reported professional driving occupations (two car drivers, one bus driver). Driving experience varied widely, with participants holding driving licences from 8 months to 46 years (M = 16.7 years, Mdn = 10.5, SD = 14.2). Self-reported annual mileage was relatively low (see Figure 15), predominantly falling below 10,000 km per year.

This pattern may reflect the urban context of the city where the study was conducted, as the Stockholm metropolitan area is well served by public transportation options (metro, buses, and commuter trains), potentially reducing the need for frequent private driving. Regarding prior exposure to CMS, only one participant reported previous experience with this technology in another experimental context.

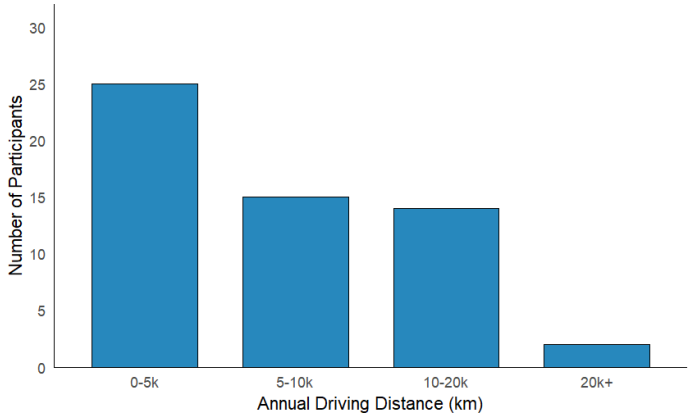

Figure 15. Distribution of participants by annual driving distance (N = 58).

The majority of participants (n = 26, 45%) reported driving 0 – 5,000 km per year, followed by those driving 5,000 – 10,000 km (n = 16, 28%) and 10,000 – 20,000 km (n = 14, 24%). Only two participants reported annual mileage exceeding 20,000 km.

Design

This study employed a mixed experimental design, combining within- and between-subjects factors. The within-subjects component replicated the original 2 × 2 × 3 × 3 factorial structure (see Table 1) used by Thulinsson & Söderlund (2024) to assess depth perception and decision making with CMS. Two tasks were employed, selected from scenarios requiring interaction with the side-view mirror (Zhang et al., 2024) and previously used in the studies presented in the literature review: Distance Judgment (Dist) and Last Safe Gap (LSG).

Table 1

Experimental factors and their levels in the design

Factor	Level
Task	Distance Judgment (Dist); Last Safe Gap (LSG)
CMS camera height	High; Low
Rearview FOV	40°; 76°; 112°
Rear vehicle distance (in Dist task)	16 m; 31 m; 39 m
Road Section (in LSG task)	A; B; C

Age was introduced as a between-subjects factor to examine potential interactions with CMS-related variables. This mixed design enabled both within-participant comparisons across conditions and between-participant comparisons across different ages.

Materials and apparatus

All 36 video clips used in the experiment were originally recorded by Thulinsson & Söderlund (2024). Three GoPro Hero 12 Black cameras were mounted on an Iveco Daily

van: one inside the cabin to capture the driver's forward view and two on the outside, one high and one low, to record the side perspectives corresponding to the CMS configurations. As the overtaking vehicle, a Volvo V40 was used.

The video clips were presented on an LG E7 OLED 65-inch 4K TV using a modified version of VQEGPlayer (Brunnström et al., 2014), which ensured complete control over presentation parameters (e.g., frame rate, resolution, screen size) and allowed the integration of task-related questions directly within the program.

A controlled video-based presentation was chosen over a computer-generated or Virtual Reality (VR) environment due to several advantages. The recordings, captured in 4K resolution (3840 × 2160 pixels), provided a faithful representation of real-world CMS use, preserving natural depth cues and visual detail that might be challenging to reproduce in a synthetic simulation, thus allowing for greater information to the driver. In addition, it avoided potential drawbacks proper to VR (Martirosov et al., 2022), such as simulation sickness, while still maintaining a natural viewing experience.

Ambient light in the laboratory was adjusted to 450 lux to approximate the in-vehicle conditions of 600 lux, reported by Thulinsson & Söderlund (2024). Although slightly lower, this difference falls within a range unlikely to affect visual perception in this experiment. Illuminance was measured from the participants' driving seat position, at eye-level height, directed horizontally toward the monitor. Lighting sources were controlled to ensure minimal glare on the screen. Seat distance from the screen was adjusted to be 1.5 times the height of the screen, as recommended by the manufacturer, to ensure image clarity and sharpness (see Figure 16). Participants used a Thrustmaster T248 steering wheel and pedal set during the experiment to simulate driving, thus increasing the ecological validity of the experiment and enhancing participant engagement. The steering wheel was used to provide responses in the LSG task, whereas a mouse and keyboard were used to record other behavioural responses

(see procedure for more details).

Another workstation was set upon the opposite side of the room to administer background and post-experiment questionnaires, as well as a contrast sensitivity test from the Freiburg Vision Test, $FrACT_{10}$ (see Figure 16; Bach, 2025a, 2025b). A 27-inch monitor (Philips 27IS) was used for the task. Screen gamma, size and seating distance were measured and adjusted according to the software requirements, with the participant seated 1 meter away from the screen. A backlit Monoyer table and Ishihara Test (2007) were used to assess visual acuity and colour vision before the start of the experiment.

The final short semi-structured interviews were recorded using the experimenter's smartphone. The audio files were stored locally on the experimenter's computer only for the time required to complete the transcription and were subsequently deleted, in accordance with the study's data-handling procedures as outlined in the informed consent (see Appendix B).

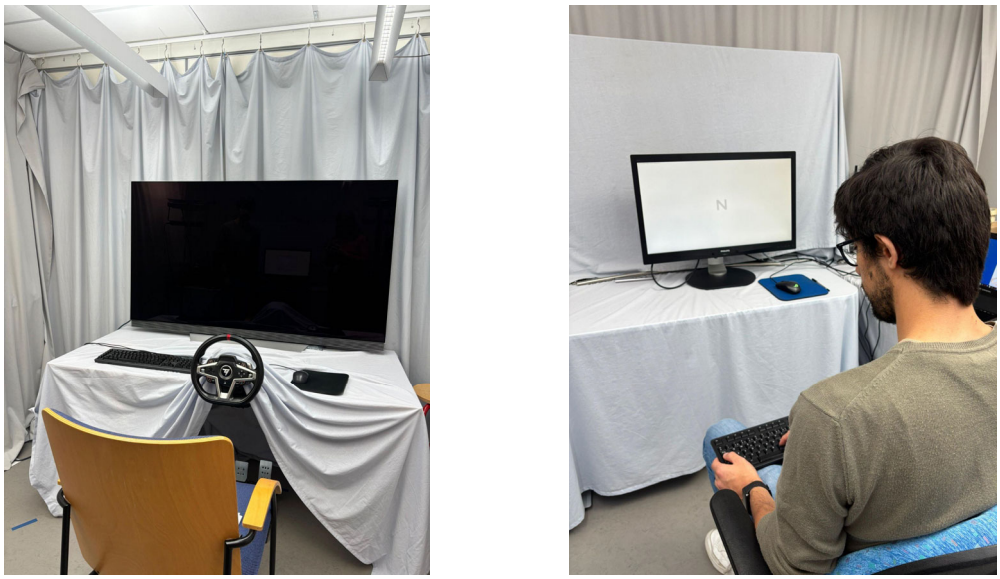

Figure 16. Laboratory configurations for the experiment.

Left panel: Experimental setup for the Camera Monitor System (CMS) evaluation tasks. The configuration included a 65-inch 4K display, a steering wheel and pedal set, and a mouse and keyboard for response input. Controlled lighting (450 lux) was maintained throughout testing. Right panel: Secondary workstation with 27-inch monitor used for administering pre- and post-experiment questionnaires and the contrast sensitivity test using FrACT$_{10}$ software. The image shows the experimenter conducting software verification by entering the letter displayed on screen.

Distance Judgment Videos. The Dist task consisted of 18 video clips, each lasting 10 s (600 frames at 60 fps). Five seconds into each clip, an audio cue prompted participants to shift their attention to the CMS rearview while maintaining their focus on the road and steering to stay within the lane. Both the ego-vehicle and the chasing car travelled at a constant speed of 90 km/h, maintaining a distance of 16, 31, or 39 meters. Rearview was presented with one of three possible FOV – 40°, 76° or 112°– obtained by cropping the wide-

angle footage captured with the GoPro camera. The order of presentation was randomised to reduce potential order effects.

Last Safe Gap Videos. The LSG task also featured 18 video clips with a length of 27.6 s (1656 frames at 60 fps each). As in the Dist task, an audio cue was introduced after five seconds to direct attention to the CMS rearview while participants continued to monitor the road and steer. Here, the ego-vehicle maintained a constant speed of 90 km/h, while the overtaking car travelled at 110 km/h. The overtaking car passes the ego-vehicle at frame 1200, with the following section showing the vehicle reentering the right lane in front of the ego-vehicle and completing the manoeuvre (see Figure 17). The videos' presentation order was randomised to reduce potential order effects.

Figure 17. Experimenter performing the LSG task.

The task required participants to monitor both the forward driving view and the CMS (displayed in the lower-left corner) while maintaining active driving engagement with hands on the steering wheel and foot on the accelerator pedal. Participants were instructed to press the left paddle shifter behind the steering wheel at the perceived last safe moment to initiate a lane change before the overtaking vehicle reached the ego-vehicle.

Procedure

This section presents, in chronological order, the steps each participant underwent during the experiment. The overall duration of each session was approximately one hour; nonetheless, some variation occurred depending on the level of detail provided by participants during the final interview.

