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Driver Visual Accommodation With Camera-Based Rear Visibility Systems Versus Rearview Mirrors

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Camera monitor systems (CMSs) are designed to replace or supplement vehicle rearview mirrors by transmitting video images to interior-mounted electronic visual displays. Research examined driver visual accommodation when using FMVSS No. 111 required mirrors versus a CMS. Two human subjects experiments examined whether visual accommodation times differed with CMS as compared to rearview mirrors as reflected in longer response times and reduced accuracy in detecting visual stimuli. Experiment 1 compared visual detection with a European-market CMS on a sedan versus outside rearview mirrors on a U.S.-market vehicle of the same model. Experiment 2 compared visual detection performance using a U.S. market Cadillac sedan having an inside rearview mirror that could also provide a camera-based image. Experiment 2 also examined whether drivers wearing bifocal lenses had any additional visual accommodation differences. CMSs tested had typical specifications of production systems with lower image magnification levels than mirrors, however, visual accommodation is not affected by stimuli size. Results showed longer visual target detection response times for the two tested CMSs compared to both outside and inside rearview mirrors for 5 of 6 comparisons, except in one case where response time was faster with the CMS on the driver side. There was not a significant difference in accuracy between CMS and mirrors, nor were any additional differences seen for participants wearing bifocal lenses. Overall, the prevalence of longer visual detection task response times for the tested CMSs versus mirrors across both experiments indicate there may be longer visual accommodation times when drivers shift their gaze from the forward roadway to a CMS compared to mirrors. Longer visual accommodation times suggest that drivers looking at CMS images may have their eyes directed away from the forward roadway for longer durations than when driving with rearview mirrors. While small differences in visual detection response times were observed for CMS, whether there are safety implications as a result of these differences cannot be established based on this study.</td></tr>
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ANPRM	Advance Notice of Proposed Rulemaking
CMS	camera monitor system
FMVSS	Federal Motor Vehicle Safety Standard

Executive Summary

Camera-based rear visibility systems, sometimes referred to as camera monitor systems, are a type of rear visibility technology designed to replace or supplement required vehicle mirrors with cameras that transmit video images to interior-mounted electronic visual displays. Federal Motor Vehicle Safety Standard No. 111, *Rear visibility,* currently requires that vehicles have rearview mirrors to give drivers a view of objects that are to their rear or to their side and rear.[1] As such, CMSs cannot be used in lieu of mirrors to satisfy these FMVSS No. 111 rear visibility requirements but can be provided as supplemental systems in addition to the required mirrors.

In 2019 the National Highway Traffic Safety Administration published an Advanced Notice of Proposed Rulemaking in response to two petitions requesting that NHTSA initiate rulemaking to allow manufacturers to install CMSs, instead of outside rearview mirrors, as a means of meeting FMVSS No. 111 rear visibility requirements on both light vehicles and heavy trucks (84 F.R. 54533, 2019). The ANPRM outlined several questions regarding whether a CMS can provide the same level of safety as FMVSS-required mirrors. Specifically, question 10 sought "comment on research concerning differences in the ability of drivers to visually discern and focus on objects in an electronic visual display as compared to objects reflected by traditional rearview mirrors." The notice specified that data relating to this question are needed to evaluate the safety of permitting CMSs as an alternative compliance option to rearview mirrors. A driver experiencing trouble focusing on and visually discerning objects displayed in a CMS image may have their eyes directed away from the forward roadway for longer durations than when driving with rearview mirrors. In considering whether to permit camera-based visibility systems to be used in place of required rearview mirrors, it is important to ensure that, at a minimum, camera-based systems provide the same level of safety, comparable visual information, and ease of use as that currently afforded by FMVSS No. 111 required rearview mirrors.

Research was conducted to examine whether the two-dimensional image of a CMS affects how drivers focus on and extract visual information without the three-dimensional cues that mirrors afford. More specifically, the research assessed whether switching visual attention from the forward roadway to CMS visual displays is associated with longer visual accommodation time as reflected in longer response times and reduced accuracy performance.

These objectives were assessed in two experiments using visual detection tasks presented to participants seated in a stationary vehicle. The tasks required participants to respond to an auditory cue by switching visual attention from the forward roadway to CMS displays or rearview mirrors. Additionally, two levels of visual detection complexity were included: a simple visual detection task ("car detection task") requiring straightforward absence/presence detection of whether a car was present in the display/mirror and a complex visual detection task ("Landolt C detection task") requiring Landolt C opening direction determination and, therefore, an additional cognitive step. Task performance was assessed using accuracy and response time, which encompassed time to move the head and eyes, visually accommodate and cognitively process the stimulus, and press the button to complete the response.

[1] Regarding a passenger-side outside mirror, FMVSS No. 111 states, "S5.3 Outside rearview mirror passenger's side. Each passenger car whose inside rearview mirror does not meet the field of view requirements of S5.1.1 shall have an outside mirror of unit magnification or a convex mirror installed on the passenger's side." The standard further expands on the requirements, including requirements for the radius of curvature of the convex mirror.

Experiment 1 compared a CMS to outside rearview mirrors in a passenger vehicle. The experiment used a European-market version of a sedan model with an original equipment CMS and a U.S.-market version of the same model with rearview mirrors and certified as meeting FMVSS No. 111. Experiment 1 sought to answer the following research questions.

1. Does response time differ for drivers switching visual attention from the forward roadway to a CMS image compared to outside rearview mirrors?
2. Does accuracy performance differ for drivers switching visual attention from the forward roadway to a CMS image compared to outside rearview mirrors?
3. Are any visual accommodation differences in response time and/or accuracy between the CMS and outside rearview mirrors influenced by visual detection task complexity?

Experiment 2 compared a CMS to an inside rearview mirror in a vehicle certified as meeting FMVSS No. 111. The experiment used a U.S. market Cadillac sedan having an inside rearview mirror that could also provide a camera-based image. Experiment 2 addressed the same research questions as the first experiment, with one addition.

> Does the need for bifocal lenses affect accuracy and response time performance differently for a CMS compared to an inside rearview mirror?

Bifocal lenses include upper and lower lens portions with differing strengths, with the lower lens having a stronger power to facilitate visual accommodation when switching to near focus. At a distance longer than 15.7 inches (400 mm, e.g., to the CMS displays in a vehicle), the bifocal lenses are too powerful for clear focus. Therefore, any visual accommodation delays experienced when switching from the forward roadway to a CMS image may be exacerbated for people who wear bifocal lenses.

Results are summarized below. For statistically significant results, the magnitude of difference is reported.

Table 1. Experiment 1 results

Comparison	**Response Time**		**Accuracy**	
	Car Visual Detection Task	**Landolt C Visual Detection Task**	**Car Visual Detection Task**	**Landolt C Visual Detection Task**
Driver-Side CMS Display Versus Outside Rearview Mirror	Longer with CMS by 57 ms (7.74%)	Shorter with CMS by 23 ms (2.36%)	No significant difference	No significant difference
Passenger-Side CMS Display Versus Outside Rearview Mirror	Longer with CMS by 29 ms (3.56%)	No significant difference	0.7 more correct responses with CMS (1.9%)	No significant difference

Table 2. Experiment 2 results

Comparison	Response Time		Accuracy	
	Car Visual Detection Task	**Landolt C Visual Detection Task**	**Car Visual Detection Task**	**Landolt C Visual Detection Task**
CMS Versus Inside Rearview Mirror	Longer with CMS by 95 ms (12.84%)	Longer with CMS by 85 ms (8.37%)	No significant difference	No significant difference
Without Bifocals Versus With Bifocals	Longer with bifocals by 42 ms (5.44%)	No significant difference	No significant difference	No significant difference

Across both Experiments 1 and 2, for the car detection task, response time was significantly longer with the tested CMS than with an inside or outside rearview mirror. However, for the Landolt C detection task, response time results were mixed, with the tested CMS being shorter for one of the three cases examined, longer for one of the three cases, and no statistically significant difference for one of the three cases. In Experiment 1 the CMS displays were closer to the centerline of the vehicle requiring less head and eye movement time. The magnitude and pattern of differences may reflect this difference in location of the CMS displays compared to that of the outside rearview mirrors. For Experiment 1, while a significant effect was still found for the car stimulus, the magnitude of difference was smaller than that of Experiment 2, suggesting shorter distance for the head and eyes to gaze toward the CMS display is perhaps offsetting the delay in visual accommodation. For the Landolt C stimulus, the additional cognitive complexity of the task, in addition to the difference in physical location may have attenuated the differences in visual accommodation time. For Experiment 2, in which image location was identical for both CMS and the inside rearview mirror, results found statistically significant longer response times with CMS for all cases.

Across both Experiments 1 and 2, for both detection task types, accuracy was essentially the same for the tested CMS versus the inside or outside rearview mirror. For five of the six cases examined, the accuracy difference was not statistically significant. For one of the six cases, participants had slightly better accuracy with the tested CMS, but the magnitude of improvement was small. However, even though accuracy was similar between the tested CMS and rearview mirrors, the increased response times suggest that participants needed a longer time to visually accommodate to gain that equivalent level of accuracy with the tested CMS.

While the methods used for this study were meant to mimic on-road visual behavior where drivers transition their gaze from the forward roadway to the CMS or rearview mirrors, the glance behavior was controlled in the sense that drivers were cued when and where to look. In contrast to on-road driving, the possibility that a driver may not see an object of importance due to the object not being in the image's field of view or due to the driver not looking at the mirror or CMS image did not exist in this experiment. This resulted in accuracy findings close to the maximum possible value of 100 percent. The object to be detected was always present in the mirror or CMS image and where the participant always looked in order to isolate factors affecting visual accommodation and this increased response time may also be seen during actual driving.

Experiment 2 found that participants with bifocal glasses or contacts always had longer response times than participants without bifocal glasses or contacts. This effect did not depend upon whether the tested CMS or inside rearview mirror was used. Vision condition (normal vision versus bifocal lenses) showed no difference on task accuracy. Therefore, the results of this study found that wearing bifocal lenses did not exacerbate differences in task accuracy and response time performance with the tested CMS as compared to an inside rearview mirror. Bifocal wearers were not included in the experiment examining outside mirror use versus CMS.

One point to be noted is that the CMS displays of the original equipment systems used in this study had lower image magnification levels than the rearview mirrors, resulting in stimuli appearing somewhat smaller in the CMS images than in the mirrors. The smaller stimulus size for CMS is because when magnification is lower, objects in the field of view, including the visual stimuli, appear visually smaller. Having a CMS that presents an image having unit magnification (i.e., no magnification) would have permitted isolation of the effects of visual accommodation separate from image magnification; however, NHTSA has not found any production CMS with unit magnification. However, despite the smaller stimulus size displayed by the CMSs studied, accuracy was high for both CMS and rearview mirror conditions. Based on the results of this study it is not possible to know the degree to which image magnification and stimulus size may have affected response times.

Another point to be noted, this study was a controlled laboratory study meant to isolate the visual accommodation step, but as the response metric is an indirect measure, it is not possible to know the actual magnitude of visual accommodation time. Additionally, observed behavior in this study does not reflect all aspects of using the CMS. The full picture of if, or how, small delays related to visual accommodation may factor within the full usage of CMSs in a moving vehicle driven under real-world conditions is beyond the scope of this study.

The longer visual detection task response times for the tested CMSs in five of the six comparisons suggest there may be longer visual accommodation times when drivers transition their gaze from the forward roadway to a CMS compared to mirrors. With CMS, response times increased by 29 ms to 95 ms (3.56% to 12.84%) compared to rearview mirrors. While the magnitudes of differences were small, these laboratory experiments were meant to isolate detection and response time in a controlled manner, which will likely have a similar effect during actual driving. However, whether there are safety implications as a result of these slightly longer durations cannot be established based on this study.

Introduction

Background Regarding Camera-Based Visibility Systems

Camera-based rear visibility systems, sometimes referred to as camera monitor systems, are a type of rear visibility technology designed to replace or supplement required vehicle mirrors with cameras that transmit video images to interior-mounted electronic visual displays. FMVSS No. 111, *Rear visibility*, currently requires that vehicles have rearview mirrors to give drivers a view of objects that are to their rear or to their side and rear. With regard to passenger vehicles, FMVSS No. 111 requires an inside rearview mirror of unit magnification and driver's side outside rearview mirror of unit magnification with a specific required field-of-view. Further, if the inside rearview mirror does not meet the field-of-view requirements outlined in S5.1.1 of the standard, then an outside mirror of unit magnification or a convex mirror is required on the passenger's side. As such, CMSs cannot be used in lieu of mirrors to satisfy these FMVSS No. 111 rear visibility requirements but can be provided as supplemental systems in addition to required mirrors.

