

# The influence of driver-age on judging the distance of approaching vehicles in digital rear-view mirrors.

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## Abstract

Digital camera-based rear-view systems are increasingly introduced as alternatives to traditional mirrors, offering potential benefits such as improved aerodynamics, reduced blind spots, and enhanced visibility. However, these systems alter the visual cues available to drivers by presenting a fixed monocular image, which might affect how distance and approach speed are judged. This study examines how driver-age influences distance estimation and decisions related to overtaking, while also assessing the impact of camera field of view and camera height. Fifty-eight licensed car drivers viewed thirty-six high-resolution driving clips showing forward-road scenes and digital rear-view perspectives with systematically varied camera settings. They completed two tasks: judging the distance of an approaching vehicle and indicating the last moment at which a lane change would be considered safe. Age influenced both perceptual judgements and lane-change decisions, though not always in the expected direction. Older drivers showed smaller overall errors, yet at wider fields of view they often shifted into overestimation, while younger drivers maintained conservative underestimation. Older drivers nevertheless selected more cautious lane-change timings in certain conditions. Apparent accuracy advantages may reflect reduced bias rather than consistently safer perception; The results highlight the importance of accounting for user diversity when evaluating camera-based rear-view systems and developing age-inclusive design strategies.

## Introduction

Automotive technology plays a central role in everyday mobility. Continuing advances in vehicle technology are aimed to improve safety and comfort for car users. Camera Monitor Systems (CMS), digital alternatives to conventional side-view mirrors, are now available in several production vehicles and have been formally approved for use under international regulations [1-3]. CMS can reduce blind spots, improve aerodynamics, lessen soiling, and enhance visibility in demanding lighting conditions through image processing and glare reduction [3-5]. At the same time, CMS differ fundamentally from mirrors because they present a fixed monocular camera view on an in-cabin display. This removes the binocular and head-movement cues available through conventional mirrors and can lead to systematic shifts in perceived distance and object motion [6-8].

Most prior research on CMS has focused on technical evaluation or task performance in aggregate, often treating drivers as a uniform group. However, differences between user subgroups can influence how rear-view information is interpreted. In particular, the relevance of age continues to grow as the driving population becomes older in many regions, and age-related changes

in perception, cognition, and crash involvement patterns have been widely documented [9-12]. Although demographic data are commonly collected in CMS studies, age effects on distance estimation, gap acceptance, and trust in visual information remain insufficiently examined.

The present work investigates how age influences perceptual judgements and safety-related decisions when using CMS. Building on earlier studies of camera height and field of view that demonstrated systematic effects on distance underestimation and overtaking decisions [13-15], we replicate the core manipulations of field of view (FOV) and camera position and extend the design by adding age as a between-subjects factor. Two driving-relevant tasks are used: Distance Judgement (Dist), in which participants estimate the distance of an approaching vehicle, and Last Safe Gap (LSG), in which they indicate the final acceptable moment for an overtaking maneuver. The study aims to determine whether CMS configuration interacts with age and whether age-related differences emerge in distance perception, gap selection, or both. In doing so, this work contributes toward developing CMS solutions that accommodate a diverse driving population. This article is a condensed version of Pifferi (2025)[16]

## Background

CMS were formally approved as replacements for Class III exterior mirrors under United Nations Regulation No. 46 and the ISO 16505 standard, which define safety, performance, and ergonomic requirements for camera-based indirect vision systems [1-3]. A CMS typically consists of an exterior camera, an electronic control unit that processes the video, and an in-cabin display that presents the rear view to the driver. By relocating the image from a reflective surface to a digital monitor, a CMS removes binocular cues and head-movement-based viewpoint changes that are perceived with conventional mirrors. They also introduce potential benefits, including reduced aerodynamic drag, less soiling, improved visibility in glare or low-light conditions, and a wider available field of view [4, 5].

Conventional mirrors preserve binocular disparity and allow drivers to adjust the effective field of view by moving their head, supporting distance scaling through both binocular and motion-based cues [7, 17]. CMS, in contrast, presents a fixed monocular perspective that relies entirely on pictorial cues for judging distance and relative motion. CMS configuration strongly affects how drivers perceive rearward distance: narrow camera fields of view tend to increase underestimation, whereas wider fields improve distance accuracy but can also encourage acceptance of smaller gaps [13, 14, 18]. Research on external camera placement indicates that camera height can systematically bias perceived

distance, with lower mounting positions often producing greater overestimation and higher positions leading to underestimation [8, 15]. On-road studies have shown that CMS may increase lane-change duration and fixation behavior relative to mirrors, although they can reduce head movements and physical effort [19, 20].