Before participation, each participant received a digital copy of the consent form (see Appendix B) via email, outlining the purpose of the study, the procedure, and the handling of data and results, while reminding them of the voluntary nature of participation and their right to withdraw at any time without need for further explanation. Upon arrival at the laboratory, participants were again offered the consent form, and after reading it, they provided written consent. Participants then completed a background questionnaire (See Appendix C) via Google Forms, reporting demographic information and details about their driving experience, including license type, years of holding it, and estimated annual driving mileage.
Next, a vision acuity test, checking each eye separately, and the Ishihara colour vision test were administered to assess normal vision or the presence of any potential deficiencies. Participants were then seated in front of the experimental setup and were provided with an English-written introduction to the experiment, explaining the function of CMS, illustrating its appearance in a vehicle, and showing how it would be displayed on the monitor during the session (See Appendix D).

The task order was counterbalanced across participants: half of the participants started with Dist, and the other half with LSG, thus minimising potential order effects. In the Dist task, participants were instructed to keep their foot on the accelerator, as they would while driving, and steer the car to follow the road. At the auditory signal, while maintaining steering, they had to look at the left-side CMS to observe the car behind. At the end of each clip, participants reported their estimated distance to the trailing car (in meters) and their

confidence in this judgment on a 7-point Likert scale (1 = completely unconfident, 7 = completely confident). These distance estimates were used to compute both absolute distance estimation error (m), calculated as the difference between the estimated and actual distance, and relative distance estimation error (%), obtained by dividing the absolute error by the actual distance. The latter was included to account for, and remain robust against, the greater variance associated with longer distances, in line with Weber's and Fechner's laws (Nutter, 2022), which assert that perceptual sensitivity decreases as stimulus magnitude increases and that perceived changes scale logarithmically with physical intensity.

In the LSG task, participants again kept their foot on the accelerator and steered the car. Upon hearing the acoustic sound, they shifted their attention to the CMS to monitor the approaching car on the left. They indicated the last moment they believed a safe lane change was still possible by pressing the left paddle shifter located behind the steering wheel (chosen because it resembled the gesture of activating a turn signal). From this task, the Time to Contact (TTC, s) was computed as the temporal difference between the moment the chasing vehicle reached the rear end of the ego-vehicle (19 s from the start of the video) and the last safe moment to change lane estimated by the participant. After each clip, participants rated their confidence in their decision on the same 7-point Likert scale used in the Dist task. Before each task, participants received written instructions explaining the task and then performed two practice trials to familiarise themselves with the procedures and equipment. During practice, participants were encouraged to ask questions to avoid any doubt or misinterpretation of instructions. Once the practice was completed and participants confirmed their understanding, the main trial began. During both tasks, the supervisor left the room and remained outside until the participant completed the session, as indicated by an on-screen message, and opened the door.

Between the two tasks, participants were offered and encouraged to take a five-minute break, allowing the supervisor to prepare the second part of the experiment on the computer, and, in the meantime, minimising potential fatigue of the participant. After completing both Dist and LSG, participants were asked to move again to the other side of the lab to undergo the contrast sensitivity test. A brief explanation of what they would have seen was offered, and the seating position was adjusted to be 1 meter from the monitor. Participants were instructed to take their time and provide their best guess, even if the stimulus was not immediately visible to them. $FrACT_{10}$ automatically advanced to the next stimulus if no answer was given within 30 seconds.

A post-experiment questionnaire (See Appendix A) was administered via Google Forms. It included questions about the perceived realism of the simulation, rated on a 10-point Likert scale, where 1 corresponded to very unrealistic and 10 to very realistic, and asked participants to rank the perspectives presented during the experiment from best to worst (ranking from 1 to 6) based on which provided the most accurate distance judgment, felt the safest, and would be preferred in real-life driving. For each ranking, participants could provide short comments explaining their reasoning. They also reported how the experiment influenced their perception of CMS technology compared to conventional mirrors, described their everyday driving style (Active, Defensive, or Passive, with definitions provided for each term) and the one they used during the experiment. Finally, two five-point Likert scales asked participants to report how they would rank their general level of concentration and their concentration during the experiment. The EHI short version was integrated in the questionnaire, asking participants to report hand preference in some predetermined actions, followed by a short semi-structured interview (see Appendix E). Participants were invited to share their experience and impressions of the experiment and to suggest possible improvements. Then, participants' attitudes toward new technologies were

explored, with a specific focus on CMS. They were asked about any issues or suggestions they encountered with CMS in the simulation, and to propose potential improvements they would like to see if they were to use the system in real life.

Finally, participants were asked to reflect on their approach to the Dist and LSG tasks, including any strategies or cues they relied on, and to elaborate on the reasoning behind their ranking of perspectives in the final questionnaire. The session concluded with an open question, giving participants the opportunity to add any further insights or remarks not covered by the questionnaire or interview.

Data analysis and results generation

During this study, both qualitative and quantitative data were collected from 30 participants. The experimental procedure was kept the same as used by Thulinsson & Söderlund (2024), with only minor additions introduced at the end of the testing to collect additional measures of interest (e.g. Contrast Sensitivity, Handedness). This ensured comparability and compatibility between the two samples, allowing the integration of the dataset and subsequent analyses on a combined sample of 58 participants. For variables and measures unique to the present study, only preliminary analyses were feasible; nonetheless, a larger sample size would be necessary to ensure sufficient statistical power and to confirm potential trends observed in the current data. Statistical analyses were conducted using RStudio (Posit team, 2025) and the following packages: *afex, emmeans, dplyr, tidyr, ggplot2, ggsignif.*

A preliminary analysis of the raw data was conducted to examine sample distributions for both the Dist and LSG tasks. The LSG data did not exhibit notable skewness or kurtosis, whereas the Dist data contained several extreme values, reflecting substantial underestimation relative to the actual distances, which could have influenced subsequent analyses. Therefore, outliers were identified and excluded based on a threshold of ±2.5 *SD* from the mean of the dependent variables (absolute and relative distance estimation errors). Specifically, the exclusion limits were

–84 m and 79 m for absolute errors, and –2.76 and 2.55 for relative errors. From the total sample of 58 participants, two were excluded from the analyses because more than half of their trials fell outside the ±2.5 *SD* range. Two additional participants showed one and two outlying values, respectively; in these cases, the outliers were replaced with the mean of the corresponding dependent variable. The remaining 56 participants were divided into two groups based on age using a median split (*Mdn* = 31.0), resulting in 26 younger (*M*age = 26.4, *SD* = 2.5) and 26 older (*M*age = 50.7, *SD* = 10.7) participants.

A Chi-Square test of independence was performed to determine whether gender distribution differed between the two age groups. No significant difference was found, $\chi^2(1, N = 56) = 0.37$, $p = .54$. Furthermore, participants' self-reported driving styles in real life and during the experiment were compared using again a chi-square test of independence to assess whether the two distributions differed. The styles were categorised as "aggressive", "defensive", or "passive", each described in the post-experiment questionnaire to help participants select the most representative option. A significant association emerged between participants' reported real-life driving styles and those adopted during the experiment, $\chi^2(4, N = 56) = 20.10$, $p < .001$, indicating that participants' experimental behaviour reflected their typical driving patterns. Additionally, because participants' age and the years they had held a driving licence appeared to follow similar distributions, their association was examined using a Pearson correlation. The two variables were highly correlated, $r(54) = .92$, $p < .001$, indicating that older participants had held their licence for a substantially longer period and, consequently, had accumulated greater driving experience than younger participants.

Visual acuity (VA) and contrast sensitivity (CS) were compared between the two age groups using data from the 28 participants in the present study, after excluding two outliers. Independent samples t-tests showed no significant age-related differences in either VA (youngers: $M = 0.95$, $SD = 0.06$; older: $M = 0.92$, SD = 0.09; $t(26) = 1.15$, $p = .26$) or CS (younger: $M = 1.97$, $SD = 0.06$; older: $M = 1.92$, SD = 0.1; $t(26) = 1.65$, $p = .11$).

The primary statistical tests used in this study include Analysis of Variance (ANOVA). When the assumption of sphericity was violated, Greenhouse-Geisser corrections were applied, with corrected degrees of freedom reported where applicable. Post-hoc pairwise comparisons were conducted using Bonferroni corrections to further explore significant main effects and interactions. Additionally, an ANCOVA was performed to assess the impact of driving style on LSG data.

Results

Participants rated the overall realism of the experiment as high, with a mean score of 7.74 on a 10-point Likert scale (1 = highly unrealistic, 10 = highly realistic; *Min* = 3, *Max* = 10, *SD* = 1.64, *Mdn* = 8). Self-reported focus during the tasks was also strong, with an average of 4.33 on a 5-point scale (1 = not focused at all, 5 = highly focused; *Min* = 2, *Max* = 5, *Mdn* = 4, *SD* = 0.71).

Preferences for camera perspectives (see Figure 18) were assessed in the post-experiment questionnaire, where participants ranked the perspectives from most to least preferred (1 = liked the most, 6 = liked the least). Participants selected Perspective B (High position – 40° FOV; *M*rank = 2.33, *SD* = 1.63, *Mdn* = 2) and Perspective A (High position – 76° FOV; *M*rank = 2.51, *SD* = 1.63, *Mdn* = 2) as the most suitable options for distance judgement and for providing a sense of safety. In contrast, Perspective F (Low position – 112° FOV) was consistently rated as the least preferred option for both criteria (*M*rank = 5.03, *SD* = 1.63, *Mdn* = 6).