On October 10, 2019, NHTSA published an ANPRM (84 F.R. 54533, 2019) seeking comment on permitting CMSs as an alternative compliance option to rearview mirrors. This ANPRM was issued by NHTSA in response to two rulemaking petitions received from manufacturers requesting that NHTSA initiate rulemaking to amend FMVSS No. 111 to allow manufacturers to install CMSs, instead of outside rearview mirrors, as a means of meeting rear visibility requirements that currently specify mirrors on both light vehicles and heavy trucks. The ANPRM sought to build on the NHTSA's "prior efforts to obtain supporting technical information, data, and analysis on CMSs so that NHTSA can determine whether these systems can provide the same level of safety as the rearview mirrors currently required under FMVSS No. 111." The ANPRM requested public comment to aid NHTSA in deciding whether (and if so, how) to propose amending FMVSS No. 111 to allow the use of CMSs as an FMVSS No. 111 compliance option alternative to required mirrors. The ANPRM outlined a number of questions for which the notice said data are needed to inform the decision regarding whether to permit CMSs in lieu of required mirrors. Specifically, question 10 of the ANPRM sought "comment on research concerning differences in the ability of drivers to visually discern and focus on objects in an electronic visual display as compared to objects reflected by traditional rearview mirrors." This research is part of NHTSA's overall research plan aimed at assessing if camera-based systems provide comparable visual information as required mirrors.

Effects of CMS on Driver Visual Behavior

As NHTSA continues to seek information specified in the ANPRM to inform a decision whether to amend FMVSS No.111 in response to petitions, NHTSA has also identified additional research questions concerning CMSs subsequent to those listed in the ANPRM. Questions remain regarding CMS performance and human factors that affect drivers' ability to safely use CMSs. For example, while CMSs have the ability to provide a wider field of view, the displayed image is subject to distortion due to the wider field of view being compressed for presentation on a smaller display area and without the ability to adjust this field of view as a driver could with mirrors by moving their head. These differences in visual image characteristics may affect drivers' visual behavior with CMS. In considering whether to permit camera-based visibility systems to be used in place of required rearview mirrors, it is important to ensure that, at a minimum, camera-based systems would provide the same level of safety, comparable visual information, and ease of use as that currently afforded by FMVSS No. 111 compliant rearview mirrors.

To examine whether the two-dimensional image of a CMS affects how drivers are able to focus on and extract visual information without the three-dimensional cues that mirrors afford, a research study was conducted to obtain information regarding how drivers' accuracy and response times in a stationary task differ when using FMVSS No. 111 required outside and inside rearview mirrors versus when using CMSs.

Visual Accommodation

One component of comparing drivers' visual behavior with CMSs to rearview mirrors is determining whether greater visual accommodation issues are seen with CMSs, due to their use of electronic visual displays, compared to FMVSS No. 111 required rearview mirrors. When changing visual focus from objects that are far to objects that are near, two actions of the eye occur: convergence and accommodation. Convergence refers to the rotation of both eyes inward to converge on an object to produce an image on the retina. Visual accommodation is the ability of the eye lens to change its focal length when focusing on objects at different depths (e.g., switching from gazing at the forward roadway to something within the interior of the vehicle). Proper convergence and accommodation are necessary for accurate distance judgments (Flannagan et al., 2001) and to perceive a single image. Due to the law of reflection,[2] mirrors reflect light and do not have an image plane, therefore images viewed in planar mirrors can provide an infinite depth of field and do not require visual accommodation (Merriam-Webster, n.d.). However, a CMS visual display provides a flat image to which drivers must accommodate their eyes when switching from fixating out the windshield to fixating on the CMS visual display. Issues with visual accommodation may affect how quickly participants can visually focus on and process the image in the display. Furthermore, trouble with visual accommodation and perceiving objects in a CMS displayed image may lead to poorer distance judgments, delays in responding to critical events, driver discomfort, or driver eye fatigue. Past research has found evidence that participants had longer response times to detecting visual stimuli in a CMS visual display replacing outside rearview mirrors (Hruska et al., 2023).

Other driver characteristics may also influence how well drivers' eyes accommodate when switching from fixating forward to a CMS visual display. Bifocal lenses include upper and lower lens portions with differing strengths, with the lower lens having a stronger power to facilitate visual accommodation when switching to near focus. At a distance longer than 400 mm (e.g., to the CMS displays in a vehicle), the bifocal lenses are too powerful for clear focus. Therefore, any accommodation delays experienced when switching from the forward roadway to a CMS image may be exacerbated for people who wear bifocal lenses.

Study Objectives

A research study consisting of two experiments obtained information regarding how drivers' visual behavior with and ability to extract information from a CMS-based visual image differs from that afforded by outside and inside rearview mirrors on vehicles that are certified as

[2] Discovered by Euclid circa 300 BCE and expanded by Descartes in 1637, it says that when a light ray strikes a smooth surface, the angle of incidence equals the angle of reflection, both measured relative to the surface's perpendicular line.

meeting FMVSS No. 111. More specifically, these experiments assessed whether switching visual attention from the forward roadway to a CMS image is associated with longer response times and reduced accuracy performance, which may indicate longer visual accommodation time. These objectives were assessed across the two experiments using visual detection tasks in a stationary vehicle requiring drivers to respond to a cue by switching visual attention from the forward roadway to CMS displays or rearview mirrors.

Two levels of visual detection complexity were also included: a simple visual detection task requiring straightforward absence/presence detection of whether a car was present in the display/mirror, and a complex visual detection task requiring Landolt C opening direction determination, which requires an additional cognitive step.

Experiment 1 compared a CMS to outside rearview mirrors. It sought to answer the following research questions.

1. Does response time differ for drivers switching visual attention from the forward roadway to CMS displays compared to outside rearview mirrors?
2. Does accuracy performance differ for drivers switching visual attention from the forward roadway to CMS displays compared to outside rearview mirrors?
3. Are any visual accommodation differences in response time and/or accuracy between the CMS displays and outside rearview mirrors influenced by visual detection task complexity?

Experiment 2 compared a CMS to inside rearview mirrors. It sought to answer the following research questions.

1. Does response time differ for drivers switching visual attention from the forward roadway to a CMS display compared to an inside rearview mirror?
2. Does accuracy performance differ for drivers switching visual attention from the forward roadway to a CMS display compared to an inside rearview mirror?
3. Are any visual accommodation differences in response time and/or accuracy between the CMS display and an inside rearview mirror influenced by visual detection task complexity?
4. Does the need for bifocal lenses affect accuracy and response time performance differently for a CMS display than for an inside rearview mirror?

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Experiment 1: Comparing a CMS to Outside Rearview Mirrors

Experiment 1 was a human subjects experiment comparing drivers' visual accommodation observed when performing a visual detection task in a stationary passenger car using two types of rear visibility technologies: CMS versus outside rearview mirrors.

Test Vehicles and Rear Visibility Technologies Tested

As no U.S. market system was readily available for testing, a European-market 2019 Lexus ES300h with an original equipment CMS and no outside rearview mirrors was leased from Toyota Motor North America, Inc. The CMS had two exterior-mounted cameras mounted on arms extending from the side of the door in the approximate position of where outside rearview mirrors would be located. CMS components also included two electronic visual displays mounted inside the vehicle just aft of the respective A-pillars at a height like that of outside mirrors (Figure 1). The vehicle's CMS camera on the driver's side had a horizontal field of view of 25° and a vertical field of view of 15°. The CMS passenger-side camera's horizontal field of view was 23.3°, and the vertical field of view was 14°. The settings of the CMS were the pre-set default values. The CMS had a lower image magnification level than the outside rearview mirrors, resulting in the stimuli appearing visually smaller in the CMS electronic visual displays compared to the outside rearview mirrors. The horizontal magnification level for the CMS was 0.35 for the driver-side displayed image and 0.20 for the passenger-side displayed image This system was a foreign-market production system and representative of real-world conditions.

A U.S. version of the same vehicle, a 2018 Lexus ES 300h, was used for the outside rearview mirrors condition. The outside rearview mirrors on this vehicle were presumed to meet FMVSS No. 111 requirements and included a driver-side planar outside rearview mirror and a passenger-side convex outside rearview mirror. The image magnification level of the driver-side mirror was presumed to be 1.0 as per FMVSS No.111. The passenger-side mirror image magnification level was not known.

For both vehicles, the inside rearview mirror was not available for use during the experiment so as not to introduce a potential confound whereby the participant could look at the inside rearview mirror before the outside rearview mirror. Test participants were permitted to adjust the outside rearview mirrors to ensure that the displayed stimulus images could be fully seen in the mirrors.

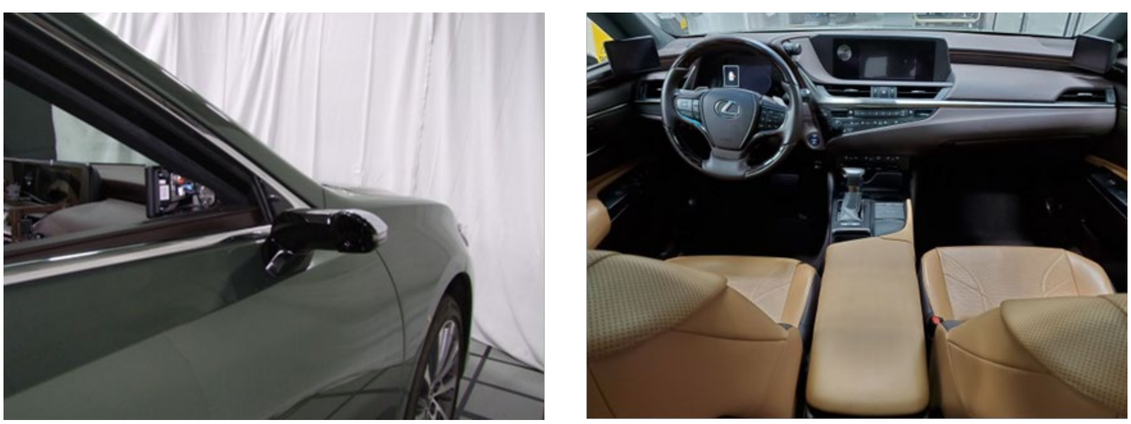


Figure 1. Experiment 1 CMS

The left side of the figure displays the passenger-side exterior mounted camera. The right side of the figure displays both the driver-side and passenger-side CMS displays.

Experiment 1 Method

Participants

Thirty-two test participants (13 male, 19 female; median age: 37 years) were included in Experiment 1. Participants:

- were ages 25 to 56;
- had active valid U.S. driver licenses with no uncorrected vision or hearing problems;
- had driven at least 3,000 miles annually;
- had no more than two points under Ohio's point system on their driver licenses; and
- had no recent criminal convictions.

An original mileage criterion was set as 11,000 annual miles, but the COVID-19 pandemic contributed to recruitment difficulties, necessitating the lowering of the required mileage to 3,000 annual miles in order to obtain the desired sample size. Participants were also required to read, write, speak, and understand English, and be willing to spend up to 3 hours participating in the study. They were required to be in good general health, not requiring assistive devices to safely operate vehicles, and able to drive continuously for several hours.

Visual Detection Tasks

To assess differences in drivers' ability to visually discern and focus on objects in a CMS display compared to rearview mirrors, participants performed a visual detection task. This task was a modified version of a Posner cueing task (Posner, 1979) whereby participants visually attended to two different visual stimulus tasks and switched visual attention between the two when signaled by an auditory cue.

To implement this task in a stationary vehicle, two large-screen electronic visual displays were used: one forward of the vehicle and one behind the vehicle. As is typical in cueing tasks, participants continually focused visual attention on the forward large-screen electronic visual display to identify and respond to a specific visual stimulus. Periodically, an auditory cue was presented signaling to the participant the need to shift visual attention to the rearward large-screen electronic visual display, viewed in either the outside mirror or CMS display, for response to a stimulus presented in that location. For either the driver-side or passenger-side locations, the rearward monitor was only visible using that location (e.g., when testing the driver-side location, the rearward monitor was not visible in the passenger-side CMS display). The participant responded to both the forward and rearward tasks by pressing buttons attached to the vehicle's steering wheel. Detection performance for both tasks was measured via accuracy and response times. This accuracy and response time performance was then compared between the outside rearview mirrors and CMS to assess differences in performance and infer any difficulties in visually discerning and focusing on the presented images due to issues with visual accommodation. Participants were instructed to respond to both tasks accurately, but as quickly as possible.