CMS relies on a processed digital video feed that enable the use of visual overlays or augmented reality elements to support, for example, gap assessment and distance scaling. Studies have demonstrated that certain overlays, such as bounding boxes or fixed-distance indicators, can improve distance judgement and overtaking performance in simulated environments [21-23]. However, excessive augmentation risks reducing situation awareness or discouraging essential behaviors such as shoulder checks [3, 23]. Regulatory limits further constrain how much of the display surface overlays may occupy [1].

Research on driving behavior shows that age is associated with changes in perceptual, cognitive, and functional capabilities. Older adults exhibit slower reaction times, reduced contrast sensitivity, more difficulty in maintaining stable headway, and fewer blind-spot checks [24-27]. At the same time, they often self-regulate their driving by avoiding high-demand contexts and adopt more conservative decision strategies [28]. Younger drivers represent a separate high-risk group, with elevated crash involvement linked to inexperience, sensation seeking, and peer influence [10, 29, 30]. Despite these well-known differences, CMS studies have rarely examined age as an explanatory and causal variable. Most report age in demographics but do not analyze it, leaving open the question of whether ageing alters distance estimation, gap acceptance, or interaction strategies when using CMS [15, 31].

Based on these findings, the present study asks whether previously observed effects of field of view (FOV) and camera height on distance judgement and overtaking-related decisions can be replicated, and whether these effects differ across age groups [13, 14]. We test the hypotheses that FOV strongly influences both distance estimation and last-safe-gap (LSG) decisions, that camera height has a more limited effect, and that age modulates these outcomes, potentially leading to larger distance-estimation errors or larger safety margins among older drivers.

## Method

The experiment employed a mixed design modeled after earlier CMS perspective research [13, 14]. Within-subjects factors were Camera Position (high, low) and FOV (40°, 76°, 112°), see **Figure 1**. For the Distance Judgement task (Dist), the actual rear-vehicle distance was 16, 31, or 39 m. For the LSG, participants viewed an overtaking sequence in one of three Road Sections (A, B, C). Age Group served as a between-subjects factor, defined by a median split of the combined dataset. Dependent variables were absolute and relative distance-estimation error in Dist and Time to Contact (TTC) in LSG, computed as the interval between the moment the participant indicated the last safe lane-change opportunity and the moment the overtaking vehicle reached the ego vehicle. Analyses used mixed ANOVAs with Greenhouse-Geisser corrections and Bonferroni-adjusted pairwise tests. Relative errors were included to account for perceptual scaling in accordance with Weber-Fechner principles [32].

### Apparatus and stimuli

Participants viewed 36 high-resolution video clips recorded with three GoPro Hero 12 Black cameras mounted on an Iveco Daily van: two exterior cameras capturing high and low CMS viewpoints and one interior camera capturing the forward scene. The videos

were displayed on a 65-inch 4K OLED monitor under controlled lighting conditions approximating typical in-vehicle luminance [4, 5]. The ego vehicle traveled at 90 km/h in all clips. In Dist, the trailing car maintained a fixed distance (16, 31, or 39 m). In LSG, an overtaking vehicle approached at 110 km/h, passing the ego vehicle at a fixed frame index corresponding to 19 s into the clip. Field-of-view variants were created by cropping the wide-angle camera recording to match the 40°, 76°, or 112° conditions used in earlier work [13, 14]. Participants provided LSG responses through the left paddle on a Thrustmaster T248 steering wheel and entered Dist estimates via keyboard. Responses were followed by confidence ratings. Viewing distance and seat position were standardized according to manufacturer recommendations for optimal visual clarity.

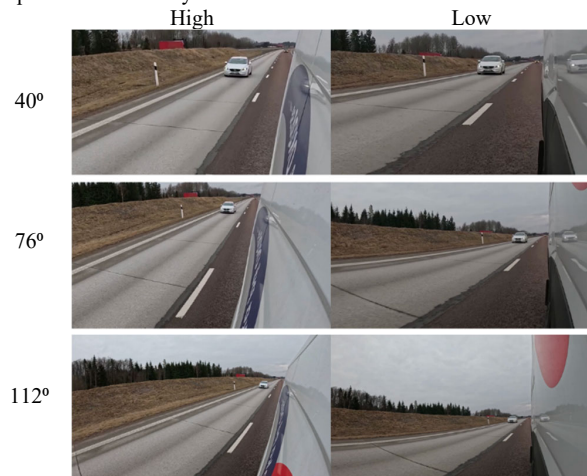


Figure 1: Snapshot recorded with the two cameras, the first column (left) for the high camera, the second column (right) for the low camera. Rows show the different Field of views. First row (top) 40, second (middle) 76, and third (bottom) 112 degrees.



