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Augmented Reality Cues and Elderly Driver Hazard Perception

Mark C. Schall Jr., **Michelle L. Rusch**, University of Iowa, Iowa City, **John D. Lee**, University of Wisconsin–Madison, and **Jeffrey D. Dawson**, **Geb Thomas**, **Nazan Aksan**, and **Matthew Rizzo**, University of Iowa, Iowa City

Objective: The aim of this study was to evaluate the effectiveness of augmented reality (AR) cues in improving driving safety among elderly drivers who are at increased crash risk because of cognitive impairments.

Background: Cognitively challenging driving environments pose a particular crash risk for elderly drivers. AR cuing is a promising technology to mitigate risk by directing driver attention to roadway hazards. We investigate whether AR cues improve or interfere with hazard perception in elderly drivers with age-related cognitive decline.

Method: A total of 20 elderly (M = 73 years, SD = 5) licensed drivers with a range of cognitive abilities measured by a speed-of-processing (SOP) composite participated in a 1-hr drive in an interactive, fixed-base driving simulator. Each participant drove through six straight, 6-mile-long, rural roadway scenarios following a lead vehicle. AR cues directed attention to potential roadside hazards in three of the scenarios, and the other three were uncued (baseline) drives. Effects of AR cuing were evaluated with respect to (a) detection of hazardous target objects, (b) interference with detecting nonhazardous secondary objects, and (c) impairment in maintaining safe distance behind a lead vehicle.

Results: AR cuing improved the detection of hazardous target objects of low visibility. AR cues did not interfere with detection of nonhazardous secondary objects and did not impair ability to maintain safe distance behind a lead vehicle. SOP capacity did not moderate those effects.

Conclusion: AR cues show promise for improving elderly driver safety by increasing hazard detection likelihood without interfering with other driving tasks, such as maintaining safe headway.

Keywords: driver behavior, simulation and virtual reality, sensory and perceptual processes, psychomotor processes, aging and individual differences, displays and controls

Address correspondence to Mark C. Schall Jr., MS, University of Iowa, Department of Mechanical and Industrial Engineering, Department of Neurology, 200 Hawkins Dr., Iowa City, IA 52242; e-mail: mark-schall@uiowa.edu.

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INTRODUCTION

Elderly drivers are at particular risk for motor vehicle crashes in challenging driving environments (Cerelli, 1995; Chandraratna & Stamatiadis, 2003; Mayhew, Simpson, & Ferguson, 2006) due to age-related visual, cognitive, and physical impairments (Ball et al., 1998; Ball, Owsley, Sloane, Roenker, & Bruni, 1993). Driving tasks that require attention to be divided between two assignments are especially difficult (Brouwer, Waterink, van Wolffelaar, & Rothengatter, 1991; Ponds, Brouwer, & van Wolffelaar, 1988). For example, elderly drivers have been observed to have trouble navigating with in-vehicle information displays and driving concurrently (Dingus et al., 1997). Elderly drivers also have more difficulty compared with middle-aged drivers perceiving hazards, such as pedestrians in the visual periphery, likely because of limitations of their useful field of view (UFOV; Bromberg, Oron-Gilad, Ronen, Borowsky, & Parmet, 2012).

Many elderly drivers attempt to compensate for their difficulties by avoiding certain situations, such as driving during rush hours and in difficult weather conditions (Hakamies-Blomqvist & Wahlström, 1998). Cognitively impaired elderly drivers who are aware of their limitations report more avoidance behaviors compared with those without impairment (Ball et al., 1998). However, reliance on compensatory strategies, such as avoidance, can be inadequate, and some drivers may underestimate their impairments, emphasizing the need for further research in the relationships of cognitive aging and innovative driver assistance technologies.

Neuropsychological tests can measure functional impairments that affect elderly driver safety (Dawson, Anderson, Uc, Dastrup, & Rizzo, 2009; Dawson, Uc, Anderson, Johnson, & Rizzo, 2010; Uc et al., 2009; Uc, Rizzo, Anderson, Shi, & Dawson, 2005). In particular, speed of processing (SOP), or the speed with