Forward Visual Detection Task

The forward large-screen electronic visual display simulated the need to focus on the forward roadway as a driver would during normal driving. The forward visual detection task involved the display of a quick succession of characters consisting mostly of letters with an occasional number appearing. Participants were instructed to respond only when the target number "3" was displayed and to withhold responses to any other forward stimuli. Stimuli were presented for 250 ms with an inter-stimulus interval of 1,300 ms. The response window for a correct detection was 650 ms. Stimuli were presented quickly to keep participants' visual focus directed forward and this response window was chosen to prevent responses happening after the subsequent stimuli appeared. The forward large-screen electronic visual display was 41 inches × 23 inches in size (47" diagonal ViewSonic N4785p-2M) and set so that the bottom of the display was at a height of 38 inches from the ground. The center of the forward visual display was placed directly forward and 15.5 ft. from the eye point of a reference 50th male percentile driver as specified in FMVSS No. 111 S14.1.5. The letters and numbers were presented in the center of the display in white font on a neutral gray background. Characters were 9 inches high and 5 inches wide. The forward visual detection task is shown in Figure 2.

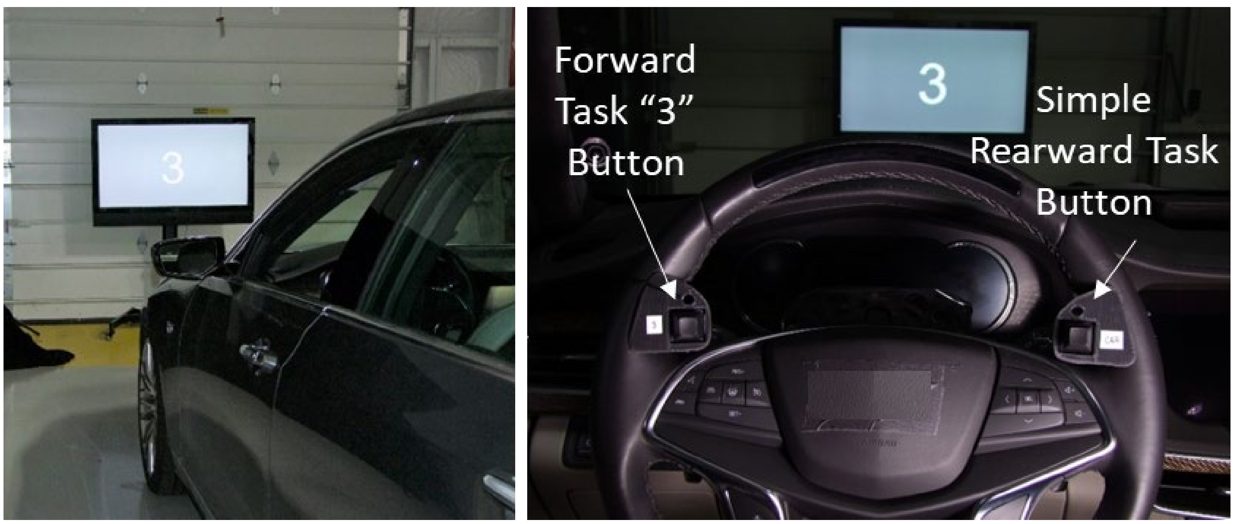


Figure 2. Forward Visual Detection Task Stimuli

Stimuli displayed on forward large-screen electronic visual display for the forward visual detection task. The left panel shows the forward stimulus from outside the vehicle. The right panel shows the task stimulus and response buttons from the driver's view. The button mounted on the steering wheel to respond to forward stimuli is labeled "3" on the left side of the steering wheel. The button on the right is for the simple rearward visual detection task.

Rearward Visual Detection Tasks

This study involved two versions of a rearward visual detection task with differing levels of complexity. The first rearward visual detection task involved simple absence/presence detection of one stimulus type (car visual detection task) and the second rearward visual detection task (Landolt C visual detection task) was a more complex detection task involving an additional cognitive decision-making step for detection. The forward visual detection task was always the same.

Car Visual Detection Task

The car visual detection task simulated the common driver behavior of using an outside rearview mirror to check for the presence of adjacent vehicles, such as prior to making a lane change.

More specifically, this task involved detecting the presence or absence of a white car depicted on a multi-lane highway image background. Once the auditory cue (a single tone) signaled for the participant to shift visual attention to the rear visibility technology, the participant responded to the presence of the white car by pressing a button labeled “car” mounted on the steering wheel.

White truck stimuli were used as catch/distractor trials to which participants were instructed to withhold a response. The auditory cue signaled for an attentional shift 50 times throughout a main trial; 40 times for car stimuli and 10 times for truck catch trials. The auditory cue and car and truck stimuli were presented simultaneously. The auditory cue played for 250 ms in duration and the car and truck stimuli were displayed for 550 ms. There was a 3,050 ms delay following the presentation of the rearward detection stimuli allowing participants to shift visual attention back to the forward visual detection task before the forward stimuli resumed. The response window for a correct detection was 1,500 ms. This response window was chosen because some research has suggested that a perception-response time (the window of time from perceiving stimulus to then making a response) of greater than 1.5 seconds is considered slow for very simple driving tasks (Koppa, 2000). The car stimuli were displayed with a height of 9 inches and a width of 9 inches in the center of the rearward large-screen electronic visual display. The truck stimuli were displayed in the center of the display with a height of 11 inches and width of 12 inches The rearward large-screen electronic visual display was 47.5 inches × 27 inches in size (55” diagonal LG 55UJ6300 with a frosted, anti-blue light filter to minimize reflections) and placed 13 ft. behind the vehicle. The car visual detection task is depicted in Figure 3. Note that the lower image magnification levels of the CMS images resulted in the stimuli appearing smaller with the CMS compared to the outside rearview mirrors. This difference is larger for the driver side compared to the passenger side due to the convex nature of the passenger-side outside rearview mirror. This difference is representative of current production designs.

Figure 3. Experiment 1: Car Visual Detection Task Stimuli Shown for Driver’s Side

The car visual detection task shown in both rear visibility technologies. The left panel displays the car visual detection task in the driver-side outside rearview mirror. The right panel displays the car visual detection task in the driver-side CMS display.

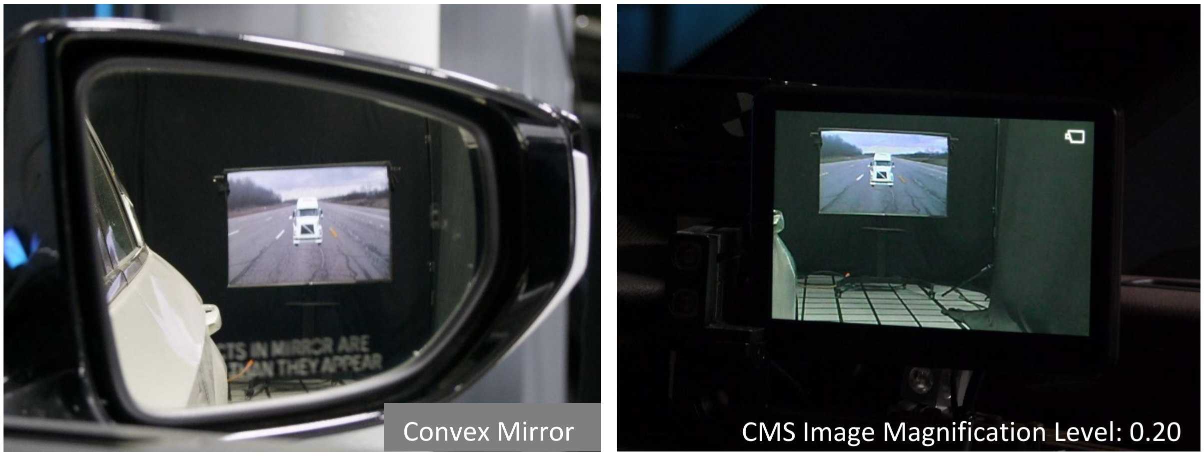


Figure 4. Experiment 1: White Truck Catch Trials Shown on Passenger's Side
The white truck catch trials shown in both rear visibility technologies. The left panel displays the white truck in the passenger-side outside rearview mirror. The right panel displays the white truck in the passenger-side CMS display.

Landolt C Visual Detection Task

Because the purpose of the experiment was to evaluate visual accommodation issues, a common stimulus for assessing visual acuity was also used to examine detection differences. The Landolt C is a standardized symbol for testing vision (Pelli et al., 1988). It consists of a circle with a break in it, causing it to resemble the letter "C." Landolt C stimuli were presented with a height of 9 inches and width of 9 inches to be similar to the size of text on a traffic sign, such as a stop sign. The Landolt C stimuli were black in color and presented on a gray background.

The task consisted of responding with the direction of the opening of a Landolt C (left, right, up, or down). Because the participant must first detect the Landolt C and then determine the orientation, this type of detection involves an additional cognitive step. Once the auditory cue signaled for the participant to shift visual attention to the rear visibility technology, the participant responded by pressing a button to indicate whether the opening of the Landolt C was up, down, left, or right. Four buttons were mounted on the steering wheel and oriented to spatially match the direction to which they corresponded. Participants were instructed to respond by pressing the button corresponding to the direction of the opening as they saw it in the mirror or CMS image, and not to reverse the direction with the mirrors. Occasionally, the auditory cue would sound, and no stimuli would be present on the rearward large-screen electronic visual display, indicating a catch trial. The number of correct hits and catch trials was the same in the Landolt C visual detection task as the car visual detection task. The timings of the stimuli and response windows were also the same as the car visual detection task. The same size large-screen electronic visual display was used in both types of rearward visual detection tasks. The Landolt C visual detection task is depicted in Figure 5. Note that the lower image magnification levels of the CMS image results in the stimuli appearing smaller compared to the outside rearview mirrors. This difference is larger for the driver side compared to the passenger side due to the convex nature of the passenger-side outside rearview mirror.

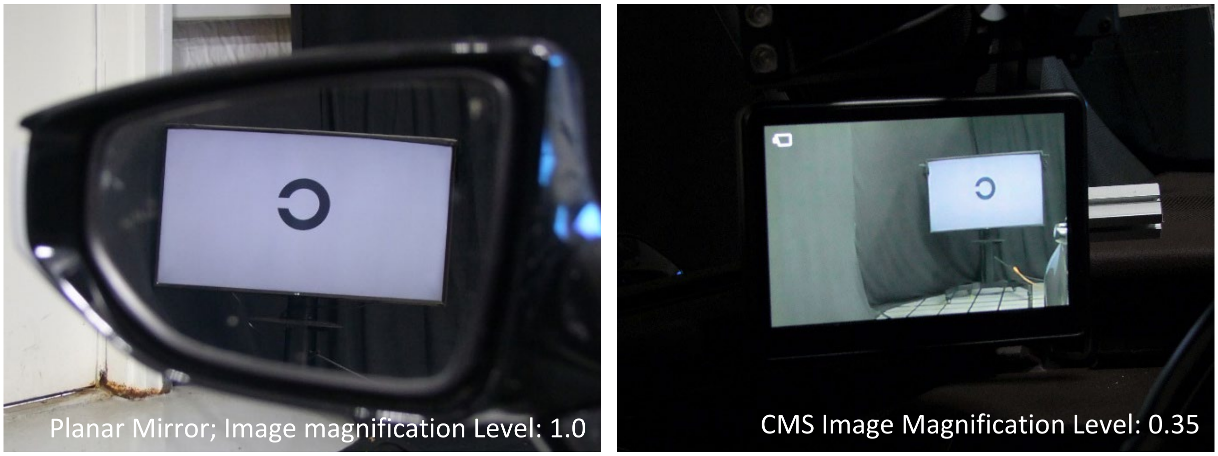


Figure 5. Experiment 1: Landolt C Visual Detection Task Stimuli on the Driver Side

The Landolt C visual detection task shown in both rear visibility technologies. The left panel displays the Landolt C visual detection task in the driver-side outside rearview mirror. The right panel displays the Landolt C visual detection task in the driver-side CMS display.

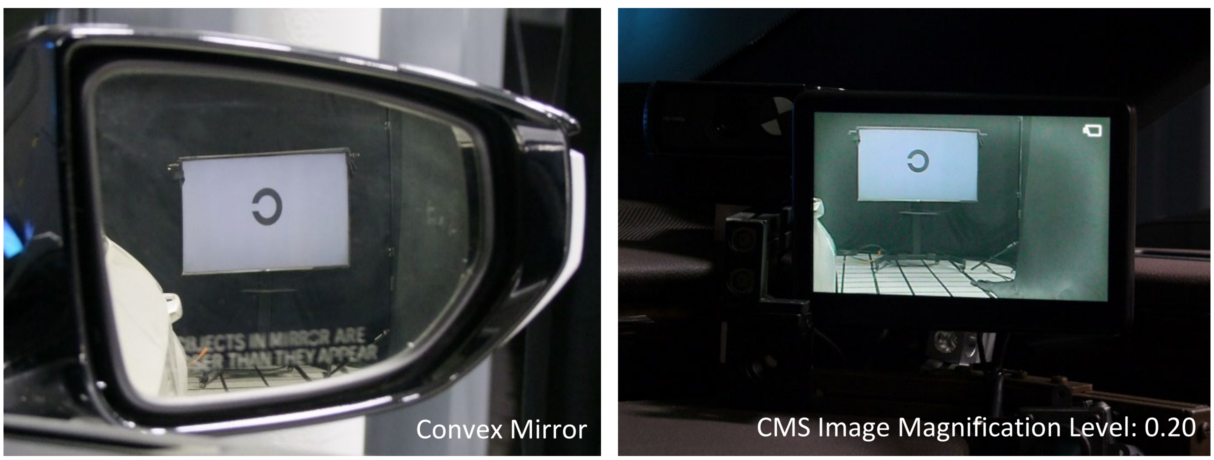


Figure 6. Experiment 1: Landolt C Visual Detection Task Stimuli on the Passenger Side

The Landolt C visual detection task shown in both rear visibility technologies. The left panel displays the Landolt C visual detection task in the passenger-side outside rearview mirror. The right panel displays the Landolt C visual detection task in the passenger-side CMS display.