Figure 2: Experimental set-up

A secondary workstation hosted questionnaires and a contrast-sensitivity test using the Freiburg Vision Test [33, 34]. Visual-acuity screening used a backlit Monoyer chart, and color vision was verified using the Ishihara plates [35].

### Participants

Data from 30 new participants were combined with 28 participants from an earlier CMS experiment using the same stimuli and procedures [13, 14]. The resulting dataset contained 58 licensed drivers aged 22–64 years ( $M = 37.7$ ,  $SD = 14.0$ ). All held a Class B license, and several reported additional professional or higher-class licenses. Driving experience ranged from 8 months to 46 years. Vision met required standards for acuity and color perception [36]. A subset ( $n = 28$ ) also completed contrast-sensitivity testing, with no age-related deficits observed. After predefined outlier screening ( $\pm 2.5$  SD of distance-error distributions), 56 participants remained in the analytic sample. A median split at 31 years yielded Younger and Older groups; age and license years were highly correlated, consistent with patterns observed in population-level driving data [9, 10]. Annual mileage was generally low, reflecting the availability of public transport in the study region.

### Procedure

Each session lasted approximately 60 minutes. After informed consent, participants completed a demographic and driving-experience questionnaire, underwent visual-acuity and color-vision screening, and received a short written introduction explaining CMS functionality with illustrated examples [3]. Participants then completed two tasks (Dist and LSG), with task order counterbalanced. Each task began with written instructions and two practice trials.

In the Dist task, participants maintained steering input while attending to the CMS display after an auditory cue at 5 s. At the end of each clip, they reported the estimated distance to the trailing vehicle and their confidence. In the LSG task, participants again maintained steering while monitoring the CMS view and pressed the paddle when they believed a lane change was still possible before the overtaking vehicle reached the ego vehicle. TTC was calculated from these responses. After each clip, they rated confidence.

Between tasks, participants were offered a short break. After both tasks, they moved to the questionnaire workstation, completed a contrast-sensitivity test, a handedness check [37], a post-experiment questionnaire on realism, preferences, and perceived differences between CMS perspectives, and a short semi-structured interview exploring strategy use, confidence, and attitudes toward CMS [31, 38]. Sessions concluded with open-ended comments on technology acceptance and suggested system improvements.

### Results

The combined dataset from both studies included 58 licensed drivers (35 male, 22 female, 1 undisclosed), aged 22 to 64 years ( $M = 37.7$ ,  $SD = 14.0$ ). Vision met required acuity and color vision standards [35, 36], and contrast sensitivity testing in a subset revealed no age related deficits [33, 34]. After planned outlier screening following criteria previously used [13, 14], 56 participants remained for analyses. Age and years since license were strongly correlated ( $r = .92$ ), consistent with known demographic patterns in driving experience [9, 10].

### Distance Judgement

Analyses of relative distance-estimation error revealed significant main effects of camera position, field of view (FOV), and real distance, as well as a significant effect of age group. Relative

errors decreased as FOV widened, with the 112° condition yielding a mean error near zero. This pattern matches earlier findings that wider FOVs improve perceptual scaling in CMS displays [8, 13, 14, 18].

Across the conditions, older participants underestimated distances less than younger participants (Older  $M = -12.2$  percent; Younger  $M = -36.7$  percent), see Figure 3. This contradicts the expectation that older adults would show larger perceptual errors due to age-related visual decline [12, 24] Instead it suggests a performance advantage linked to driving experience [39].

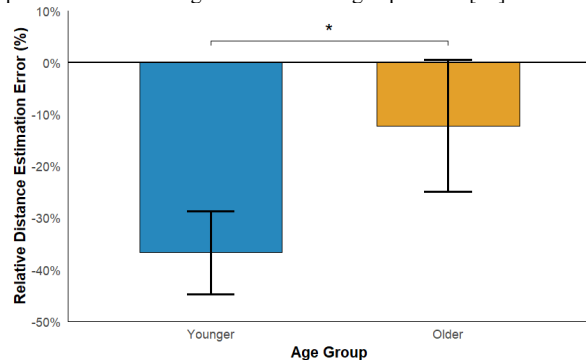


Figure 3: Main effects of Age group on Relative Estimation Error. Positive values indicate overestimation of rearward distance. Error bars represent  $\pm 1$  SEM. Negative values indicate an underestimation of the actual distance.