TABLE 1: Neuropsychological Tests That Measure Declines in Speed of Processing

Exam	Resource	Description
Trail Making Test Part A (TMT-A)	Reitan (1955, 1958)	A visual search and visuomotor speed task that assesses attention, sequencing, mental flexibility, and motor function. This task requires a participant to "connect the dots" of 25 consecutive targets on a sheet of paper. In Version A, the targets are all numbers (1, 2, 3, etc.). The participant's goal is to finish the test as quickly as possible, and the time taken to complete the test is used as the primary performance metric.
Grooved Pegboard Test (Pegs)	Matthews & Klove (1964)	A visuomotor coordination task that assesses manipulative dexterity and coordination important for driving. This task consists of placing 25 pegs, which have a key along one side, into 25 randomly oriented slots on a board. The pegs must be rotated to match the hole before they can be inserted.
Useful Field of View Task (UFOV)	Ball & Owsley (1993); Edwards et al. (2005)	A sequential test of speed of processing for visual attention that relies on subtests of processing speed, divided attention, and selective attention.

which an individual performs a cognitive activity, is one of the best indicators of cognitive aging (Salthouse, 1996). A recent confirmatory factor analysis of 345 elderly drivers evaluated a select battery of neuropsychological tests for their relevance to driving performance (Anderson et al., in press). The results showed that it was possible to isolate an SOP latent factor on the basis of the Trail Making Test Part A (TMT-A), Grooved Pegboard Test (Pegs), and the UFOV task, which itself has been reported to be sensitive to crash involvement (Ball, Edwards, & Ross, 2007; Ball & Owsley, 1993; Horswill et al., 2008; Owsley et al., 1998). Table 1 describes the neuropsychological tests that composed the SOP factor. The current study used this SOP factor to characterize cognitive functions relevant to driving among elderly drivers using prototype assistance technologies.

In-vehicle driver assistance technologies, such as augmented reality (AR) cuing, may help direct driver attention to roadway hazards (Ho, Reed, & Spence, 2007; Ho & Spence, 2005; Scott & Gray, 2008), improve target detection (Yeh & Wickens, 2001), and reduce collision involvement (Kramer, Cassavaugh, Horrey, Becic, & Mayhugh, 2007; Lee, McGehee, Brown, & Reyes, 2002). AR combines natural and artificial stimuli by projecting computer graphics on a transparent plane (Azuma, 1997; Azuma et al., 2001). The graphical augmentation can highlight important roadway objects or regions or provide informative annotations. However, adding these graphical cues may also interfere with driver perception of secondary objects and tasks, thereby decreasing driver accuracy and increasing response time for detecting roadway hazards (Schall, Rusch, Lee, Vecera, & Rizzo, 2010) because of masking, crowding, interposition, and divided attention. Furthermore, poor system reliability can affect user trust (Bliss, 1997; Sorkin, 1988). High false alarm (FA) rates caused by hypersensitive systems have the potential to irritate a driver, leading to a decline in driver responsiveness and overall task performance (Bliss & Acton, 2003; Lees & Lee, 2007; Maltz & Shinar, 2004).

Although some research has been performed to evaluate methods for directing driver attention with the use of AR cues (Kim, & Dey, 2009; Tonnis, Sandor, Lange, Klinker, & Bubb, 2005), limited research has been conducted on the effectiveness of AR cuing for elderly drivers with age-related cognitive impairments. This study assessed the utility of AR cues in alerting elderly drivers with age-related cognitive impairments to potential roadside hazards, such as pedestrians. The question was whether cognitively impaired elderly drivers benefited from, or were distracted by, additional information intended to alert or warn them. We tested whether AR cues improve or degrade driver response rates and response times to potential hazards.

METHOD

Participants

Participants were 20 elderly drivers (between 65 and 85 years; $M = 73$ years, $SD = 5$; males = 13, females = 7) recruited from the general population. Telephone screening prior to enrollment excluded drivers with confounding medical conditions (e.g., neurodegenerative disease, anxiety, depression) and those taking specific medications (e.g., stimulants, narcotics, hypnotics) that could influence performance. Consent was obtained in accord with institutional guidelines. All participants possessed a valid U.S. driver's license and had normal or corrected-to-normal vision (determined through near and far visual acuity and contrast sensitivity).

Participants self-reported their driving history and frequencies on the Mobility Questionnaire (Stalvey, Owsley, Sloane, & Ball, 1999). They reported an average of 56 years ($SD = 6$) of driving experience. Weekly mileage was 1 to 50 miles (4/20 = 20%), 51 to 100 miles (8/20 = 40%), 101 to 150 miles (2/20 = 10%), or more than 150 miles per week (6/20 = 30%). Of the 20 participants, 4 (20%) drove 2 to 4 days per week, 5 (25%) drove 5 to 6 days per week, and 11 (55%) drove 7 days a week.