Instrumentation and Equipment

In Experiment 1, PsychoPy (Pierce et al., 2019) stimuli presentation software was used to present each task as well as gather accuracy and response time inputs. PsychoPy is an open-source package for running experiments using the Python computer programming language. The software provides precise presentation and response timing, as well as precise and accurate response measurement.

Experimental Design

Experiment 1 was a 2 (Rear Visibility Technology) × 2 (Rear Visibility Technology Location) × (Rearward Detection Task Type) mixed design. Rear visibility technology was a within-subjects variable with two levels: outside rearview mirrors and CMS. Rear visibility technology location was a within-subjects variable with two levels: driver-side and passenger-side. All participants in Experiment 1 had normal or corrected-to-normal single-focus vision (i.e., no multi-focal corrective lenses). Participants completed one experimental session in which they performed the task four times, once respectively for the driver-side outside rearview mirror, driver-side CMS display, passenger-side outside rearview mirror, and passenger-side CMS display. The order of conditions was randomized and quasi-counterbalanced. Participants completed both rear visibility technology locations for one rear visibility technology (i.e., driver-side and passenger-side mirror before driver-side and passenger-side CMS display or vice versa) before experiencing the other rear visibility technology. This was done for logistical reasons, as changing between rear visibility technologies involved use of a different vehicle. Additionally, rearward detection task type was a between-subjects variable with two task types: a car visual detection task and Landolt C visual detection task. Participants only completed one type of rearward visual detection task. The overall experimental design for Experiment 1 is summarized in Table 3.

Table 3. Summary of experimental design for Experiment 1

	Rearward Visual Detection Task	Vision	Rear Visibility Technology	Location	Participants
Experiment 1	Car Visual Detection	Single	Outside Rearview Mirrors	Driver-Side	16
				Passenger-Side	
			CMS	Driver-Side	
				Passenger-Side	
	Landolt C Visual Detection	Single	Outside Rearview Mirrors	Driver-Side	16
				Passenger-Side	
			CMS	Driver-Side	
				Passenger-Side	

Procedure

At the start of each experimental session, the participant was asked to read an informed consent form providing study information and detailing the experimental protocol. After the participant confirmed they read the form, an experimenter presented a brief oral summary of the protocol and participation requirements, after which the participant was given another opportunity to ask questions. Once all questions had been answered, the participant was asked to sign an electronic version of the consent form on a tablet computer. Following informed consent, the participant received instructions about the forward and rearward tasks.

The experimenter then showed the participant the first test vehicle, asked the participant to sit in the driver seat and adjust the seating position to the person's preferred normal driving position. For the rearview mirrors, the participant was also instructed to adjust them to view the rearward large-screen electronic visual display in the center of the image. The participant did not adjust the CMS display as this was fixed and the displayed image was not dependent on driver position or height. The participant first completed a practice trial with the first rear visibility technology of the specific counterbalanced order. The practice was a shorter, 3-minute version of the full task. If the participant scored an accuracy of less than 80 percent on either the forward or rearward visual detection task, the participant completed a second practice trial. All participants met the performance criteria in two practice trials.

Following practice, the participants completed two trial sets consisting of 50 trials each. In Experiment 1, after the two sets, the participant was offered a break while the vehicle used for the second rear visibility technology condition was prepared. After the break, the participant was shown the second vehicle with the second rear visibility technology and completed the remaining two trial sets (also consisting of 50 trials each). Following completion of all four trial blocks, the participant was debriefed on the purpose of the experiment and paid for participation.

A breakdown of time for each component of an experimental session is as follows.

- Instructions and pre-brief (10 min)
- Practice (3 min)
- Trial set 1 (10 min)
- Trial set 2 (10 min)
- Vehicle switch and mid-session break (10 min)
- Trial set 3 (10 min)
- Trial set 4 (10 min)
- Post-trial debriefing and payment (5 min)

Each participant's experimental session lasted about 1.5 hours.

Office of Management and Budget and Institutional Review Board Approval

This study and associated data collection received Paperwork Reduction Act clearance from the Office of Management and Budget (OMB Control No. 2127-0756). Approval of the study methods and procedures was also obtained from the Sterling Institutional Review Board.

Experiment 1 Results

To assess accuracy performance, mixed-effects logistic regressions were performed on the outcome of the task: correct or incorrect. Models included rear visibility technology and rear visibility technology location as fixed effects, as well as a random intercept for participant. For response time analyses, linear mixed effects regressions were performed with fixed effects of rear visibility technology and location, as well as a random intercept for participant. Car and Landolt C visual detection tasks were analyzed separately. A p value of $< .05$ was used to characterize significance. Statistical analyses were performed using the *lmer* package in R (R Core Team, 2021) and figures were created using the *ggplot2* package (Wickham, 2009).

Since this research was specifically interested in comparing visual detection with a CMS to outside rearview mirrors, two specific planned comparisons of the rear visibility technology × rear visibility technology location interaction were of interest. These planned comparisons are listed in Table 4.

Table 4. Planned comparisons for rear visibility technology × location analyses

Planned Comparisons	
1	Driver-side CMS display compared to driver-side outside rearview mirror
2	Passenger-side CMS display compared to passenger-side outside rearview mirror

Car Visual Detection Task

Accuracy

To evaluate whether visual accommodation delays resulted in differences in participants' performance in terms of detection accuracy, an analysis was performed on the correct/incorrect responses in the rearward visual detection tasks. Of the 50 trials in a set, the 10 catch trials were not included in the analysis to be consistent with the response time data (i.e., there was no response time to measure for a catch trial). Therefore, the maximum number of correct responses was 40. Results of a mixed-effects logistic regression found a significant rear visibility technology × location interaction ($\beta = 0.44$, $p < .05$). Results found an odds ratio of 3.06, meaning participants were more likely to have a correct response with the passenger-side CMS displayed image compared to the passenger-side outside rearview mirror. Accuracy did not significantly differ between the driver-side CMS image and the driver-side outside rearview mirror ($p = .18$). Means and standard deviations can be viewed in Table 5. Results can be viewed graphically in Figure 7.

Table 5. Means and standard deviations for accuracy performance on the car visual detection task with outside rearview mirrors/CMS

Location	Rear Visibility Technology	Mean Correct Responses (*n*)	Mean Incorrect Responses (*n*)	Mean Correct (%)	Standard Deviation (%)
Driver-Side	Outside Rearview Mirror	39.6	0.4	98.9	10.4
	CMS	39.2	0.8	98.0	14.1
Passenger-Side	Outside Rearview Mirror	38.9	1.1	97.2	9.6
	CMS	39.6	0.4	99.1	16.5

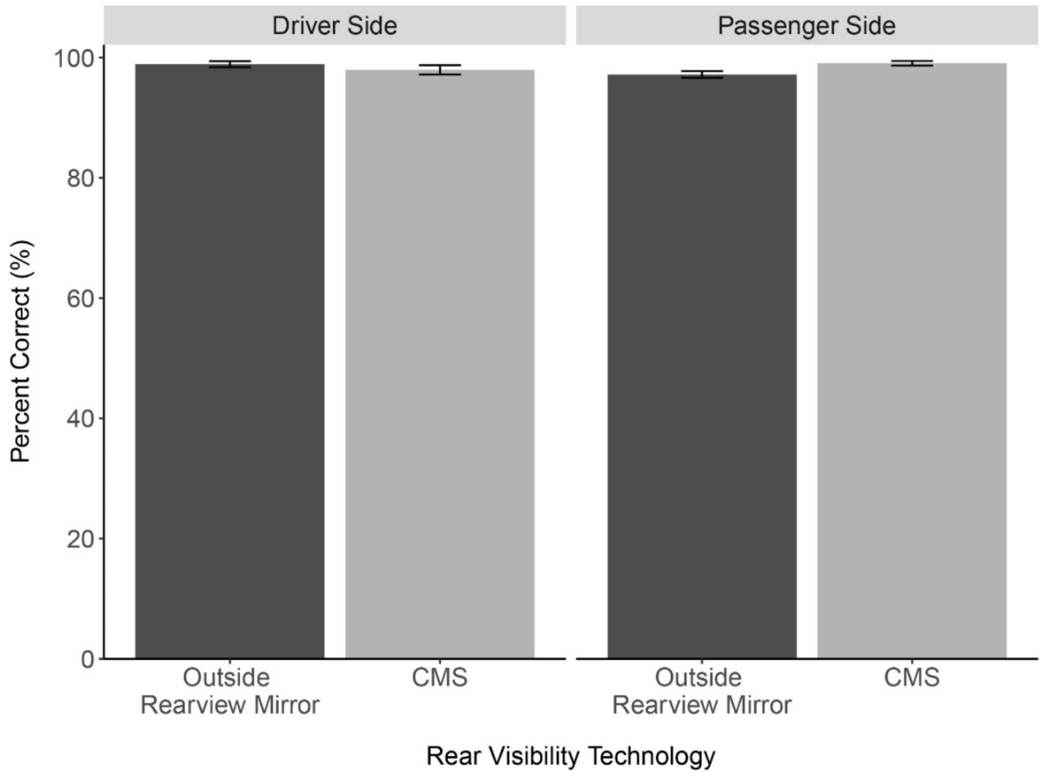


Figure 7. Experiment 1: Accuracy Performance for Car Visual Detection Task
Mean percentage of correct detections on the car visual detection task. Error bars are standard error.

Response Time

To further evaluate any differences in detection performance, an analysis was performed on detection response times in the rearward visual detection tasks. Results from a linear mixed-effects model found a significant rear visibility technology × location interaction, $F(1, 2497) = 15.95$, $p < .05$. Response times in the CMS condition were longer for both the driver-side and passenger-side locations compared to the outside rearview mirrors. Response time to the driver-side CMS image was 57 ms longer than the driver-side outside rearview mirror. Response time to the passenger-side CMS image was 29 ms longer than the passenger-side outside rearview mirror. Response time was 7.74 percent longer to the driver-side CMS image compared to the driver-side outside rearview mirror and 3.56 percent longer to the passenger-side CMS image compared to the passenger-side outside rearview mirror. Means and standard deviations can be viewed in Table 6. Results can be viewed graphically in Figure 8.

Table 6. Means and standard deviations for response times on the car visual detection task with outside rearview mirrors/CMS

Location	Rear Visibility Technology	Mean (s)	Standard Deviation (s)
Driver-Side	Outside Rearview Mirror	0.736	0.109
	CMS	0.793	0.113
Passenger-Side	Outside Rearview Mirror	0.815	0.114
	CMS	0.844	0.107

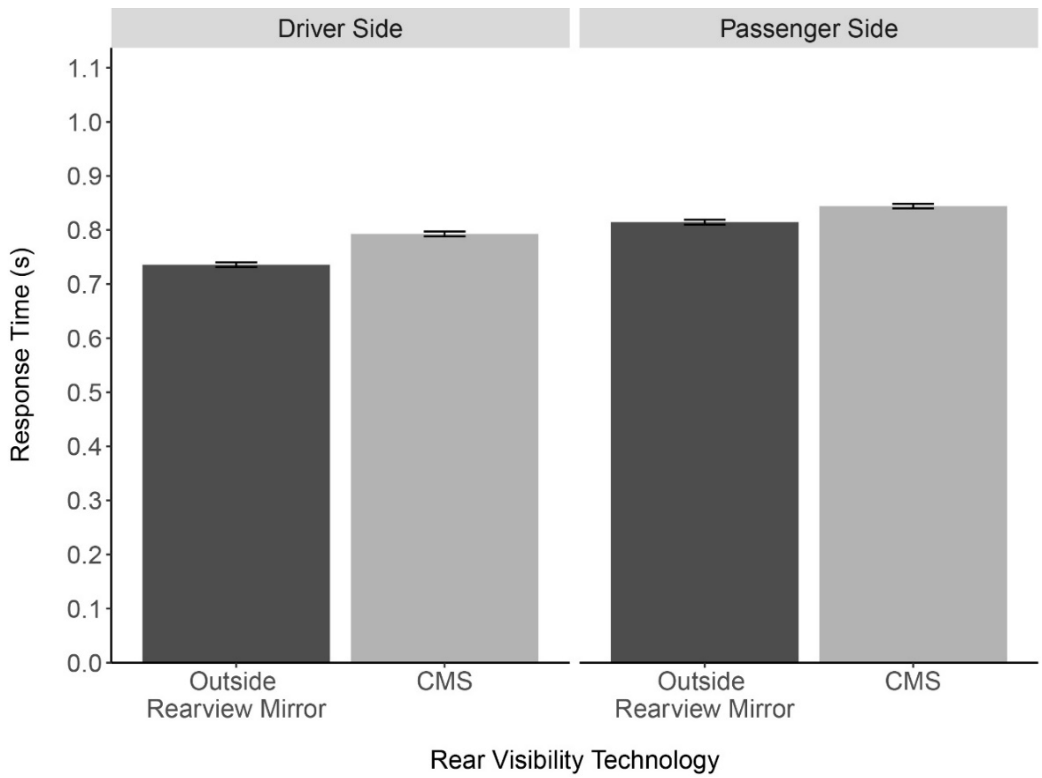


Figure 8. Experiment 1: Response Time for Car Visual Detection Task

Mean response times on the car visual detection task. Error bars are standard error.