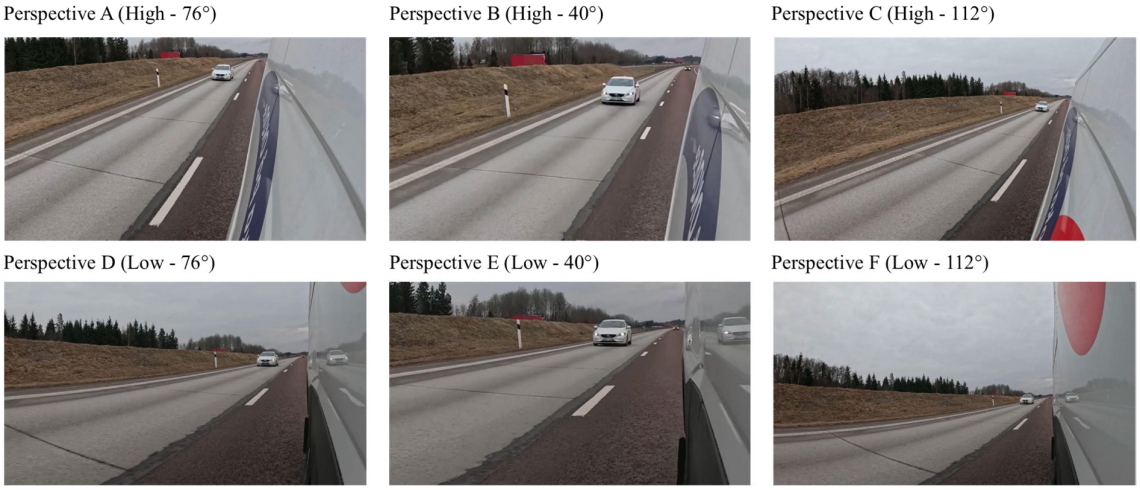

Figure 18. Camera perspectives presented during the experiment and ranked in the post-experiment questionnaire.

Mixed 2x3x3x2 ANOVAs were performed for both the Distance Estimation (Dist) and Last Safe Gap (LSG) tasks, analysing Absolute and Relative Distance Estimation Errors, as well as TTC. For the Dist task, within-subject effects of Camera Position (high, low), FOV (40°, 76°, 112°), and Real Distance (16, 31, 39 m) were analysed, along with the between-subjects effect of Age Group (younger and older). For the LSG task, within-subject variables included Camera Position (high, low), FOV (40°, 76°, 112°), and Road Section (A, B, C), with Age Group (younger and older) as a between-subjects factor. In the following sections, main effects and interactions are reported, followed by post-hoc analysis where relevant.

Dist task - Absolute Distance Estimation Error (estimated distance - real distance)

Results from the mixed ANOVA on absolute distance estimation error are reported in Table 2.

Table 2

Results of the ANOVA for the main effects of Age Group, Camera Position, FOV, and Real Tested Distance on Absolute Distance Estimation Error.

Variables	Df	F value	*p* value	ηp^2
Camera Position	1, 54	20.45	< .001***	.275
Real Distance	2, 108	12.93	< .001***	.193
FOV	1.33, 71.57	86.51	< .001***	.616
Age Group	1, 54	4.52	.038*	.077
Age Group x Camera Position	1, 54	0.13	.718	.002
Age Group x Real Distance	2, 108	2.67	.074	.047
Age Group x FOV	1.33, 71.57	2.25	.130	.040
Camera Position x Real Distance	1.38, 74.30	2.17	.137	.039
Camera Position x FOV	1.69, 91.19	0.89	.397	.016
Real Distance x FOV	2.60, 140.57	14.78	< .001***	.215
Age Group x Camera Position x Real Distance	1.38, 74.30	3.52	.051	.61
Age Group x Real Distance x FOV	2.60, 140.57	0.76	.500	.014
Age Group x Camera Position x FOV	1.69, 91.19	0.01	.999	< .001
Camera Position x Real Distance x FOV	2.66, 143.87	1.54	.499	.028
Age Group x Camera Position x Real Distance x FOV	2.66, 143.87	0.47	.678	.009

Note. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

A significant main effect of Camera Position was found, indicating that CMS camera height substantially affected participants' distance estimation and absolute error of judgment. In particular, the lower camera position produced smaller underestimation error, resulting in more precise judgments with respect to the higher camera position (see Figure 19).

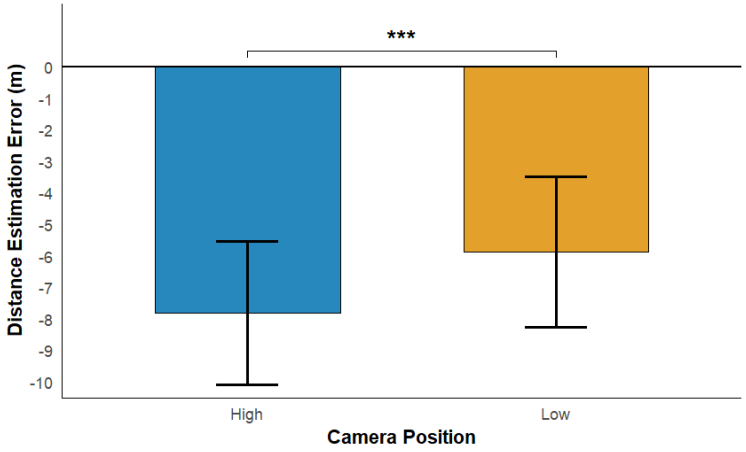

Figure 19. Absolute Distance Estimation Error by Position.

Error bars represent ±1 Standard Error of the Mean (SEM). Asterisks (***) denotes a significant difference at $p < .001$.

Despite this performance advantage, post-experiment interviews and questionnaire responses revealed that the low camera position was generally not preferred. Several participants described it as feeling "too close to the road," reporting discomfort or reduced trust in this perspective (see Qualitative Results section). Significant main effects were also observed for FOV and Real Distance, showing that both the field of view and the actual distance of the chasing car influenced estimation accuracy. Post-hoc tests with Bonferroni correction showed no significant difference in distance estimation error between 16 m and 31 m ($p = .99$).

However, error increased significantly at 39 m compared to both 16 m and 31 m ($p < .001$; see Figure 20).

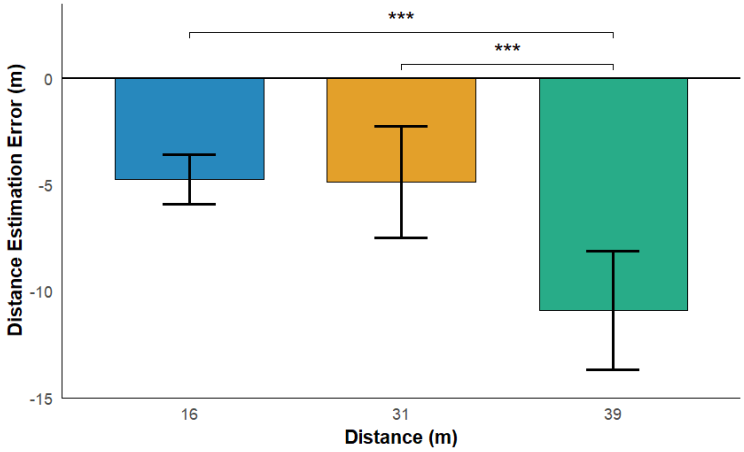

Figure 20. Main Effect of Distance on Absolute Estimation Error.

Error bars represent ±1 SEM. Asterisks indicate significant pairwise differences after Bonferroni correction: *** $p < .001$.

Similarly, all FOV conditions (40°, 76° and 112°) differed significantly from one another (all $p < .001$), with estimation error decreasing linearly as the FOV widened and becoming non-significantly different from zero at 112° (see Figure 21).

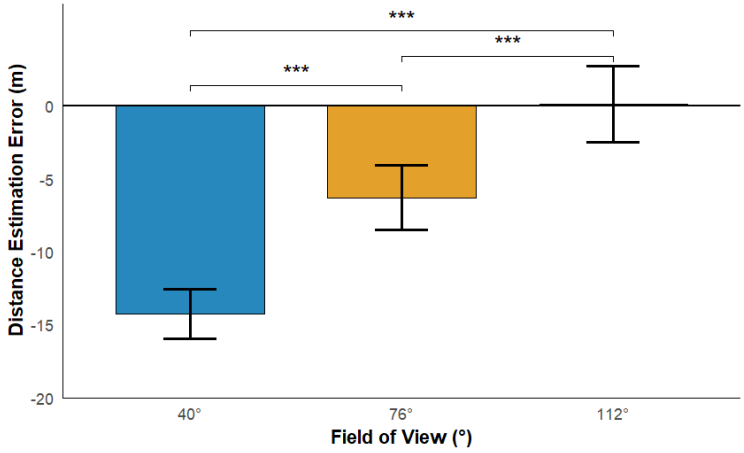

Figure 21. Main Effect of Field of View (FOV) on Absolute Distance Estimation Error. Error bars represent ±1 SEM. Asterisks indicate significant pairwise differences after Bonferroni correction: *** $p < .001$.

A main effect of age group emerged, highlighting performance differences in distance judgment between younger and older participants. Contrary to the initial hypothesis (H3a), younger participants indicated significantly shorter estimated distances, resulting in a greater underestimation, while older participants made more accurate judgments. This finding contradicts the expectation that older drivers would produce larger absolute distance estimation errors due to perceptual and behavioral differences. Instead, these results suggest that increased driving experience, accrued over years of holding a driving license, may have enabled older drivers to develop more precise distance judgment abilities compared to their younger counterparts.

A significant Real distance × FOV interaction was also present, suggesting that the effect of distance on estimation error varied depending on the FOV used in the side-view monitor. A closer inspection of the interaction showed that the influence of distance on estimation accuracy depends strongly on the FOV (see Figure 22): a narrow FOV (40°) produced the greatest underestimation errors, particularly at longer distances. Both 16 m and 39 m distances showed a linear reduction in underestimation error as FOV increased, with their errors becoming non-significantly different from zero under the 112° FOV condition.