However, closer inspection of the 31-m condition, where the age effect was largest, revealed an important nuance, see Figure 4. At the widest FOV (112°), older participants transitioned from underestimation into overestimation, producing small positive errors (high position  $M = +0.38$  m; low position  $M = +0.26$  m). Younger participants continued to underestimate distance (high  $M = -0.16$  m; low  $M = -0.08$  m). This shows that older drivers' improved mean accuracy reflects proximity to zero error, not uniformly safer or more conservative perception. Their judgements crossed into overestimation when the FOV was wide, a pattern not observed in younger participants.

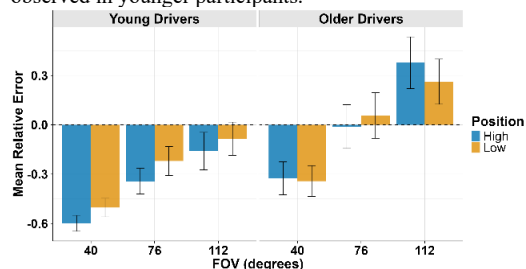


Figure 4: Signed distance error at 31 m as a function of field of view, camera position, and age group. Positive values indicate overestimation of rearward distance. Error bars represent  $\pm 1$  SEM. Negative values indicate an underestimation of the actual distance.

These findings align with observations that wider FOVs can compress motion-in-depth cues [13-15], and they highlight that improved accuracy in aggregate measures may conceal shifts in error direction, with potential safety implications.

### Last Safe Gap

FOV exerted a strong influence on TTC. Widening the FOV from 40° to 76° reduced TTC by 1.61 s, and increasing it from 76° to 112° reduced it by an additional 1.12 s. The total reduction of 2.73 s corresponds to accepting a gap approximately 15 m shorter at the tested speeds. This replicates earlier findings that wider FOVs can lead drivers to select smaller gaps [13, 14, 23].

Road section had a smaller effect (about 0.5 s difference), and camera position had no reliable influence on TTC.

The age-group main effect was not significant, but a strong Age × FOV interaction emerged. Under the narrowest FOV (40°), younger participants pressed the response paddle 1.86 s later than older participants (equivalent to signaling LSG 11.2 m closer to the ego vehicle). This indicates that younger adults allowed smaller safety margins when visual information was restricted. The age difference disappeared at wider FOVs, consistent with the idea that limited visual information disproportionately challenges less experienced drivers [25, 30].

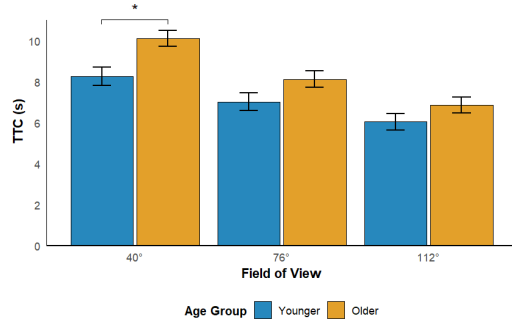


Figure 5: Interaction of Age Group and Field of View on Time To Contact (TTC). Error bars represent  $\pm 1$  SEM. Asterisks indicate significant pairwise differences with Bonferroni correction: \*  $p < .05$ .

Together with the Dist findings, this pattern suggests that age interacts with CMS FOV in different ways across tasks: older drivers show smaller perceptual errors but may shift into overestimation under wide FOV, whereas younger drivers show larger underestimation but maintain conservative bias across FOVs.

### Qualitative Findings

Post-experiment interviews provided context for the quantitative outcomes.

Participants reported using road markings, rate of image expansion, and the ego-vehicle's length as distance cues, consistent with earlier CMS-perception literature [7, 17]. The Dist task was described as "too close to the road" or "distorting," matching prior findings that eccentric camera placements reduce trust [19, 31].

Despite the potential advantage of the low camera position in Dist performance, participants consistently preferred higher camera positions [5, 20]. The low-112° perspective was frequently described as "too close to the road" or "distorting," matching prior findings that eccentric camera placements reduce trust [19, 31].

Participants expressed conditional acceptance, emphasizing system reliability, low latency, and environmental robustness as essential prerequisites [3, 4]. Many proposed overlays such as reference lines or distance indicators, aligning with suggestions in earlier work on AR-enhanced CMS [21, 22]. Several participants valued CMS for improved clarity and reduced blind-spot risk, but

others highlighted concerns about cost, durability, and failure modes.