Landolt C Visual Detection Task

Accuracy

Results from a logistic regression analysis did not find a significant rear visibility technology × location interaction (p = .09) for accuracy of task performance. Correct/incorrect responses did not differ between the driver-side CMS image and the driver-side outside rearview mirror nor between the passenger-side CMS image and the passenger-side outside rearview mirror. Means and standard deviations can be viewed in Table 7. Results can be viewed graphically in Figure 9.

Table 7. Means and standard deviations for accuracy performance on the Landolt C visual detection task with outside rearview mirrors/CMS

Location	Rear Visibility Technology	Mean Correct Responses (*n*)	Mean Incorrect Responses (*n*)	Mean Correct (%)	Standard Deviation (%)
Driver-Side	Outside Rearview Mirror	38.6	1.4	96.6	18.2
	CMS	39.6	0.4	98.9	10.4
Passenger-Side	Outside Rearview Mirror	35.4	4.6	88.6	31.8
	CMS	36.6	3.4	91.5	27.8

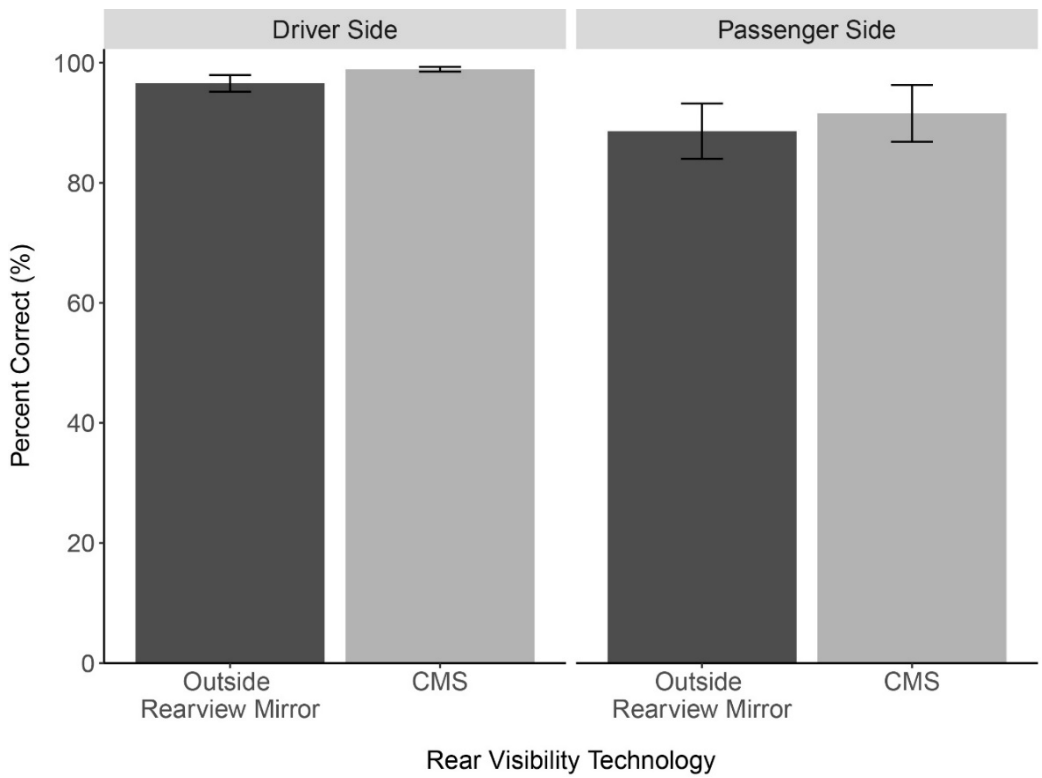


Figure 9. Experiment 1: Accuracy Performance for Landolt C Visual Detection Task

Mean percentage of correct detections on the Landolt C visual detection task. Error bars are standard error.

Response Time

Results from a linear-mixed effects analysis found a significant rear visibility technology × location interaction, $F(1, 2385.0) = 10.22$, $p < .05$. Response times to the driver-side CMS image were shorter by 23 ms compared to the driver-side outside mirror. Response time was 2.36 percent shorter to the driver-side CMS image compared to the driver-side outside rearview mirror. Response times did not differ between rear visibility technologies for the passenger-side ($p = .37$). Means and standard deviations can be viewed in Table 8. Results can be viewed graphically in Figure 10.

Table 8. Means and standard deviations for response times on the Landolt C visual detection task with outside rearview mirrors/CMS

Location	Rear Visibility Technology	Mean (s)	Standard Deviation (s)
Driver-Side	Outside Rearview Mirror	0.976	0.169
	CMS	0.953	0.145
Passenger-Side	Outside Rearview Mirror	1.06	0.166
	CMS	1.07	0.174

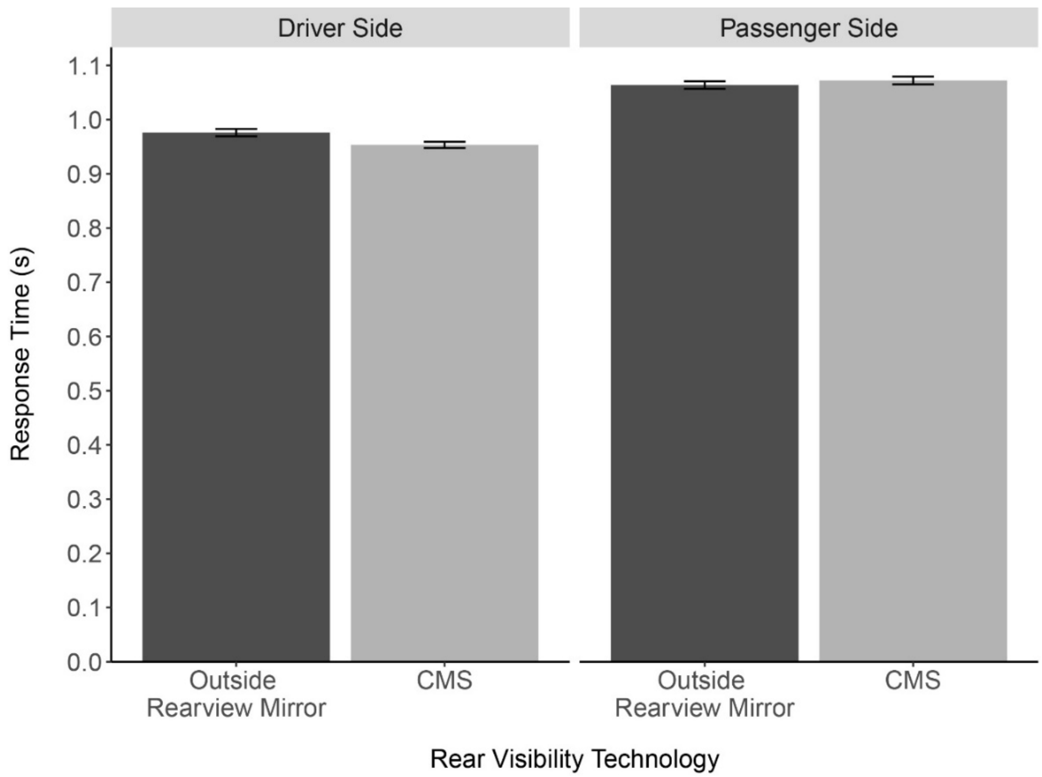


Figure 10. Experiment 1: Response Time for Landolt C Visual Detection Task

Mean response times on the Landolt C visual detection task. Error bars are standard error.

Experiment 1 Discussion

Findings regarding whether response time differs for drivers switching visual attention from the forward roadway to a CMS image compared to outside rearview mirrors.

For Experiment 1, for the car visual detection task, response time was longer with the tested CMS than with the outside rearview mirror. However, for the Landolt C visual detection task, the trend for response time for CMS versus an outside rearview mirror was mixed, with response time with the tested CMS being shorter than that for the driver-side outside rearview mirror and no difference between the passenger-side outside rearview mirror and the tested CMS. It is also worth noting the magnitude of difference in response times was small overall, even when statistical tests met criteria for significance.

Findings regarding whether accuracy performance differs for drivers switching visual attention from the forward roadway to a CMS image compared to outside rearview mirrors.

For Experiment 1, task accuracy was essentially the same for the tested CMS as compared to outside rearview mirrors. There was one statistically significant difference. For the simple rearward visual detection task, participants made more correct responses with the passenger-side CMS image compared to the passenger-side mirror, although the numerical difference was small (99.1% versus 97.2%). For the complex rearward visual detection task, correct/incorrect responses did not differ between the tested CMS and outside rearview mirrors for either the driver side or passenger side. While there was a statistically significant difference for correct/incorrect responses on the simple rearward visual detection task, in practicality, accuracy performance was high across all conditions.

There is a possibility that the accuracy findings of this study reflect a ceiling effect (i.e., accuracy cannot exceed 100%). For the car detection task, accuracy ranged from 97.2 percent to 99.1 percent. For the Landolt C visual detection task, accuracy ranged from 88.6 percent to 98.9 percent. The possibility of a ceiling effect is discussed in the conclusions section of this report.

Findings regarding whether any visual accommodation differences in response time and/or accuracy are influenced by visual detection task complexity.

For Experiment 1, overall, the magnitude of differences in response times was less for the Landolt C visual detection task compared to the car visual detection task showing that for response time, task complexity affects the differences between CMS and outside rearview mirrors.

Experiment 2: Comparing CMS to an Inside Rearview Mirror

While the focus of Experiment 1 was to compare a CMS to FMVSS No. 111 compliant outside rearview mirrors, Experiment 2 was designed to compare an FMVSS No. 111 compliant inside rearview mirror to a camera-based visibility system presenting an electronic image in the same location as the inside rearview mirror.

A second aim of Experiment 2 was to examine whether drivers who wear bifocals have additional trouble switching their visual focus from the forward roadway to a CMS image within the vehicle at the location of a normal inside rearview mirror. The inability of the eye to focus on objects at different distances is called presbyopia. Difficulty with close vision associated with presbyopia increases with age sometime after mid-forties (American Optometric Association).

Increased accommodation times with age have been seen in driving (Lockhart & Shi., 2010). Bifocal lenses correct presbyopia by adding a stronger lens power in the bottom portion of the glasses to facilitate visual accommodation when switching to near focus. However, this stronger power gives best distance at a normal reading position of about 400 mm (Rockwell et al., 1988). At a longer distance (e.g., to the CMS displays in a vehicle), the bifocal lenses are too powerful for clear focus. Bifocals do not provide clear vision between the distances of about 2 to 6 feet, distances some CMS displays are likely to fall within from the driver's eyes. Bifocal lenses include upper and lower lens portions with differing strengths, with the lower lens having a stronger power to facilitate visual accommodation when switching to near focus. At a distance longer than 400 mm (e.g., to the CMS displays in a vehicle), the bifocal lenses are too powerful for clear focus. Therefore, any accommodation delays experienced when switching from the forward roadway to a CMS image may be exacerbated for people who wear bifocal lenses. Additionally, when viewing a CMS replacing the inside rearview mirror, drivers wearing bifocal lenses may actually be looking through the upper portion of the lens and not even utilizing the accommodation aid bifocal lenses provide.