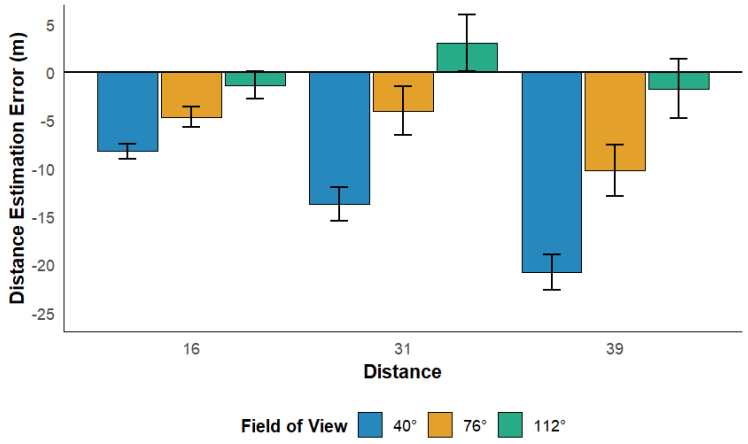

Figure 22. Interaction of Real Distance and Field of View on Absolute Distance Estimation Error. Error bars represent ±1 SEM.

Interestingly, the 31 m condition exhibited an anomalous pattern: as the FOV widened, participants' performance improved drastically compared to other distances, ultimately leading to the only condition where participants overestimated the chasing car's distance from the ego-vehicle (thus indicating it to be farther away than it actually was, which in a real driving context could lead to a rear-end collision). However, when the analyses were repeated using Relative Distance Estimation Error, which accounts for proportional increases in perceptual error with greater distances, the distance × FOV interaction was no longer significant (p = .35), consistent with the Weber–Fechner Laws and the expectation of perceptual error scaling with the increase of distance.

Dist task - Relative Distance Estimation Error (absolute error / real distance)

Results from the mixed ANOVA for Relative Distance Estimation Error are reported in Table 3.

Table 3

Results of the ANOVA for the main effects of Age Group, Camera Position, FOV, and Real tested Distance on Relative Distance Estimation Error.

Variables	Df	F value	*p* value	ηp²
Camera Position	1, 54	20.90	< .001***	.279
Real distance	2, 108	9.05	< .001***	.144
FOV	1.34, 72.42	91.00	< .001***	.628
Age group	1, 54	4.54	.038*	.078
Age Group x Camera Position	1, 54	0.05	.824	< .001
Age Group x Real Distance	2, 108	1.88	.159	.034
Age Group x FOV	1.34, 72.42	2.15	.140	.038
Camera Position x Real Distance	1.78, 95.85	1.05	.348	.019
Camera Position x FOV	1.72, 92.83	0.76	.453	.014
Real Distance x FOV	2.38, 128.68	1.10	.342	.020
Age group x Camera Position x Real Distance	1.78, 95.85	3.77	.031*	.065
Age group x Camera Position x FOV	1.72, 92.83	0.02	.965	< .001
Age group x Real Distance x FOV	2.38, 128.68	0.43	.688	.008
Camera Position x Real Distance x FOV	2.88, 155.42	1.76	.160	.031
Age group x Camera Position x Real Distance x FOV	2.88, 155.42	0.57	.632	.010

Note. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

The main effects observed in the absolute error analysis were maintained when conducting the ANOVA on relative distance estimation error. Significant main effects were

found for Camera Position, Real Distance, and FOV. The age Group effect also remained significant, with older participants again outperforming younger ones. On average, older participants showed a mean underestimation of -12.2%, compared to -36.7% for younger participants (see Figure 23).

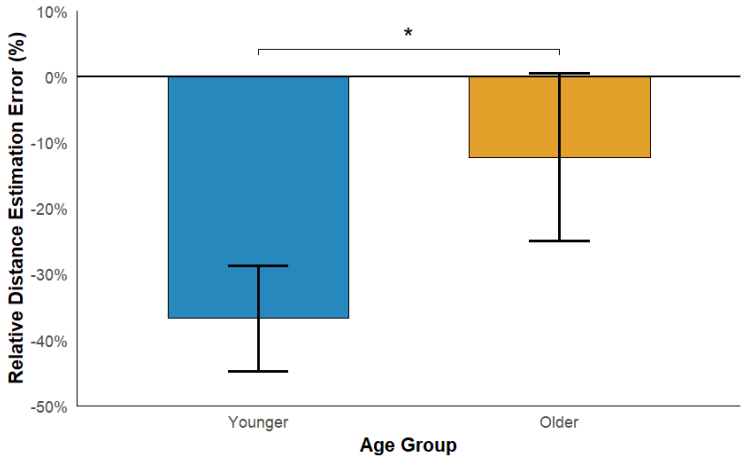

Figure 23. Main effect of Age group on Relative Estimation Error.

Error bars represent ±1 SEM. Negative values indicate an underestimation of real distance. Asterisk (*) denotes a significant difference at $p < .05$.

Post hoc tests with the Bonferroni correction were used to further investigate the nature of the aforementioned effects. Relative distance estimation error did not differ significantly between 16 m and 39 m ($p = .99$), indicating that, when accounting for proportional scaling, estimation error remained relatively constant across increasing distances. However, significant differences were found between 16–31 m ($p < .001$) and 31–39 m conditions ($p = .003$), with the 31 m condition showing the smallest relative underestimation (–15.8%) compared to 16 m (–29.6%) and 39 m (–28.0%) (see Figure 24).

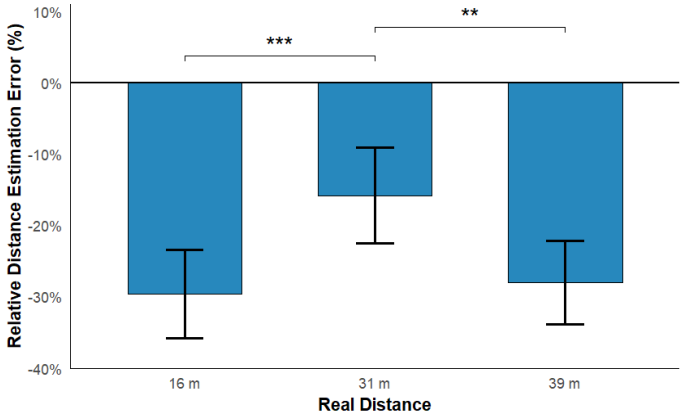

Figure 24. Main Effect of Real Distance on Relative Distance Estimation Error.

Error bars represent ±1 SEM. Negative values indicate an underestimation of the real distance. Asterisks indicate significant pairwise differences with Bonferroni correction: *** $p < .001$, ** $p < .01$.

The effect of FOV remained consistent with the pattern observed for the Absolute Distance Error: relative errors decreased as FOV widened, with significant differences between all three FOV conditions (all $p < .001$). Under the 112° FOV condition, the estimated mean error reached –0.9%, which was not significantly different from zero (see Figure 25).

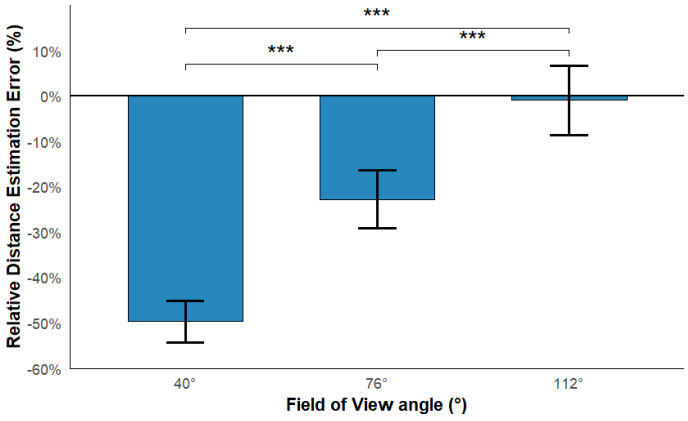

Figure 25. Main Effect of Field of View on Relative Distance Estimation Error.

Error bars represent ±1 SEM. Negative values indicate an underestimation of the real distance. Asterisks indicate significant pairwise differences with Bonferroni correction: *** $p < .001$.

The distance × FOV interaction was no longer significant (p = .35), but a significant three-way interaction emerged among Age Group × Camera Position × Real Distance highlighting a different pattern in the interaction of Camera Position and Real Distance between age groups (see Figure 26).

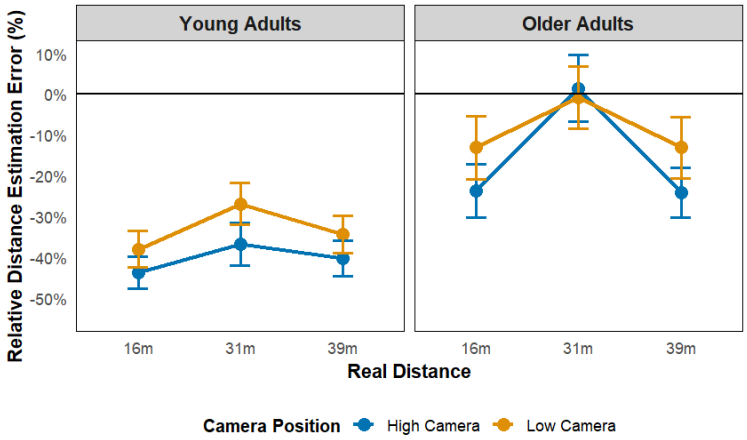

Figure 26. Interaction effect between Age Group, Camera Position, and Real Distance on Relative Distance Estimation Error.

Error bars represent ±1 SEM. Negative values indicate an underestimation of the actual distance.

In particular, post-hoc comparisons revealed that at the intermediate car distance (31m), young adults underestimated distance much more than older adults across both camera positions. The difference between age groups at 31 m was statistically significant for both high, $t(74.2) = -3.06$, $p = .003$, and low, $t(74.2) = -2.10$, $p = .04$, positions.