### Discussion

The present study examined how camera field of view and camera position influence distance perception and lane-change decisions in Camera Monitor Systems, and whether these effects differ across age groups. The results replicated earlier findings showing that field of view is a dominant factor in CMS-based perception [13, 14, 18] and extended prior work by demonstrating systematic, but nuanced, age-related differences in distance judgement and last safe gap selection.

Age differences were more complex than mean accuracy measures suggested. On average, older participants showed smaller underestimation in relative distance-estimation error, contradicting expectations based on age-related visual decline [24, 40]. However, examining the 31 m condition across field-of-view levels revealed an important pattern: under the widest field of view, older participants shifted into positive signed error, producing slight overestimations, whereas younger participants continued to underestimate distance. Thus, the performance advantage of the older group reflects reduced bias magnitude, not consistently safer perception. Overestimation may be riskier than underestimation because it can promote acceptance of smaller gaps when the trailing vehicle appears farther away than it actually is. The interaction of age with perspective geometry suggests that aging does not simply improve or impair performance; instead, different age groups react differently to visual distortions introduced by CMS FOV manipulation.

In the LSG task, age-related differences appeared primarily under the narrowest field of view. Older adults selected larger safety margins than younger adults, in line with reports of more conservative strategies among older drivers [28, 39]. Younger participants chose significantly smaller margins when visual information was restricted, consistent with established findings linking youth to higher risk tolerance and sensation seeking [10, 29]. When the field of view expanded, the age difference disappeared, indicating that constrained visual information may amplify strategy differences that are otherwise muted under clearer visual conditions.

Interview responses help explain these patterns. Participants described distance-estimation as cognitively demanding, often relying on road markings, the rate of looming, or heuristics such as the length of the ego vehicle. Several noted that lower camera positions flattened depth cues, which may have contributed to stronger errors among younger participants, who tended to rely on fewer or less stable cues. Older participants frequently emphasized the need for clear and predictable visual information, a preference consistent with their more conservative LSG responses. Many participants expressed conditional acceptance of CMS, citing reliability, latency, environmental durability, and clear depth cues as prerequisites for adoption [4, 31, 38]. Suggested improvements included overlays that indicate distance or reference lines, echoing findings from AR-enhanced CMS work [21, 22].

Together, the results show that CMS configuration interacts with user characteristics. Wide fields of view improve accuracy but may encourage smaller safety margins. Low camera positions improve accuracy but reduce subjective trust. Age interacts selectively with perspective geometry: younger drivers consistently underestimate distance, whereas older drivers may overestimate under wide FOV. This indicates that age differences cannot be captured by mean accuracy alone and that CMS designs should

avoid configurations that push particular user groups toward potentially unsafe biases.

### Limitations and future work.

The age distribution was skewed toward younger adults, and the median-split boundary produced an older group that was not substantially older in absolute terms. A broader age range would help clarify whether the observed patterns reflect age, experience, or both. Participants were also CMS novices; longitudinal studies could reveal how calibration and strategy evolve with familiarity. Finally, although realism ratings were high, real-world eye-movement behavior, workload, and adaptation should be investigated in simulator or on-road studies to assess how drivers integrate CMS information in naturalistic contexts.

### Conclusions

This study showed that camera field of view and camera position shape distance perception and lane-change decisions when using Camera Monitor Systems, but the way these factors interact with driver age is more nuanced than mean values suggest. Older drivers displayed smaller overall underestimation than younger drivers, yet at the widest field of view their estimates frequently shifted into overestimation, while younger drivers maintained consistent underestimation across conditions. In the lane-change task, age differences emerged primarily when visual information was most constrained, with older drivers selecting larger safety margins under narrow field-of-view settings.

These findings indicate that age influences how drivers interpret the geometric distortions inherent to digital rear-view imagery and that configurations that improve performance for one group may introduce risks for another. Effective CMS design should therefore account for age-related patterns in perceptual bias rather than relying solely on mean accuracy. Future systems may benefit from visual references or adaptive presentation strategies that stabilize distance scaling across diverse users.

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### Disclosure

Any use of generative AI in this manuscript adheres to ethical guidelines for use and acknowledgment of generative AI in academic research[41]. Each author has made a substantial contribution to the work, which has been thoroughly vetted for accuracy, and assumes responsibility for the integrity of their contributions.

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