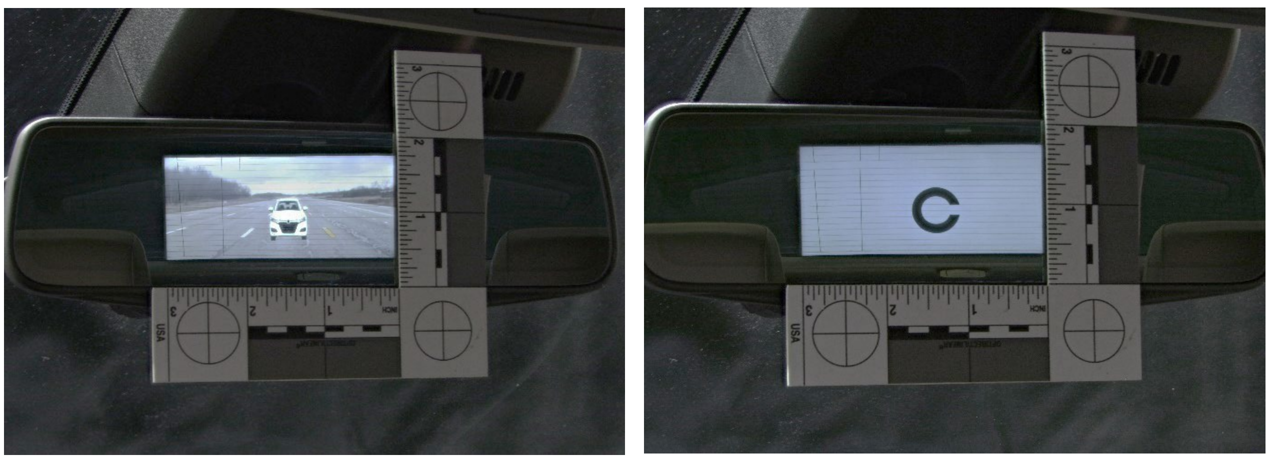
Because switching from the forward roadway to a CMS image may lead to visual accommodation delays, it is also possible that drivers who experience trouble switching from far to near may find their visual issues exacerbated when shifting focus to a CMS image. This would mean that drivers wearing bifocal lenses may have trouble visually accommodating to both an inside rearview mirror and a CMS display in that location due to its distance to the driver, but then also have a compounding accommodation issue due to having to focus on the displayed image compared to a mirror with an infinite depth of field. Past research has found that participants with prescription eyeglasses subjectively reported less acceptance of a digital outside mirror replacement compared to those requiring no eye correction, perhaps due to fatigue caused from constant re-focusing (Babu et al., 2022). While that study did not specifically narrow the focus to bifocal lenses, it anticipated that if constant re-focusing to a CMS display is troublesome, any effects would be worse with bifocal wearers. To investigate this possibility, about one-half of participants recruited for Experiment 2 were drivers who wore bifocal glasses or bifocal contact lenses.

Test Vehicle

One vehicle was used for testing: a U.S. market 2018 Cadillac CT6 with an OE inside rearview mirror system having two possible modes: an inside rearview mirror mode or camera image mode. Mode selection was accomplished using a toggle control located at the bottom of the inside rearview mirror housing. The inside rearview mirror on this U.S. model sedan was certified as being compliant with all applicable FMVSS and, therefore, was presumed to meet FMVSS No. 111 requirements.

The CMS's exact field of view angle and image magnification level was unknown, but the system tested was a production system in a U.S. market passenger car and representative of real-world conditions. The image magnification level of this production system resulted in the car stimulus in the CMS image being displayed at about half the size of the car stimulus when viewed in the inside rearview mirror. The pictures below demonstrate the relative size differences of the stimuli in each rear visibility technology.

Inside Rearview Mirror



CMS

Figure 11. Relative Size of Stimuli in Rear Visibility Technologies

The top panel displays both types of stimuli in the inside rearview mirror. The bottom panel displays both types of stimuli in the CMS display.

Experiment 2 Method

Participants

Sixty-three participants (26 male, 37 female; median age: 48 years) were included in Experiment 2. Participants:

- were 25 to 65 years old;
- had active valid U.S. driver licenses with no uncorrected vision or hearing problems;
- had driven at least 3,000 miles annually;
- had no more than two points under Ohio's point system on their driver licenses; and
- had no recent criminal convictions.

Again, an original mileage criterion was set as 11,000 annual miles, but the COVID-19 pandemic contributed to recruitment difficulties necessitating the lowering of the required mileage to 3,000 annual miles in order to obtain the desired sample size. Participants also had to be able to read, write, speak, and understand English, and be willing to spend up to 3 hours participating in the study. Participants were required to be in good general health, not requiring assistive devices to safely operate vehicles, and be able to drive continuously for several hours.

About half of the participants recruited had any type of prescription bifocal glasses or contacts as assessed via self-report.[2] The average age of participants in the single vision condition was 41.41 years and the average age of participants in the bifocals condition was 54.65 years.

Visual Stimulus Detection Tasks

Forward Detection Task

The same forward visual detection task used in Experiment 1 was also used in Experiment 2.

Rearward Detection Task

The same rearward visual detection tasks used in Experiment 1 were also used in Experiment 2. Images of the rearward visual detection tasks in Experiment 2 can be seen in the following figures. Note that the lower image magnification level of the CMS resulted in the stimuli appearing visually smaller in the CMS displayed image compared to the inside rearview mirror.

[2] This study did not gather specific prescription information and did not differentiate between the different types of bifocal lenses (i.e., segmented, round, d-shape).

Car Visual Detection Task

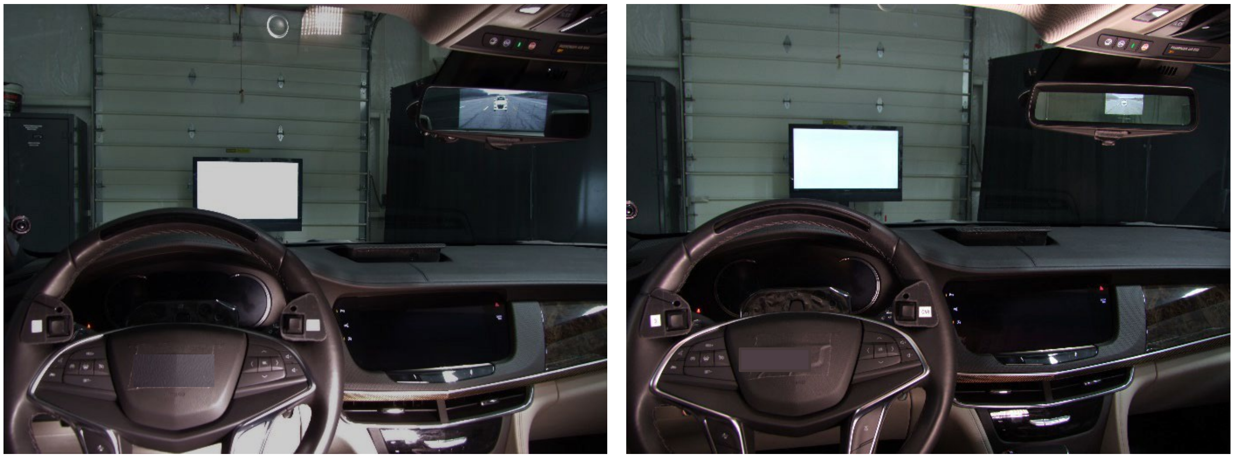


Figure 12. Experiment 2: Car Visual Detection Task Stimuli

The car visual detection task shown in both rear visibility technologies. The left panel displays the car visual detection task in the inside rearview mirror. The right panel displays the car visual detection task in the CMS display.

Landolt C Visual Detection Task

Figure 13. Experiment 2: Landolt C Visual Detection Task Stimuli

The Landolt C visual detection task shown in both rear visibility technologies. The left panel displays the Landolt C visual detection task in the inside rearview mirror. The right panel displays the Landolt C visual detection task in the CMS display.

Instrumentation and Equipment

PsychoPy (Pierce et al., 2019) stimuli presentation software was used to present each task as well as gather accuracy and response time inputs.

Experimental Design

Experiment 2 was a 2 (Rear Visibility Technology) × 2 (Rearward Visual Detection Task) × 2 (Vision Type) mixed design. Rearward visual detection task was a between-subjects variable with two tasks: car visual detection task and Landolt C visual detection task. Like Experiment 1, the car visual detection task was a present or absent detection task, while the Landolt C rearward visual detection task required an additional discernment, increasing the task complexity. Again, participants only completed one type of rearward detection task. Rear visibility technology was a within-subjects variable with two levels: inside rearview mirror and CMS. Vision was a between-subjects variable with two levels: normal or corrected-to-normal vision with single vision lenses or corrected-to-normal vision with bifocal lenses. Progressive or tri-focal lenses were not permitted. Participants performed the task twice, once with the inside rearview mirror and once with the CMS, the order of which was randomized and counterbalanced. The overall experimental design for Experiment 2 is summarized in Table 9.

Table 9. Summary of experimental design for Experiment 2

<table>
<tr><th></th><th>Rearward Visual Detection Task</th><th>Vision Type</th><th>Rear Visibility Technology</th><th>Participants</th></tr>
<tr><td rowspan="8">Experiment 2</td><td rowspan="4">Car Visual Detection</td><td rowspan="2">Single Vision</td><td>Inside Rearview Mirror</td><td rowspan="2">16</td></tr>
<tr><td>CMS</td></tr>
<tr><td rowspan="2">Bifocals</td><td>Inside Rearview Mirror</td><td rowspan="2">15</td></tr>
<tr><td>CMS</td></tr>
<tr><td rowspan="4">Landolt C Visual Detection</td><td rowspan="2">Single Vision</td><td>Inside Rearview Mirror</td><td rowspan="2">16</td></tr>
<tr><td>CMS</td></tr>
<tr><td rowspan="2">Bifocals</td><td>Inside Rearview Mirror</td><td rowspan="2">16</td></tr>
<tr><td>CMS</td></tr>
</table>

Procedure

The general procedure for Experiment 2 was the same as Experiment 1. At the start of each experimental session, the participant was asked to read an informed consent form providing study information and detailing the experimental protocol. After the participant confirmed they read the form, an experimenter presented a brief oral summary of the protocol and participation requirements, after which the participant was given another opportunity to ask questions. Once all questions had been answered, the participant was asked to sign an electronic version of the consent form on a tablet computer. Following informed consent, the participant received instructions and guidelines about the forward and rearward tasks.

The experimenter then showed the participant the first test vehicle and had the participant sit in the driver seat and adjust the seating position to a normal driving position. The participant was also instructed to adjust the rear visibility technology to view the rearward large-screen electronic visual display in the center of the image. The participant first completed a practice trial with the first rear visibility technology of their specific counterbalanced order. The practice was a shorter, 3-minute version of the full task. If participants scored an accuracy of less than 80 percent on either the forward or rear detection task, the participant completed a second practice. All participants met performance criteria in 2 practice trials.

Following practice, the participants completed two trial sets, one with each rear visibility technology. Following completion of both trial sets, the participant was debriefed on the purpose of the experiment and paid for participation.

A breakdown of time for each component of an Experiment 2 session is as follows.

- Instructions and pre-brief (10 min)
- Practice (3 min)
- Trial set 1 (10 min)
- Trial set 2 (10 min)
- Post-trial debriefing and payment (5 min)

Each participant's experimental session lasted about 45 minutes.

Experiment 2 Results

To assess accuracy performance, mixed-effects logistic regressions were performed on the outcome of the task: correct or incorrect. Rear visibility technology and vision type were included as fixed effects, as well as a random intercept for participant. For response time analyses, linear mixed effects regressions were performed with fixed effects of rear visibility technology and vision type, as well as a random intercept for participant. Because the average age of participants in the bifocals group was higher, age was also included as a fixed effect and results are reported after holding age constant. Simple and complex rearward visual detection tasks were analyzed separately. A p value of $< .05$ was used to characterize significance.

Car Visual Detection Tasks

Accuracy

Results from a logistic regression found no significant effects for rear visibility technology ($p = .06$), vision type ($p = .74$), or the rear visibility × vision type interaction ($p = .63$) for correct/incorrect responses. Means and standard deviations can be viewed in Table 10. Age did not have a significant effect on performance. Results can be viewed graphically in Figure 14.