At the shortest distance (16m), a significant age group difference emerged only in the low camera position, $t(74.2) = -2.00$, $p < .05$, with young adults again underestimating more than older adults. No significant differences were observed at 39m (all $p > .09$), although the pattern of underestimation by young adults remained visible across conditions.

To further examine the three-way interaction between Age Groups × Position × Real Distance, repeated-measures ANOVAs were conducted for each age group separately. The Camera Position × Real Distance interaction was not significant for older participants, $F(1.78, 48.16) = 2.70$, $p = .083$, $\eta p^2 = .091$, nor for younger participants, $F(2, 54) = 1.15$, $p = .325$, $\eta p^2 = .041$, indicating that the effect of camera position did not change as a function of distance in either group. The above-mentioned three-way ANOVA was also examined by calculating the difference between low and high camera positions (low minus high) for each participant at each distance. Paired-samples t tests with Bonferroni correction were then performed to compare these difference scores across the three distances separately for each age group. No pairwise comparison reached significance after correction in either age group.

LSG task - Time To Contact (TTC, last safe moment (19 s) - estimated last safe moment)

In the LSG task, TTC was computed as the difference between the actual collision time (19 s into the video) and the participant's estimated last safe moment to change lane. Higher TTC values, therefore, indicate earlier responses (more conservative), whereas lower values indicate later responses. Results from the mixed ANOVA for TTC are reported in Table 4.

Table 4

Significant ANOVA Results for the effect of age group, camera height, FOV, and road section on Time To Contact.

Variables	Df	F value	*p* value	ηp²
Camera Position	1, 56	1.88	.176	.032
Road Section	2, 112	6.31	.002**	.101
FOV	1.45, 81.03	151.25	< .001***	.730
Age Group	1, 56	3.18	.080	.054
Age Group x Camera Position	1, 56	0.07	.787	.001
Age Group x Road Section	2, 112	0.01	.993	< .001
Age Group x FOV	1.45, 81.03	5.75	.01*	.093
Camera Position x Road Section	2, 112	1.45	.239	.025
Camera Position x FOV	2, 112	0.02	.979	< .001
Road Section x FOV	3.36, 188.21	1.46	.222	.025
Age Group x Camera Position x Road Section	2, 112	0.60	.550	.011
Age Group x Road Section x FOV	3.36, 188.21	1.03	.386	.018
Age Group x Camera Position x FOV	2, 112	2.18	.122	.037
Camera Position x Road Section x FOV	3.30, 184.76	0.67	.586	.012
Age Group x Camera Position x Road Section x FOV	3.30, 184.76	0.75	.538	.013

Note. * = $p < .05$, ** = $p < .01$, *** = $p < .001$.

FOV significantly affected TTC, with estimates decreasing for wider fields of view. Post-hoc analyses with Bonferroni correction confirmed that all pairwise comparisons between the three FOVs were significant (see Figure 27). Widening the FOV from 40° to 76° reduced TTC by 1.61 seconds, $t(112) = 10.22$, $p < .001$, and increasing it further from 76° to 112° led to an additional reduction of 1.12 seconds, $t(112) = 7.08$, $p < .001$. Overall, the cumulative decrease from 40° to 112° amounted to 2.73 seconds, $t(112) = 17.30$, $p < .001$. At the experimental speeds (with ego-vehicle travelling at 90 km/h, and being approached by the chasing vehicle at 110 km/h after 19 seconds), this corresponded to accepting a gap approximately 15 meters shorter when using the widest FOV compared to the narrowest.

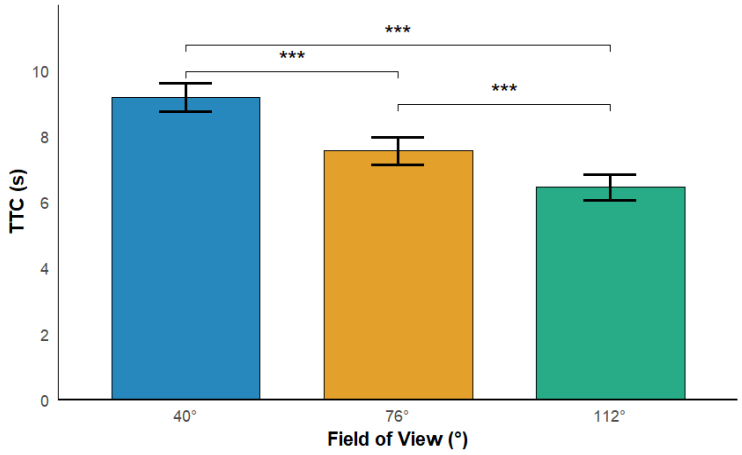

Figure 27. Main effect of Field of View on Time To Contact.

Error bars represent ±1 SEM. Asterisks indicate significant pairwise differences with Bonferroni correction: *** $p < .001$.

A significant main effect of ROad Sections was also observed. Post-hoc comparisons showed that participants responded, on average, 0.5 s later in road section A than in road section C, $t(112) = 3.51$, $p = .002$. This means they signalled the LSG at a point roughly 3 meters closer to the ego-vehicle.

No significant main effect of Age Group was found; however, a significant interaction emerged between Age Group and FOV. Post-hoc analyses showed that, under the 40° FOV condition, younger participants responded 1.86 s later than older participants, $t(63.6) = -2.55$, $p = .01$, equivalent to signalling the LSG 11.2 meters closer to the ego-vehicle (see Figure 28).

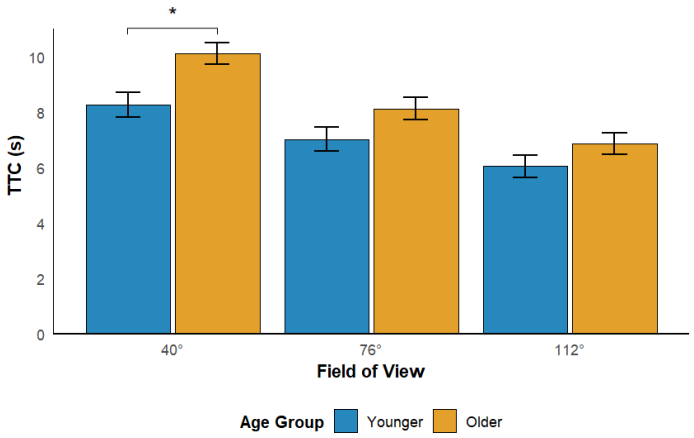

Figure 28. Interaction of Age Group and Field of View on Time To Contact.

Error bars represent ±1 SEM. Asterisks indicate significant pairwise differences with Bonferroni correction: * $p < .05$.

To test whether TTC judgments could be influenced by individual driving tendencies, an ANCOVA was conducted, including both self-reported driving style during the experiment and real-life driving style. Adding these covariates did not significantly improve model fit (experimental driving style: $p = .35$; real-life driving style: $p = .70$), indicating that neither variable provided additional explanatory value beyond the factors already analysed.

Qualitative results - short interviews

After the conclusion of the Dist and TTC tasks, the completion of the post-experiment questionnaire and contrast sensitivity test, participants took part in a semi-structured

interview lasting approximately 15 minutes. The interview focused on their experience during the experiment, their views on CMS technology, the strategies they used to approach the tasks, their preferences in the offered perspectives, and any additional reflections they wished to share.

The interviews were manually transcribed verbatim and subsequently coded using Taguette (Rampin & Rampin, 2021). Open codes were generated inductively, guided by the research objectives, and the analysis provided additional insights into participants' attitudes toward CMS and the experimental setup. The main aspects that emerged are presented below.

Tasks performance and used strategies. Participants reported employing diverse cognitive strategies when performing the experimental tasks, with notable differences between LSG and Dist tasks. For the LSG task, participants predominantly relied on intuitive, feeling-based judgments (P3, P6, P7, P9, P10, P14, P17), describing their decisions as based on "feeling" or "intuition" rather than explicit calculation. Others used more concrete visual cues, such as the centre-line dashes on the road (P2, P15, P24, P25), the approaching vehicle's speed or rate of size increase (P4, P12, P19, P25, P26), or the ego-vehicle's length (P11, P13) as a spatial reference.

Distance estimation strategies were similarly varied but more explicitly anchored to visual references. Many again relied on road markings such as centre-line dashes (P1, P2, P16, P20, P22, P24-27) or the roadside delineators (P5, P6, P7, P9, P15). The ego-vehicle's length served as a mental ruler for several participants, who reported mentally multiplying this dimension to estimate distances. Some participants relied on more unconventional analogies, such as imagining a "familiar room" (P5) or the length of a "25-meter or 50-meter swimming pool" (P17). Overall, the distance estimation task was reported as more difficult than the LSG task (P2, P3, P7, P9, P18).

Perspectives perception and feedback. Participants demonstrated strong and consistent preferences regarding camera positioning, with the higher camera position favoured over the lower alternative. Among higher perspectives, perspective B was most frequently recognised as optimal, offering what participants described as the most natural view of the rear scene. Participants justified their preference, reporting that higher positions allowed them a better overview of the surroundings compared to the lower perspectives. In fact, lower perspectives were consistently reported to be “too low”, “too close to the ground” or positioned “almost at ground level”, particularly perspective F. P12 specifically noted that with low positions “you cannot really judge the vehicle distance and how fast is it approaching", while P14 observed that low and wide camera angles created perceptual distortions where objects “either looked very close or very far”.