Pearson's correlation for the relationship between weekly mileage and number of days driven was 0.41 ($p = .073$). Spearman's correlation was almost identical (0.40, $p = .078$), suggesting that there were no influential outliers.

Cognitive Assessment

All participants were tested with a set of standardized neuropsychological tools administered by a trained technician during a single session. An SOP composite was calculated through a principal component analysis combining the UFOV task, TMT-A, and Pegs (Anderson et al., in press).

Participants were screened for UFOV impairments with the Visual Attention Analyzer, Model 3000 (Vision Resources, Chicago, IL; Ball & Owsley, 1993; Edwards et al., 2005). The UFOV task involves four subtests designed to assess (a) processing speed, (b) divided attention, (c) selective attention, and (d) selective attention with a simultaneous same–different discrimination at fixation. We calculated a total UFOV score by summing the four subtest measure scores as in previous studies (e.g., Anderson et al., in press; Dawson et al., 2009, 2010). Scores of at least 350 on Subtest (c) or 500 on Subtest (d) defined UFOV impairment. These selective attention subtests measure SOP when distracting stimuli are present (Ball et al., 1993).

Apparatus

The simulator used in this study, SIREN, has a four-channel display, 150° forward view, and 50° rear view (Lees, Cosman, Fricke, Lee, & Rizzo, 2010). The screen was located in front of a 1994 GM Saturn simulator cab. Two flat-panel speakers (8.5 × 4.5 in.) mounted on the far left and right of the vehicle dashboard were used to present verbal instructions from the researchers. Instructions and scenario questions were presented from the speakers at 83 dBA. All participants were instructed on how to drive in the simulator and allowed to make seat, steering wheel, and mirror adjustments to accommodate individual comfort preferences.

AR Cue

The AR cue used in this study comprised broken yellow lines that gradually elongated and converged in a series of eight phases to form a complete rhombus (Figure 1). This rhombus was not filled to convey information to the driver without obstructing roadway objects. The size, length, and direction of tilt of the rhombus elements signaled the position and distance of the object being highlighted. The converging lines conveyed motion mapped to the relative speed of the driver's vehicle. Motion onset can attract attention to objects (Abrams & Christ, 2003) and was included in the AR cue design to help direct older drivers' attention to

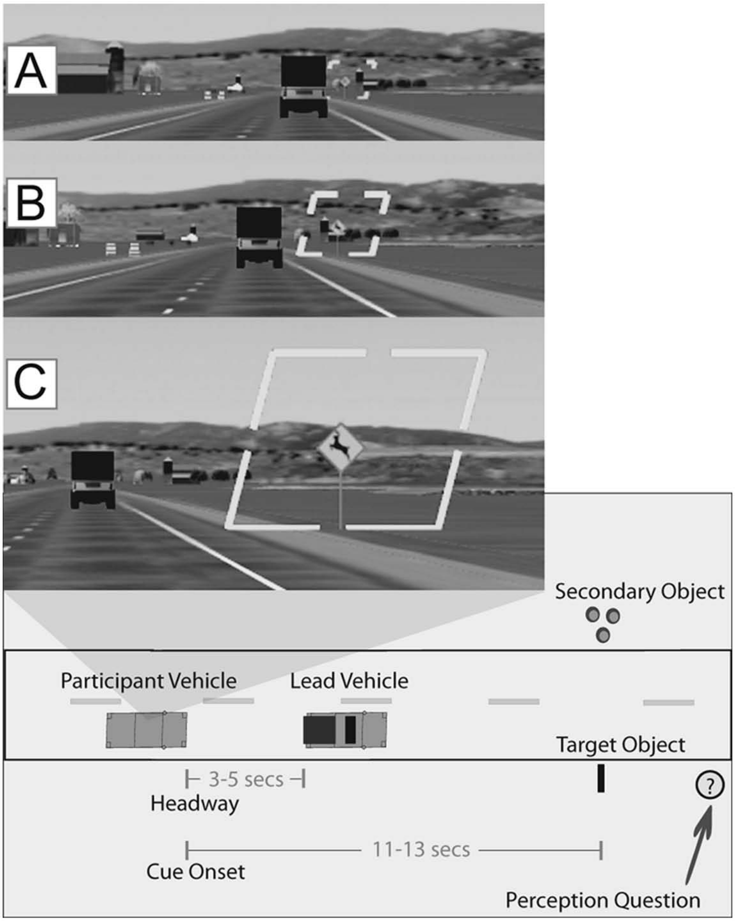

Figure 1. The augmented reality (AR) cue gradually converged in eight phases to form a complete rhombus. The illustration presents the cue at (A) Phase 3, (B) Phase 5, and (C) Phase 7.

targets they have trouble noticing (e.g., pedestrians). The color yellow was chosen to convey a warning rather than an immediate threat (Chapanis, 1994; Gelasca, Tomasic, & Ebrahimi, 2005). The continuously enlarging rhombus subtended 0.7° of visual angle at onset and 16.7° when the vehicle passed. The AR cue was always centered on the object it was highlighting with the base positioned below the object being highlighted.