Table 10. Means and standard deviations for accuracy performance on the car visual detection task with the inside rearview mirror/CMS

Vision Type	**Rear Visibility Technology**	**Mean Correct Responses (*n*)**	**Mean Incorrect Responses (*n*)**	**Mean Correct (%)**	**Standard Deviation (%)**
Single Vision	Inside Rearview Mirror	39.6	0.4	99.1	9.6
	CMS	39.4	0.6	98.4	12.4
Bifocals	Inside Rearview Mirror	39.7	0.3	99.2	9.1
	CMS	39.2	0.8	98.0	14.0

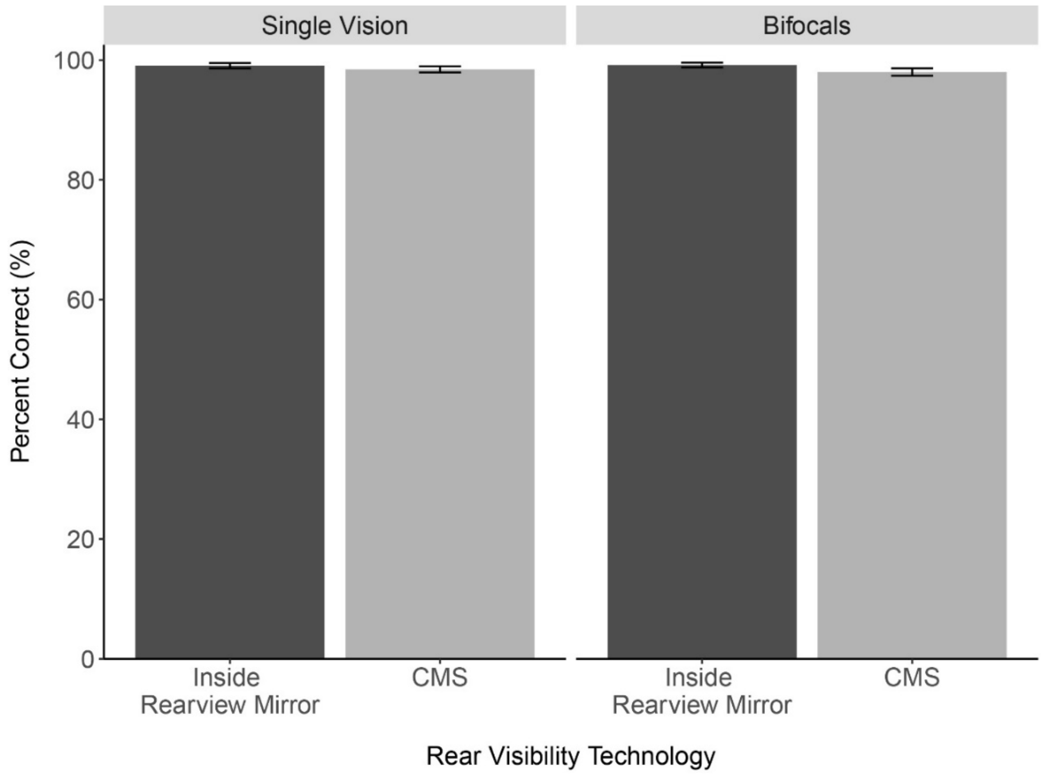


Figure 14. Experiment 2: Accuracy Performance for Car Visual Detection Task

Mean percent of correct detections on the car visual detection task. Error bars are standard error.

Response Time

Results from a linear mixed-effects analysis found significant effects for rear visibility technology, $F(1, 2426.92) = 632.89$, $p < .05$, and a marginally significant effect for vision type, $F(1, 37.13) = 3.87$, $p = .06$. Overall, response times in the CMS condition were longer by 95 ms compared to the inside rearview mirror condition. This means that response times were 12.84 percent longer in the CMS condition compared to the inside rearview mirror condition. Response times were longer for participants with bifocals by 42 ms compared to participants with single vision. This means that participants who wore bifocals had response times that were 5.44 percent longer compared to participants who did not wear bifocals. Results did not find a significant rear visibility technology × vision type interaction ($p = .50$). Age did not have a significant effect on response time. Means and standard deviations can be viewed in Table 11. Results can be viewed graphically in Figure 15.

Table 11. Means and standard deviations for response times on the car visual detection task with the inside rearview mirror/CMS

Vision Type	Rear Visibility Technology	Mean (s)	Standard Deviation (s)
Single Vision	Inside Rearview Mirror	0.718	0.095
	CMS	0.807	0.103
Bifocals	Inside Rearview Mirror	0.754	0.101
	CMS	0.854	0.120

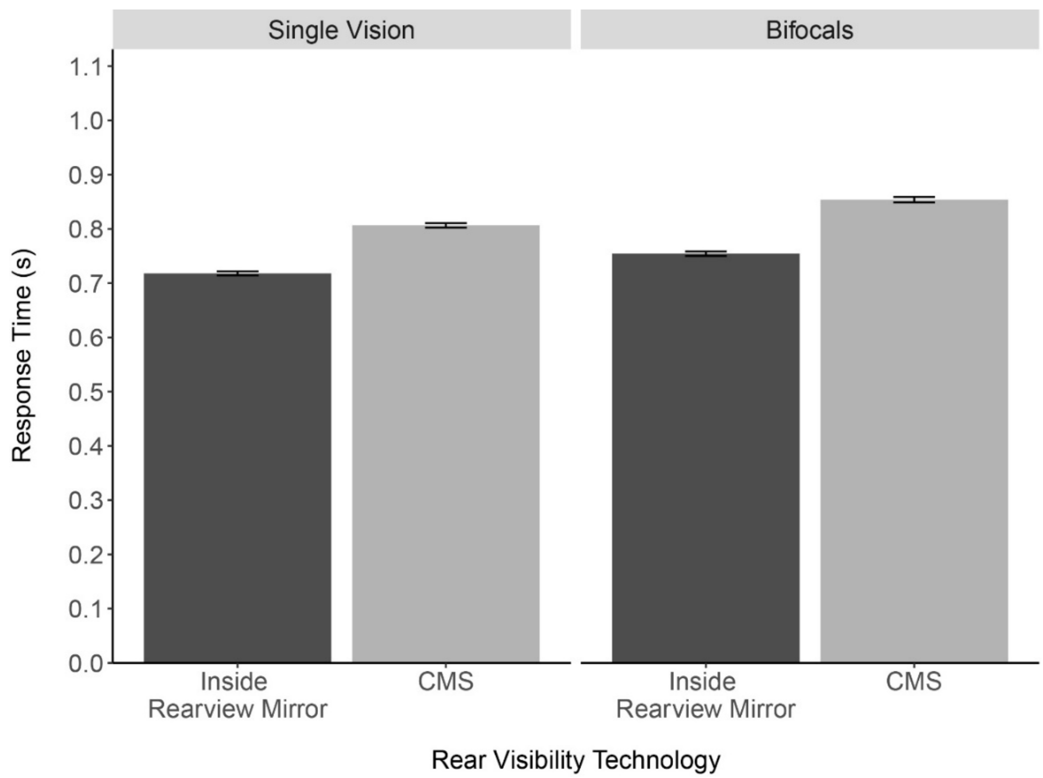


Figure 15. Experiment 2: Response Time for Car Visual Detection Task

Mean response times on the car visual detection task. Error bars are standard error.

Landolt C Visual Detection Task

Accuracy

Results from a logistic regression found no significant effects for rear visibility technology (p = .15), vision type (p = .31), or the rear visibility × vision type interaction (p = .53) for correct/incorrect responses. Age did not have a significant effect on performance. Means and standard deviations can be viewed in Table 12. Results can be viewed graphically in Figure 16.

Table 12. Means and standard deviations for accuracy performance on the Landolt C visual detection task with the inside rearview mirror/CMS

Vision Type	Rear Visibility Technology	Mean Correct Responses (*n*)	Mean Incorrect Responses (*n*)	Mean Correct (%)	Standard Deviation (%)
Single Vision	Inside Rearview Mirror	38.9	1.1	97.2	16.5
	CMS	38.7	1.3	96.7	17.8
Bifocals	Inside Rearview Mirror	38.5	1.5	96.3	19.0
	CMS	37.8	2.2	94.4	23.0

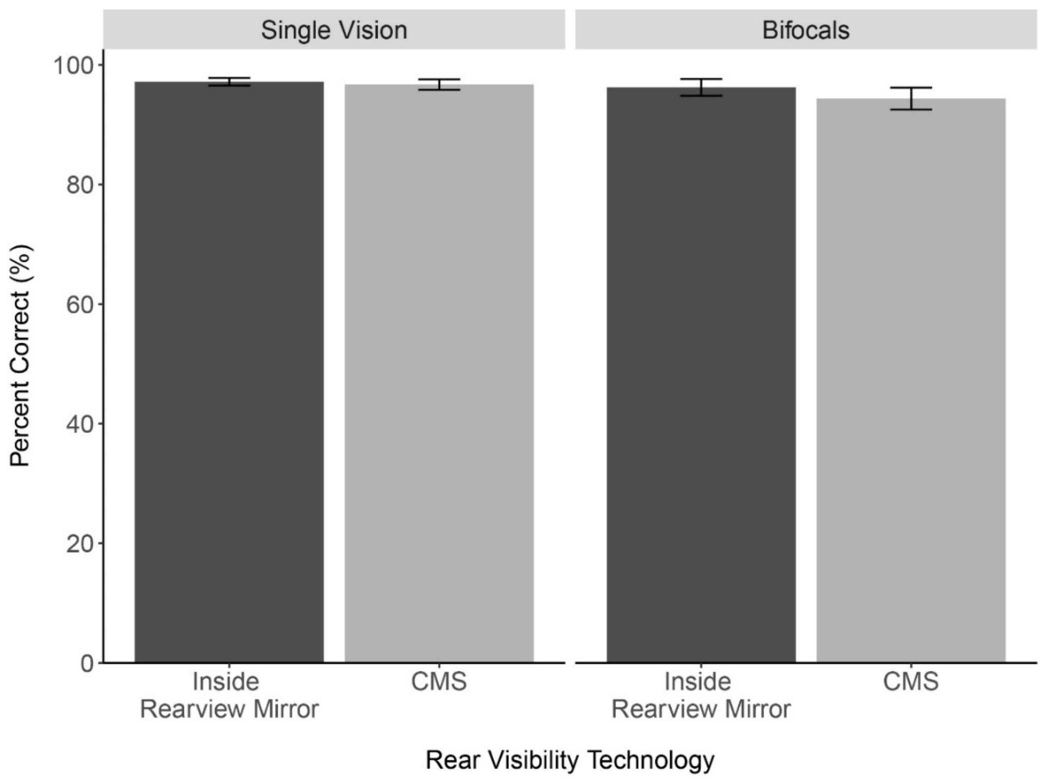


Figure 16. Experiment 2: Accuracy Performance for Landolt C Visual Detection Task

Mean percent of correct detections on the Landolt C visual detection task. Error bars are standard error.

Response Time

Results from a linear mixed-effects analysis found a significant effect for rear visibility technology, $F(1, 2426.91) = 374.98$, $p < .05$. Response times for the CMS condition were longer by 85 ms compared to the inside rearview mirror condition. This means that response times were 8.37 percent longer in the CMS condition compared to the inside rearview mirror condition. Response times did not differ between vision type groups ($p = .57$) and there was not a significant rear visibility technology × vision type interaction ($p = .10$). Age did have a significant effect on response time, $F(1,2431.32) = 2.70$, $p < .05$. As age increased, response time increased, but when holding age constant, the effect of rear visibility technology was still present. Means and standard deviations can be viewed in Table 13. Results can be viewed graphically in Figure 17.