Perceived benefits of CMS. CMS was perceived positively, and most of the participants demonstrated a positive attitude towards it. Multiple participants reported that its employment may increase security and reduce accidents thanks to various benefits: the ability to maintain greater focus on the road and requiring less body movement to check the mirror (P12) (thus highlighting also an ergonomic aspect), the potential to eliminate blind-spots (P9), and reduce the risk of damaging protruding parts of the vehicle or hit something with it (P10, P16), particularly in narrow environments or parking situations (P28). Participants also valued the visual quality provided by CMS, describing the view as clear (P13, P15, P18) or noting that the available image appeared to be larger than on standard mirrors (P27). Some suggested that CMS could offer improved visibility in adverse conditions such as rain and fog (P13), low light or winter settings (P18), or icy conditions (P30).

Proposed CMS enhancements. When asked to report potential enhancements or changes they would like to see implemented in CMS, participants proposed extending this technology beyond a passive video display by incorporating intelligent, augmented features

that would actively support driving decisions. The most frequently proposed enhancement involved making the system able to measure distance and have object detection capabilities. Multiple participants (P1, P2, P4, P7, P10, P12, P13, P15, P17, P20) proposed that CMS should provide quantitative distance information via numerical distance readouts, reference lines superimposed on the image, or automated visual and acoustic warnings when lane changes would be unsafe (P7, P12, P17). P1 proposed integrating multiple camera perspectives with dynamic switching based on the situation (e.g., when a vehicle approaches). Others (P9, P11, P12, P15) suggested adjustable camera angles that could be modified manually by the driver or dynamically by the system, depending on vehicle state and manoeuvre.

Conditional acceptance of CMS Technology. Rather than expressing clear approval or rejection, many participants described a set of conditions that CMS technology would need to meet before they would consider adopting it. Eight participants (P5, P7, P9, P10, P14, P18, P27, P29) explicitly emphasised reliability, safety, and technical robustness as central prerequisites. These concerns ranged from general expectations of technological dependability ("technology must be working perfectly all the time for it to be reliable", P5) to more specific requirements, including the absence of latency (P7) and consistently high image quality (P15). Participants also recognised the possibility of system failure inherent to digital technologies, mentioning risks such as blank screens (P29), unexpected malfunction ("not everything can always go 100% right", P18), or environmental interference ("camera could get foggy", P15).

Some participants expressed caution about adopting CMS based on comparisons with conventional mirrors, which they described as stable and unproblematic in everyday use. P14 and P26 reported not perceiving clear benefits of switching, while others (P14, P10) noted

that the CMS view did not differ meaningfully from what they already see using traditional mirrors.

Economic considerations also emerged as an acceptance criterion. P1 expressed concerns that CMS may be more expensive both to purchase and to repair, a point raised by P2 as well. Similarly, P7 reported feeling no urge to replace their current vehicle and, if doing so, no particular motivation to invest much money in optional features.

In line with this idea of not (directly) switching to CMS, several participants suggested a dual-system approach, framing CMS as a complement rather than a replacement for existing mirrors. P10 suggested that an analogue option, glass side-view mirrors, should remain available as a backup, while P15 stated they would keep both CMS and mirrors as "spontaneously one of them can get foggy". In line with P15 assumption, environmental durability was raised as a recurring prerequisite, with participants highlighting potential dust accumulation on the lens (P2) or the presence of snow and rain (P16) disrupting image quality.

Collectively, these findings revealed that acceptance of CMS is conditional and multifaceted. As a novel technology entering a domain where the current solution (conventional mirrors) is still perceived as stable and adequate, CMS faces the challenge of demonstrating clear advantages to justify its adoption. Participants, in fact, expressed caution, emphasising the need for proven reliability and environmental robustness, as well as the ability of the system to sustain failure with fallback systems before committing to it. Furthermore, the price emerged as a decisive factor for some participants in determining whether they would adopt this new technology or continue relying on traditional mirrors. Overall, CMS was viewed as a potentially valuable augmentation to existing technology, rather than an essential or urgent replacement, reflecting a pragmatic approach in which benefits must clearly outweigh risks and costs.

Discussion

Thesis Overview and Key Findings

This study investigated how age influences the use and perception of Camera Monitor Systems, and examined how variations in perspective, specifically Camera Position and offered FOV, affect distance estimation and decision-making during driving-related tasks. Thirty participants were recruited and asked to complete two experimental tasks: a Distance estimation task (Dist) in which they judged the distance of an approaching vehicle, and a Last Safe Gap task (LSG), in which they indicated the last safe moment at which they would still consider safe to perform a lane change. Experimental clips systematically varied Camera Position (high vs. low), FOV (40°, 76°, 112°), and, depending on the task, either the Real Distance of the approaching vehicle (16 m, 31 m, 39 m in the Dist task) or the Road Section (A, B, C in the LSG task). Participants were divided into younger and older adult groups to assess age-related differences in tasks performance.

To increase statistical power, the collected data were combined with results from a previous study by Thulinsson & Söderlund (2024), which employed an equivalent experimental design and procedure, thus resulting in a total sample of 58 participants. After data preparation and removal of two outliers, analyses were conducted. Results highlighted that across both tasks, perspective manipulations presented clear effects. Both FOV and Camera Position impacted how drivers judged distances, and FOV had an effect on the decision for lane change when choosing the Last Safe Gap. Notably, different behaviours were observed between Age Groups in Distance judgment and Last Safe Gap selection. In the following sections, results will be discussed separately for each task in relation to the initial research questions and hypotheses.

Dist Task. Consistent with H1a and findings by Thulinsson & Söderlund (2024), FOV emerged as the strongest predictor of distance estimation accuracy ($\eta p^2 = .616$ for

absolute error and $\eta p^2 = .628$ for relative error), with significant differences between all three tested FOVs. In particular, the 112° FOV produced the most accurate estimations, which did not significantly differ from zero (indicating a perception through the CMS monitor comparable to viewing the real distance directly), whereas narrower FOVs led to greater underestimation of actual distance. As also noted by Thulinsson & Söderlund (2024), this pattern likely arises because narrower FOVs make objects appear closer than they actually are, thereby inducing underestimation. Furthermore, wider FOVs allow for a greater amount of visual information within the driver's visual field, increasing the availability of cues that support distance perception. This interpretation aligns with Schmidt et al. (2016) and Terzis (2016a), who highlighted that CMS inherently provide fewer depth cues than conventional mirrors due to the lack of binocular cues and the fixed camera viewpoint. A wider FOV may, therefore, partly compensate for this limitation by providing additional monocular depth cues. For instance, by increasing the visibility of roadside delimiters poles or centre-line dashes, which many participants reported using to judge the distance of the chasing vehicle.

Camera Position also had a significant effect, with a large effect size (absolute error: $\eta p^2 = .275$; relative error: $\eta p^2 = .279$), contradicting H1b and diverging from results by Thulinsson and Söderlund (2024). Participants showed smaller underestimation errors with the low camera position ($M = –5.88$ m) compared to the high position ($M = –7.81$ m). These findings partly align with Bernhard and Hecht's (2022) study, which reported that higher camera placements tend to produce greater underestimations, while lower positions are typically associated with overestimation. Although no overestimation was observed in the present study, the overall pattern in that higher placements tended to produce stronger underestimation. Furthermore, consistent with Bernhard et al. (2023), who reported that participants generally preferred higher camera positions, with few favouring lower ones, the present study similarly found that most participants identified Perspective F (i.e., low

position, 112° FOV) as the least desirable for judging distance and for perceived safety. In both the post-experiment questionnaire and interviews, participants stated that this perspective provided poor information about the distance and relative speed of the chasing vehicle. This preference may be explained by the reduced depth information offered by lower camera positions. At lower viewpoints, vehicles and surrounding objects overlap more in the image displayed on the monitor and appear flattened against the background, limiting, for instance, the visible space between them. This reduces the available information in the image and may increase reliance on depth cues that provide limited information about inter-object distance (e.g., occlusion). In contrast, higher positions expose more of the inter-object and background space, improving access to cues such as relative height and revealing the spatial relationships between foreground and background objects.

Considering results from both FOV and Camera Position, perspectives producing smaller underestimation error could appear preferable, as it could translate to more precise and efficient manoeuvring. Nonetheless, employing a configuration of FOV or position that results in extremely low underestimation, or even errors not significantly different from zero, as with the 112° FOV, may pose safety risks if drivers happen to overestimate the actual distance, perceiving the chasing vehicle as farther away than it actually is. It is therefore necessary to critically ponder what constitutes an appropriate balance between enabling optimal performance and ensuring user safety.

As expected, estimation errors varied significantly with real distance, consistent with the Weber–Fechner laws: discriminating changes becomes more difficult as stimulus magnitude increases, making far distances harder to estimate precisely than closer ones. Nonetheless, an interesting and unforeseen effect was observed, with distance 31 m producing absolute errors comparable to 16 m, then translating into a significantly lower relative error. This non-linear pattern at intermediate distance requires further investigation. It

may reflect an optimal distance where multiple utilised depth cues converged optimally, or where participants' strategies (such as counting road markings and objects, or mentally projecting reference lengths) were most efficiently applied, to then become obsolete and less functional at longer distances.

Results in the Dist task by Age Group, which showed a significant medium effect ($\eta p^2 = 0.77$), contradicted our initial hypothesis that older drivers would show larger errors in distance judgments compared to the younger ones (H3a), particularly in narrower FOV (H3b). Instead, the older group produced smaller errors than the younger group. These hypotheses were grounded in evidence that older adults typically experience age-related declines in visual perception (e.g., reduced visual acuity, decreased contrast sensitivity; Fillit et al., 2017; Van Den Berg et al., 2007; Weale, 1961) that are highly relevant to driving. They also typically exhibit difficulties in distance-related driving tasks, such as distance maintenance (Doroudgar et al., 2017) or lane changes (Lavallière et al., 2011). Given that narrower FOVs were expected, and indeed found, to increase underestimation overall, we hypothesised this effect to interact with age and amplify performance differences between groups. However, no such interaction emerged, and performance across FOV conditions did not differ significantly between younger and older adults. Furthermore, no significant visual differences were observed between the two age groups in this study, neither in Visual Acuity nor in Contrast Sensitivity.