Experimental Design and Procedure

A factorial design was used to assess the effect of AR cuing as a within-subject variable. The experiment consisted of six driving scenarios that were separated into three unique pairs. Each pair contained one driving scenario conditioned with AR cues (referred to as "cued" scenarios) and one scenario that was not conditioned with AR cues (referred to as "uncued" scenarios) (Figure 2). The term *instance* conveys the order of presentation of each pair.

In each instance, the uncued roadway scenario always preceded the cued roadway scenario. The uncued scenarios were not counterbalanced across instances to test for potential practice or learning effects. Each of the three cued scenarios included a different level of cue reliability implemented as a

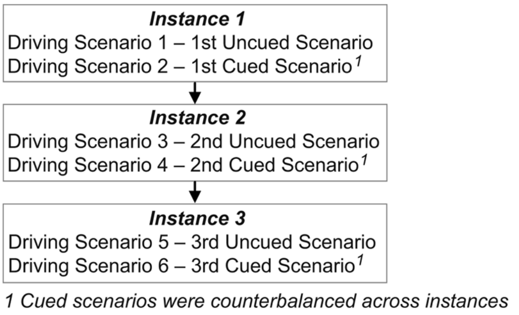

Figure 2. Flow diagram of instances.

within-subject variable. The three reliability levels were (a) 0% FAs and 0% misses (no cue), (b) 15% FAs and 0% misses, and (c) 0% FAs and 15% misses. The FAs and misses in the second and third reliability levels were predetermined by the experimenters and were the same for each participant. For example, in the second reliability case (15% FAs, 0% misses), the AR cue was presented at two separate roadside locations with no object highlighted for all participants. Participants were always warned that the AR cue may not be 100% reliable. The cued scenarios were counterbalanced across instances to avoid bias related to reliability of the AR cue.

All roadway scenarios were two-lane rural highways, roughly 6 miles in length, with similar road characteristics (i.e., landscape, road width). In each of the six scenarios, participants approached six roadside object types, as listed in Table 2. Of these object types, three were labeled *target* objects and represented roadside hazards, including pedestrians and vehicles (that might enter the road ahead of the driver) and warning signs (that announced crossings by pedestrians or deer). The other three object types were labeled *secondary* objects because they were nonhazardous, stationary objects that would not, in normal conditions, be expected to move in the real world (commercial objects, construction objects, recreational signs). Each object type had two classifications attributed with it, with each having the same target or secondary object connotation. For example, the pedestrian object type could be either a male or a female, with both classifications considered target objects because they might enter the road ahead of the driver in the real world and thus present a hazard.

Target objects were presented roughly every half mile (12 per scenario) and could be seen on either side of the roadway unless the object presented was a warning sign. Warning signs were placed only on the driver (right) side of the roadway, as typical in the real world. Secondary objects (presented with 9 of the 12 target objects in each scenario) were always located on the other side of the roadway directly opposite the target objects. The presence of a secondary object was randomized to prevent anticipation in all scenarios regardless of cuing.

The AR cue highlighted only target objects. Highlighting occurred when the participant was within 350 m of a target object and was visible for 11 to 13 s while the participant approached at speeds between 60 and 70 mph. The AR cue was updated eight times, every 43.75 m, to enclose the target as the participant approached it. Because secondary objects were classified as nonhazardous, they were never cued. Target and secondary objects were always visible from a distance and were never obscured (e.g., by objects in the foreground). All participants were shown the target and secondary objects prior to the experiment to familiarize them with the objects and their classifications. Participants were informed that only target objects would be cued.

In all scenarios, participants were asked to flash the high beams as soon as they could classify an upcoming target object (i.e., gender of pedestrian, type of vehicle, type of warning sign). Participants were not asked to respond to the secondary objects using the high beams or any other manual control. As soon as a participant flashed the high beams, a white box occluded both target and secondary objects to prevent participants from "cheating" by looking back at the objects when asked a question about them. Immediately after passing a target object in all scenarios, participants were asked a recorded question about the target (six possibilities) or secondary objects (six possibilities) that he or she may have passed in the preceding 200 m. Half of the questions were about target objects, and half were about secondary objects, in random order.