Table 13. Means and standard deviations for response times on the Landolt C visual detection task with the inside rearview mirror/CMS

Vision Type	Rear Visibility Technology	Mean (s)	Standard Deviation (s)
Single Vision	Inside Rearview Mirror	1.01	0.147
	CMS	1.09	0.146
Bifocals	Inside Rearview Mirror	1.02	0.176
	CMS	1.11	0.177

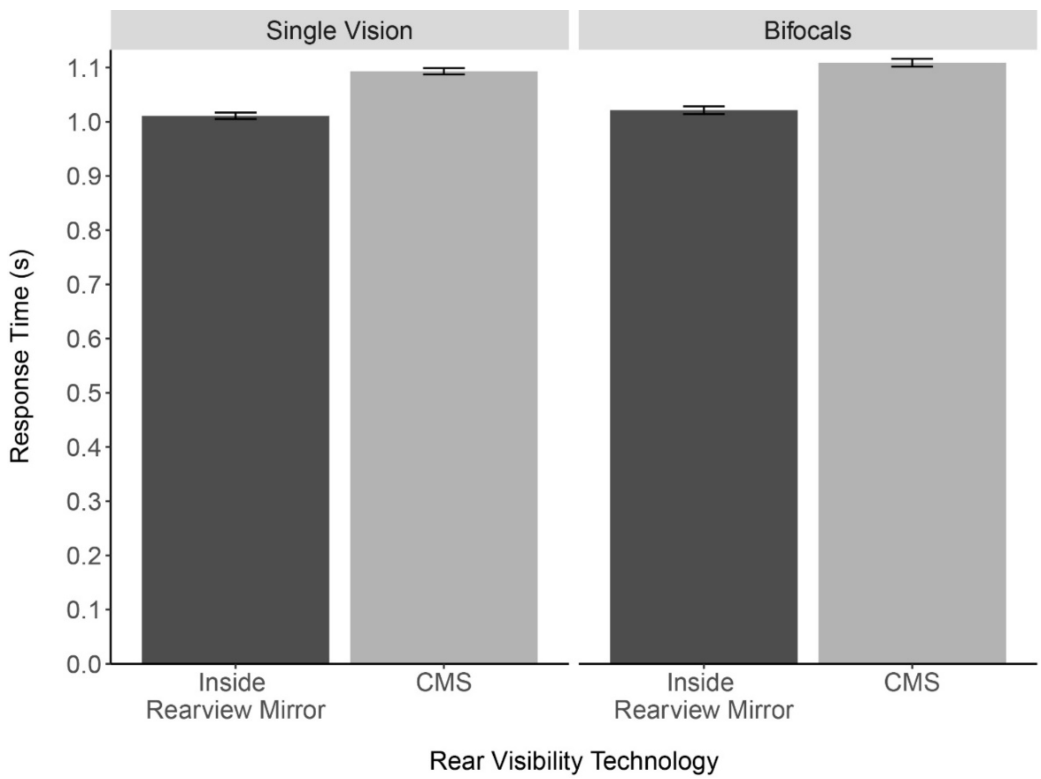


Figure 17. Experiment 2: Response Time for Landolt C Visual Detection Task

Mean response times on the Landolt C visual detection task. Error bars are standard error.

Experiment 2 Discussion

Findings regarding whether response time differs for drivers switching visual attention from the forward roadway to a CMS image compared to the inside rearview mirror.

Results found statistically significant differences in response times when detecting an object in the tested CMS image compared to the inside rearview mirror. For both the car and Landolt C rearward visual detection tasks, response times were longer for the CMS image compared to the inside rearview mirror. For the car visual detection task, response times were 95 ms longer with the tested CMS and for the Landolt C visual detection task, response times were 8 ms longer with the tested CMS. For the car rearward visual detection task, this represents 26 percent of the inside rearview mirror response time for both non-bifocal wearing and bifocal wearing participants, and therefore, may have important implications in real world driving. For the Landolt C rearward visual detection task, that difference represents 8 percent of the inside rearview mirror response time.

There were no interactions when comparing vision type. Participants with bifocal glasses or contact lenses always had longer response times than participants without bifocals, although only statistically significantly with the car rearward visual detection task. This effect did not depend upon whether a CMS or inside rearview mirror was used. The longer response times seen with bifocal glasses or contacts was consistent with the fact that bifocals do not offer clear vision at a distance from about 1.5 to 6 feet, which encompassed the locations of both the inside rearview mirror and the CMS display. There was no difference for vision condition on accuracy.

Findings regarding whether accuracy performance differs for drivers switching visual attention from the forward roadway to a CMS image compared to the inside rearview mirror.

For Experiment 2, for both rearward detection tasks, accuracy was essentially the same for the tested CMS versus an inside rearview mirror. For all four of the cases examined, the accuracy difference was not statistically significant.

There is a possibility that the accuracy findings of this study reflect a ceiling effect (i.e., accuracy cannot exceed 100%). For the car visual detection task, accuracy ranged from 98.0 percent to 99.2 percent. For the Landolt C detection task, accuracy ranged from 94.4 percent to 97.2 percent. The possibility of a ceiling effect is discussed in the Conclusions section of this report.

Findings regarding whether any visual accommodation differences in response time and/or accuracy between the CMS and the inside rearview mirror are influenced by detection task complexity.

For Experiment 2, for the car visual detection task, response time was longer with the tested CMS than with the inside rearview mirror. However, for the Landolt C visual detection task, while the response time for the tested CMS versus the inside rearview mirror was statistically different, the magnitude of difference was small and may not have safety implications. The tested CMS versus rearview mirror response time difference for the Landolt C task was less than for the car visual detection task. These results suggest that task complexity may affect the differences between CMS and rearview mirrors.

Findings regarding whether certain vision corrections, such as the need for bifocal lenses, affect accuracy and response time performance differently with a CMS compared to an inside rearview mirror.

Experiment 2 found that participants with bifocal glasses or contact lenses had consistently longer response times than participants without bifocals, although only statistically significantly with the car rearward visual detection task. This effect did not depend upon whether a CMS or inside rearview mirror was used. The longer response times seen with bifocal glasses or contacts was consistent with the fact that bifocals do not offer clear vision from about 1.5 to 6 feet, a range which the inside rearview mirror and also the CMS display were within. There was no difference for vision condition on accuracy.

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Conclusions

Research was conducted to obtain information regarding how a drivers' visual behavior and ability to extract information from a CMS-based electronic visual image differs from that afforded by outside and inside rearview mirrors. Two experiments were conducted in which one involved comparing outside rearview mirrors versus a corresponding CMS condition and the other involved only the inside rearview mirror and a corresponding CMS condition. Both experiments assessed whether switching visual attention from the forward roadway to CMS visual displays was associated with longer visual accommodation time as reflected in longer response times and reduced accuracy of performance. In both experiments, participants in a stationary vehicle were presented with visual detection tasks to which they responded by switching visual attention from the forward roadway to CMS displays or rearview mirrors. Experimental results are summarized in the following tables. Table 14 summarizes the results from Experiment 1.

Table 14. Experiment 1 Results

Comparison	Response Time		Accuracy	
	Car Visual Detection Task	**Landolt C Visual Detection Task**	**Car Visual Detection Task**	**Landolt C Visual Detection Task**
Driver-Side CMS Versus Outside Rearview Mirror	Longer with CMS by 57 ms (7.74%)	Shorter with CMS by 23 ms (2.36%)	No significant difference	No significant difference
Passenger-Side CMS Versus Outside Rearview Mirror	Longer with CMS by 29 ms (3.56%)	No significant difference	0.7 more correct responses with CMS (1.9%)	No significant difference

Table 15 summarizes the results from Experiment 2.

Table 15. Experiment 2 Results

Comparison	Response Time		Accuracy	
	Car Visual Detection Task	**Landolt C Visual Detection Task**	**Car Visual Detection Task**	**Landolt C Visual Detection Task**
CMS Versus Inside Rearview Mirror	Longer with CMS by 95 ms (12.84%)	Longer with CMS by 85 ms (8.37%)	No significant difference	No significant difference
Without Bifocals Versus With Bifocals	Longer with bifocals by 42 ms (5.44%)	No significant difference	No significant difference	No significant difference

Across both Experiments 1 and 2, for the car detection task, the results showed a statistically significant difference in response time. Response time was longer with the tested CMS compared to the inside or outside rearview mirrors. However, for the Landolt C detection task, response time results were mixed, with the response times with the tested CMS being shorter for one of the three cases examined, longer for one of the three cases, and no statistically significant difference for one of the three cases.

In Experiment 1, the CMS displays were closer to the centerline of the vehicle, requiring less head and eye movement time. The magnitude and pattern of differences may reflect this difference in location of the CMS displays compared to that of the outside rearview mirrors. For Experiment 1, while a significant effect was still found for the car stimulus, the magnitude of difference was smaller than that of Experiment 2, suggesting shorter distance for the head and eyes to gaze toward the CMS display is perhaps offsetting the delay in visual accommodation. For the Landolt C stimulus, the additional cognitive complexity of the task, in addition to the difference in physical location may have attenuated the differences in visual accommodation time. For Experiment 2, in which image location was identical for both CMS and the inside rearview mirror, results found statistically significant longer response times with CMS for all cases. Across both Experiments 1 and 2, for both tasks, accuracy was essentially the same for CMS versus an inside or outside rearview mirror. For five of the six cases examined, the accuracy difference was not statistically significant. For one of the six cases, participants had slightly better accuracy with the CMS, but the magnitude of improvement was small. However, even though accuracy was similar between the tested CMS and rearview mirrors, the increased response times suggest that participants may have needed a longer time to visually accommodate to gain that equivalent level of accuracy with the tested CMS.

There is a possibility that the accuracy findings of this study reflect a ceiling effect (i.e., accuracy cannot exceed 100%). For the car visual detection task, accuracy ranged from 97.2 percent to 99.2 percent (over both experiments). For the Landolt C visual detection task, accuracy ranged from 88.6 percent to 98.9 percent (again, over both experiments). These results suggest that while the CMS displays presented stimuli at a smaller size than that seen with the rearview mirrors, they seem to have provided a sufficiently clear image to permit comparable accuracy for the tasks implemented in these experiments.

While the methods used for this study were meant to mimic on-road visual behavior where drivers transition their gaze from the forward roadway to the CMS or rearview mirrors, the glance behavior was controlled in the sense that drivers were cued when and where to look. In contrast to on-road driving, the possibility that a driver may not see an object of importance due to the object not being in the image's field of view or due to the driver not looking at the mirror or CMS image did not exist in this experiment. This resulted in accuracy findings close to the maximum possible value of 100 percent. The object to be detected was always present in the mirror or CMS image and where the participant always looked in order to isolate factors affecting visual accommodation and this increased response time may also be seen during actual driving.

Experiment 2 found that participants with bifocal lenses or contacts always had longer response times than participants without bifocal glasses. This effect did not depend upon whether a CMS or inside rearview mirror was used. The longer response times seen with bifocal glasses or contacts was consistent with expected longer response times for bifocals due to the location of the tested CMS displays and inside rearview mirror, but the results did not show that wearing bifocals exacerbated the increases in response time when using the tested CMS. The use of bifocal lenses had no effect on accuracy for the tasks used in this study and the particular tested CMS.

One point to be noted when interpreting the results is that the CMS displays of the original equipment systems used in this study had lower image magnification levels than the rearview mirrors, resulting in stimuli appearing somewhat smaller in the CMS images than in the mirrors. The smaller stimulus size for CMS is because when magnification is lower, objects in the field of view, including the visual stimuli, appear visually smaller. Having a CMS that presents an image having unit magnification (i.e., no magnification) would have permitted isolation of the effects of visual accommodation separate from image magnification; however, NHTSA has not found any production CMS with unit magnification. While holding image magnification constant could have provided a more isolated assessment of visual accommodation effects, only production systems with their OEM-selected image magnification levels were available for use in testing. Furthermore, presenting a unit magnification image on a CMS would require a display measuring about 10 inches diagonally to provide the same field of view as an FMVSS No.111 compliant mirror. As explained in SAE J3155, "the original development of mirror fields of view in the [United States] envisioned that drivers would be able to expand the usable field of view through head movement. A CMS would presumably not allow for an expanded field of view through head movement so either the CMS field of view is expanded while also enlarging the monitor size to maintain the same displayed object size or the CMS field of view is expanded without changing the monitor's size so that objects in the CMS appear smaller than they would in a typical mirror." The document notes that past research has found that drivers expand the field of view of mirrors by about 30 percent through head turn and lateral movement. Therefore, a monitor installed at the base of the A-pillar would need to measure 10-in diagonally to present the minimum field of view plus an additional 30 percent in the horizontal direction to provide the same effective field of view as a typical mirror. However, SAE concludes "the size of the monitor makes for a difficult, if not impossible, packaging option" (SAE, 2021). However, despite the smaller stimulus size of the systems studied, accuracy was high for both CMS and rearview mirror conditions, suggesting the somewhat smaller stimuli were similarly perceptible compared to mirrors. Based on the results of this study it is not possible to know the degree to which image magnification and stimulus size may have affected response times.

Lastly, this study was a controlled laboratory study meant to isolate the visual accommodation step, but as the response metric is an indirect measure, it is not possible to know the actual magnitude of visual accommodation time. Additionally, behavior in this study does not reflect all aspects of using the CMS. The full picture of how delays related to visual accommodation factor within the full usage of CMSs in a moving vehicle driven under real-world conditions is beyond the scope of this study.

The longer visual detection task response times for the tested CMSs in five of the six comparisons suggest there may be longer visual accommodation times when drivers transition their gaze from the forward roadway to a CMS compared to mirrors. With CMS, response times increased by 29 ms to 95 ms (3.56% to 12.84%) compared to rearview mirrors. While the magnitude of difference was small, these laboratory experiments were meant to isolate detection and response time in a controlled manner, and increased response times seen with the tested CMSs suggest an increased response time may also be seen in actual driving. Even though the response time differences were small, the differences would be anticipated to affect each glance associated with a particular maneuver resulting in longer visual accommodation times for drivers using a CMS. This means drivers would likely have their eyes directed away from the forward roadway for slightly longer durations when driving with CMS compared to rearview mirrors. However, whether there are safety implications as a result of these slightly longer durations cannot be established based on this study.

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