That being said, given the available sample in this study, the median split used for statistical analysis resulted in an age boundary of 31 years, meaning that the “older” group was not substantially older in absolute terms. A larger sample, especially with a higher number of older participants, might reveal effects that were not detected here. Importantly, participants’ age correlated strongly with years of driving licence, suggesting that greater

driving experience in the older adults may have contributed to their smaller underestimation errors relative to younger, less experienced drivers.

LSG Task. Our results from the LSG task confirm the expected effects hypothesised in H2a, with FOV showing a significant effect and yielding the largest observed effect size ($\eta p^2 = .730$). Narrower FOV confirmed producing the longest TTC estimates, which decreased linearly as the field of view widened. These findings align with Thulinsson & Söderlund (2024) and mirror those observed in the Dist task. It is therefore plausible that the distance underestimation effect found for each FOV in the Dist task also led participants to choose longer TTCs in the LSG task. With narrower FOVs, the chasing vehicle seems to appear already closer to the ego-vehicle at the start of the video, prompting earlier last safe gap selections. The 112° FOV, in fact, resulted in the shortest TTCs (i.e., longest waiting time before pressing the button to signal LSG). However, as also reported by participants, wider perspectives tend to distort the image. This produces a situation in which the chasing vehicle initially appears farther away than in the other FOVs, and its size in the mirror does not increase linearly. Instead, it becomes noticeably larger only when the vehicle is much closer, resulting in a sudden and less predictable change. Although the observed difference between TTCs produced across FOV conditions translates into a more or less accurate last safe gap selection, potentially indicating more or less efficient driving, it is important to consider the extent to which performance should be prioritised relative to safety. A FOV should avoid producing abrupt, unexpected visual changes and should feel comfortable for the driver, particularly considering the possibility of occasional longer reaction times and the need to preserve adequate safety margins.

In line with H4, our results show that older drivers selected longer safety margins compared to younger participants during the LSG task. However, such a difference was significant only when the

presented CMS video had a FOV of 40°. In that case, the older group selected the LSG 1.86 s before the younger group (≈ 10 meters before). Such findings align with literature where older drivers are reported to adopt more caution and employ self-regulatory and compensatory driving strategies (Eby et al., 2016; Molnar & Eby, 2008), whereas younger drivers are reported may take higher risks due to inexperience or factors such as overconfidence, sensation seeking or peer influence (Doroudgar et al., 2017; Lyon et al., 2020; Scott-Parker et al., 2013). Such behaviours may have emerged only with the narrowest FOV as it is the one where the chasing car appears to be the closest since the beginning of the video, leading to a faster response in the older group, and a relatively longer waiting time for younger drivers. Nevertheless, it should be noted that participants were instructed to identify "the last moment when it is still safe to change lanes and drive out in front of the overtaking car" (see Appendix D), thus leading to behaviours that may not perfectly reflect real-life driving behaviour (where most drivers would not wait for the last moment to perform a manoeuvre).

Beyond the predefined hypotheses, we also observed a significant effect of Road Sections shown in the videos on TTC. Although this effect was smaller compared to other factors, and present only between two of the three road sections (A – C = 0.5 s ≈ 3 m), it suggests that environmental cues available in the scene can meaningfully influence decision making.

Limitations and Future Research

The present study had several limitations related to the available sample. Because recruitment was voluntary and conducted primarily through online platforms, reaching older

participants proved challenging, and some drop-out occurred. Flyers advertising and explaining the experiment were therefore distributed, but participation from older adults remained low, likely due to language requirements, limited time availability, or the need to reach and be in person at the laboratory. Younger participants were more readily accessible and willing to participate. As a consequence, the median split used for the analyses produced an "older" group that was not substantially older in absolute terms than the younger group, which may have limited the detection of age-related effects. Future work would benefit from expanding the sample and increasing the representation of older drivers to allow a clearer distinction between the two age groups, potentially making age-related visual, perceptual, and behavioral aspects documented in the literature more visible. This is particularly relevant because age-related declines in visual function often emerge later than the age of some participants classified as "older" in the present study (starting from 31 years; Fillit et al., 2017; Van Den Berg et al., 2007; Weale, 1961).

Furthermore, given the strong correlation observed between reported age and years of driving licence, further analyses could be performed on the latter to assess whether and in what way greater driving experience may influence task performance.

After each video in both the Dist and LSG tasks, participants also reported their confidence in the response they had given. Examining this measure in more detail may offer insight into which variables (e.g., narrower or wider FOV, higher or lower camera positions) increase or reduce perceived confidence in the task and whether this changes between Age Groups. Additionally, comparing confidence ratings with actual performance for each perspective could reveal whether self-perceived efficiency aligns with objective accuracy.

Finally, given the novelty and still limited availability of CMS technology in civilian vehicles, this study involved participants with no prior experience using such systems. This allowed observation of their performance and impressions when interacting with a

completely unfamiliar technology. Future research could include a longitudinal component in which participants return for repeated sessions, enabling examination of whether familiarity with CMS improves accuracy and confidence over time.

Conclusion

This thesis aimed to investigate the innovative technology of CMS by examining how system configuration and users' characteristics influence perceptual judgments and safety-related decisions during driving. The results confirmed that both Camera Position and FOV substantially affect driver performance in distance estimation and LSG selection, In addition, the distance of the following vehicle played a critical role in determining estimation accuracy, highlighting its relevance when defining optimal CMS configurations.

Importantly, driver age, previously unexplored in CMS research, was found to modulate both perceptual and decision-making processes, indicating that CMS effectiveness depends not only on technical configuration but also on user characteristics. As hypothesised, older drivers selected more conservative LSGs, suggesting a more cautious decision-making strategy consistent with known age-related driving behaviour. However, contrary to the initial hypothesis, younger participants produced larger distance underestimation errors, whereas older drivers demonstrated more accurate distance judgments. This result suggests that greater driving experience may enhance distance judgment abilities, leading to more precise estimations when behind the wheel.

These findings, therefore, contribute to evidence that effective CMS design must account for both system configuration and user variability, including age-related differences in perception and decision-making.

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Appendix A

Post-experiment questionnaire

How realistic did the experiment feel?

1	2	3	4	5	6	7	8	9	10
Very unrealistic									Very realistic

Which perspectives offered the best distance judgment? Please rank from 1 (best) to 6 (worst)

	1	2	3	4	5	6

Brief motivation for what led to these choices:

[Open-ended response]

Which perspectives did you perceive as the safest? Please rank from 1 (best) to 6 (worst)

	1	2	3	4	5	6

Brief motivation for what led to these choices: [Open-ended response]

Which perspectives would you prefer to drive with in real life? Please rank from 1 (best) to 6 (worst)

	1	2	3	4	5	6

] | | | | | |

] | | | | | |

Brief motivation for what led to these choices: [Open-ended response]

After the experiment, I am more positive about digital side-view mirrors as an alternative to traditional mirrors:

☐ True ☐ False ☐ Unchanged

Which of the following driving styles best suits you in everyday life?

☐ Active driving style: tend to be goal-oriented in their driving style, with a clear focus on reducing travel time. This style is characterised by smaller safety margins and frequent lane changes and overtaking.

☐ Defensive driving style: This driving style is about being aware of potential dangers in traffic and acting proactively to avoid them. Defensive drivers maintain a greater distance from other vehicles, follow speed limits and traffic rules, and are prepared for unexpected situations.

☐ Passive driving style: Passive drivers prioritise caution and avoidance of confrontation in traffic. They may prefer to maintain a lower speed than average, often choose to give way to other vehicles, and actively avoid situations that may be perceived as stressful or risky.

In today's experiment, I applied the following driving style:

☐ Active driving ☐ Defensive driving style ☐ Passive driving style

I usually have good concentration:

	1	2	3	4	5	
	Strongly disagree					Strongly agree

During the experiment, I had good concentration:

	1	2	3	4	5	
	Strongly disagree					Strongly agree

Edinburgh Handedness Inventory (EHI)

Please indicate which hand you prefer for each of the following activities

	Left hand strongly preferred	Left hand preferred	No preference	Right hand preferred	Right hand strongly preferred
Writing	☐	☐	☐	☐	☐
Drawing	☐	☐	☐	☐	☐
Throwing	☐	☐	☐	☐	☐
Using scissors	☐	☐	☐	☐	☐
Brushing teeth	☐	☐	☐	☐	☐
Using a knife	☐	☐	☐	☐	☐

(without a fork)					
Using a spoon	☐	☐	☐	☐	☐
Using a broom (dominant hand)	☐	☐	☐	☐	☐
Striking a match	☐	☐	☐	☐	☐
Opening a jar	☐	☐	☐	☐	☐

Appendix B

Consent form and information about the study

Title of study	How CMS perspective impacts driver depth perception and decision making
Principal Investigator	Prof. Kjell Brunnström Phone: 070 - 8419105 Email: Kjell.brunnstrom@ri.se
Date of study	July – September 2025
Time of study	Days and times to be agreed with individual participants
Expected duration	~ 60 minutes
Location	RISE – Perception Lab - 5th floor

Information about the activity

The present experiment is part of a master's thesis research intended to investigate the future evolution of digital side-view mirrors (Camera Monitoring System, CMS) and adoption by new users.

To collect data during the experiment, we need your informed consent. If you agree to take part in the study, please read the following information carefully and sign the consent form on the last page.

Please note: Possession of a valid driving licence is required to participate in this experiment.

What is the research about?

This experiment has the purpose of investigating how users understand and interact with Camera Monitoring Systems while performing driving-related tasks. In this way, researchers

want to better understand how this technology functions and is perceived across different driving scenarios.

How is the study structured?

You will begin by completing a background questionnaire with questions about you and your driving experience. After that, the test leader will guide you through a short vision screening to check visual acuity and colour vision.

You will then sit in front of a TV monitor and be presented with a series of pre-recorded videos depicting real driving scenarios. Most of the screen will display the road ahead, seen through the windshield, while a smaller section in the corner will simulate the view from the side-view mirror Camera Monitoring System.

The video presentation is divided into two parts. After the first part, you will have time to take a break before continuing with the second one.

After the videos, you will complete a follow-up questionnaire, and two short tests will be administered to assess contrast sensitivity and handedness preference.
Finally, you will be asked some questions in the form of an interview about your experience and opinions regarding the Camera Monitoring System. This last part will take around 15 minutes.

All answers from the questionnaires and interviews will be recorded, transcribed, and anonymised. The collected data will be included in a larger dataset and analysed in aggregate form only, not individually.

This study does not evaluate your personal performance or skills. Its purpose is solely to explore how Camera Monitoring Systems are perceived and used by potential users and how driving experience can be improved using this system.

Possible consequences and risks of participating in the study:

There are no known risks associated with participating in this study.

Data management and confidentiality:

- All test results and collected data will be anonymised. Your responses will not be linked to your identity or booking information. Data will be analysed as part of a larger dataset and not on an individual basis.
- Interviews, after the participant's consent, will be recorded to allow for accuracy during the data analysis. All the recordings will be anonymised, and once the transcription has been verified for accuracy, the original audio files will be deleted.
- Only the researchers involved in the data analysis will have access to the data and recordings.

What happens to my results?

All data will be anonymised so that no individual can be identified. The aggregated results will be presented in a master's thesis for the Human-Machine Interaction program at the University of Trento (Italy) and may also be used in future scientific publications.

Voluntary participation

Participation in this study is entirely voluntary. You may choose to withdraw from the experiment at any time without providing a reason. Withdrawing will not result in any negative consequences.

You will receive a gift card with the value of 200 SEK regardless of whether you completed the experiment or not.

Compensation and insurance responsible:

Research Principal:	RISE Research Institutes of Sweden
Responsible for the study:	Prof. Kjell Brunnström Email: Kjell.brunnstrom@ri.se
Test Leader for the study:	Gabriele Pifferi Email: gabriele.pifferi@studenti.unitn.it
Project team	Kjell Brunnström Gabriele Pifferi

No	Consent item	Mark X Below
1	I confirm that I have read and understood the participant's information sheet for the above study and have had the opportunity to ask questions.	
2	I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason.	
3	I consent to the anonymous use of the test scores obtained by the research team in scientific reports and journals.	
4	I agree to take part in the above study.	
5	I confirm that I received a gift card as a compensation with value of 200 SEK	Signature

Participant (Name): Participant (signature and date)

Researcher (Name): Researcher (signature and date)

N.B. You should keep a copy of this consent form and the participant information sheet for your records.

Appendix C

Background questionnaire

What is your age? (years)

[Open-ended response]

Which of these best describes you?

☐ Woman

☐ Man

☐ Non-Binary

☐ I prefer not to say

☐ Other (fill-in option)

Which is the highest driving licence you pursued (B for common driving licence)

[Open-ended response]

How long have you had your driver's licence? (years)

[Open-ended response]

Approximately how many kilometres do you drive in a year? Please select the option that best suits you.

☐ 0 - 5 000 km/year (0 - 500 mil/year): Do not drive a car on a daily basis or for very short distances.

☐ 5 000 - 10 000 km/year (500 - 1 000 mil/year): Use the car rarely. This category includes, for example, people living in a city who rely on the car for weekend trips or certain specific errands, but who otherwise use alternative means of transport.

☐ 10 000 - 20 000 km/year (1000 - 2 000 mil/year): A range that is close to what many consider to be average annual mileage. Regular users, such as medium-distance

commuters or those who use their car regularly for a mix of errands, work, and leisure travel.

☐ 20 000+ km/year (2 000+ mil/year): This range represents individuals who use their car very intensively, such as those with long commutes, those who travel frequently for personal reasons or in their profession.

Do you have experience as a driver in commercial transport? What type of vehicle?

☐ Yes, truck

☐ Yes, bus

☐ Yes, car

☐ No, no experience as a driver in commercial transport

☐ Other (fill-in option)

Do you have previous experience with Camera Monitor System (CMS) technology?

☐ Yes, I drive a vehicle with CMS

☐ Yes, I did an experiment/simulation with CMS

☐ No, I never tried CMS before

☐ Other (fill-in option)

Appendix D

Background & Instructions

Welcome to our experiment on Camera Monitoring Systems (CMS) for cars. These systems will replace conventional physical side-view mirrors with digital cameras and screens. See a sample image of how the system looks below.

In this experiment, you will interact with a simulated car equipped with a CMS. This will help us understand how people perceive their surroundings in different driving situations.

You will be presented with a driving situation with pre-recorded video clips where you will sit in front of a TV screen that simulates a car windshield. In the bottom left corner of the screen, an image corresponding to the left side mirror will be displayed. See the example image below.

In the simulation, you will drive the following van that is approximately 6 meters long.

The experiment is divided into two parts, each with a different task. The time required for each part is 10-15 minutes and 20-25 minutes, respectively. A break of at least 5 minutes is required between these parts.

Task description: Distance judgement

1. **Look ahead:** Each experiment session begins with the forward view showing you driving on a highway. You should follow the road ahead by steering with the steering wheel and keeping your foot on the accelerator. It is important that you follow the road as closely as possible, as in a real driving situation.

2. **Change focus:** When you hear a beep, continue steering the car, ensuring control of the vehicle and the road, but shift your attention to the side mirror and observe the car behind.

3. **Estimation of distance to the car behind:**

After the video clip ends, questions will be presented on the screen asking you to estimate the distance (in meters) between your car and the car behind seen in the side mirror and indicate how confident you are in your estimate.

4. **Repetition:** Once you have filled in your answer, the next video clip will be presented on the screen. Points 1 to 3 are repeated for a total of 18 different video clips.

Training:

Before the beginning of the real task, you will go through two practice rounds to familiarise yourself with the setting and procedure. During the practice, feel free to ask the test leader any questions and request clarifications.

After the practice rounds, the test leader will start the experiment and leave the room.

Generally

- Distance perception is individual and varies between people. You will not be judged on your performance, and your genuine answers are of value, as we are interested in your intuitive perception of distance.
- If you have any questions or concerns before the experiment, do not hesitate to let the test leader know, and they will be happy to assist you.
- If problems arise during the experiment, the test leader is available outside the room; otherwise, communication should be avoided until the end of this phase.
- Your participation is voluntary. You can withdraw at any time without providing a reason, and this will have no consequences for you. If you choose to end your participation, please inform the test leader clearly.

After you have completed the assessment for all 18 video clips, this part about distance judgment of the experiment is complete.

If you feel ready, please let the test leader know. We will then begin the training rounds, followed by part about distance judgment of the experiment.

Task description: Last Safe Gap (LSG)

1. **Look ahead:** Each experiment session begins with the forward view showing you driving on a highway. Your task is to follow the road ahead by steering with the steering wheel and keeping your foot on the accelerator. It is important that you follow the road as closely as possible, as in a real driving situation.

2. **Change focus:** An audible signal warns of an obstacle ahead in your lane. This means you will soon need to change lanes. Continue steering the car but shift your attention to the side mirror and the overtaking car.

3. **Safe lanes change assessment:** Your task is to indicate the last moment when it is still safe to change lanes and drive out in front of the overtaking car. Press the left button behind the steering wheel at this moment. Your answer will be recorded digitally. After the video clip ends, you indicate how confident you feel about your assessment.

4. **Repetition:** Once you have filled in your answer, the next video clip will be presented on the screen, and you will be asked to perform the same task. Points 1 to 3 are repeated for a total of 36 different video clips.

Training:

Before the beginning of the real task, you will go through two practice rounds to familiarise yourself with the setting and procedure. During the practice, feel free to ask the test leader

any questions and request clarifications.

After the practice rounds, the test leader will start the experiment and leave the room.

Generally

- Driving style and perception vary between individuals. There is no predetermined “correct” time to change lanes, and you will not be judged on your results. Your genuine responses are valuable, as we are interested in your intuitive perception and personal judgment.
- Even if you feel that the last safe time for lane changes has already passed, it is better to press "late" than not to press at all.
- If you have any questions or concerns before the experiment, do not hesitate to let the test leader know and they will be happy to help.
- If problems arise during the experiment, the test leader is available outside the room; otherwise, communication should be avoided until the end of this phase.
- Your participation is voluntary. You can withdraw at any time without providing a reason, and this will have no consequences for you. If you choose to end your participation, please inform the test leader clearly.

If you feel ready, please let the test leader know. We will then begin the training rounds, followed by part about LSG of the experiment.

Appendix E

Interview questions

General Experience

- Can you tell me about your experience during the experiment?

  [Can you elaborate more about this...]
- How could the experiment be improved?

View of technology / CMS

- How do you feel about new technologies being added to cars today, like new displays, sensors, or safety systems?
- Have you had previous experience with CMS?
    - How do you feel about CMS?
- How did today's experience influence your idea of this technology?
- If you had the opportunity to improve CMS, what would you change, add, or remove to make it better for drivers?

Task-specific Reflection

- Thinking about the Distance Judgment task, can you describe how you approached it?
    - What were some strategies or cues you used?
- And for the Last Safe Gap task, how did you decide when it was safe to change lanes?
    - What were some strategies or cues you used?
- In the final questionnaire, you ranked CMS views based on aspects like safety, everyday use, and distance judgment. Can you explain your reasoning behind that order?
- Is there anything we have not discussed that you think is important to share, either about the CMS, the driving tasks, or your experience in general?