TABLE 2: Description of Targets and Secondary Objects and their Classification

Object Type	Classification	Target Object	Secondary Object
Pedestrian	Male	X	
Pedestrian	Female	X	
Vehicle	Car	X	
Vehicle	Truck	X	
Warning sign	Pedestrian	X	
Warning sign	Deer	X	
Commercial	Phone booth		X
Commercial	Dumpster		X
Recreational sign	Rest area		X
Recreational sign	Recreational activity		X
Construction	Stationary trailer		X
Construction	Barrel		X

A car-following task was added to all scenarios to make the experiment more representative of actual road demands whereby assistive cues might provide a benefit (Schall et al., 2010). The lead vehicle's speed fluctuated between 60 and 70 mph. Participants were instructed to maintain a 3- to 5-s headway from the lead vehicle at all times. A message appeared in all scenarios at the bottom of the screen that read "Too Close" if the participant adopted headway of 3 s or less. A message also appeared that read "Not Close Enough" and a tailing vehicle honked if the participant fell more than 5 s behind.

Dependent and Independent Variables

To evaluate the effectiveness of AR cuing, two outcome measures were used to assess ability to direct attention, and two outcome measures were used to assess interference. Cuing may draw attention to cued objects, causing other objects to be neglected (Yeh & Wickens, 2001). Interference associated with neglect of uncued objects could undermine AR systems because many important hazards that drivers will need to respond to may not be cued. To assess this possibility, we measure driver response accuracy regarding uncued objects. Cuing could also interfere with drivers' attention to vehicle control. To assess this possibility, we measure drivers' ability to maintain the specified headway. Table 3 defines each outcome measure associated with directing attention and interference.

Differences in the outcome measures described in Table 3 were examined as a function of the following independent variables: cuing (cued, uncued), instance (order of scenario presentation), age, gender, and SOP composite.

Analysis

Linear mixed models were fit to the data with the use of likelihood-based methods. These models included the main effects of age (continuous), gender, SOP composite (continuous), cuing (cued vs. uncued), instance (Instances 1 through 3), and cuing reliability. Contrary to expectations, cuing reliability showed no effects on any of the outcome measures in preliminary analysis and was dropped from subsequent analyses. Preliminary analyses also showed that the effects of some predictors of interest (e.g., cuing) vary across target type. For that reason, different mixed models were completed for each type of target: pedestrians, vehicles, and warning signs.

The following two-way interactions were tested: (a) cuing by instance, (b) instance by SOP, and (c) cuing by SOP. Collectively, these systematic effects allowed us to distinguish between cuing-related and non-cuing-related effects. Main and interaction effects of cuing

TABLE 3: Outcome Measures to Assess Effectiveness of Augmented Reality Cues

Outcome Measure	Definition
Directing attention	
Response rate (count)	The number of times a participant accurately used the high beams to identify target objects.
Time to collision at response (TCR)	The time in seconds before potential collision with the target object when the participant activated the high beams. Larger TCR values indicate faster response times.
Interference	
Question response accuracy (QA)	The number of times a participant correctly identified target and secondary objects in response to questions during the scenarios.
Headway variation (HV)	The variance in a participant's headway from the lead vehicle in those segments of the scenarios when he or she was within 400 m of a target object.

would suggest AR cue effects. A main effect of instance in a beneficial direction (e.g., improving response rates) may suggest a general learning effect, whereas a main effect of instance in a detrimental direction (e.g., declining response rates) may suggest a potential fatigue effect.

When interactions between covariates (e.g., SOP) and factors were significant, slopes and standard errors were estimated. Predicted estimates for the lowest quartile ($\leq$–1.35) and highest quartile ($\geq$1.17) SOP indices were plotted to illustrate two-way interactions between SOP and cuing levels for headway variation.

Higher-order effects (i.e., three-way interactions) were examined, found to be not significant, and dropped from subsequent analyses. The model that included the three-way interactions did not show a better fit based on Akaike information criterion compared with models that included only two-way interactions.

We performed formal tests of the model assumptions in the analysis of the count data. We found that despite the fact that counts are discrete and have a lower bound of zero, the residuals from the pedestrian counts and the warning sign counts showed no significant departure from normality, on the basis of the Kolmogorov-Smirnov test, the Cramer-von Mises test, and the Anderson-Darling test. We also found no significant correlation between the predicted values and the magnitude of the residuals, suggesting that the assumption of homoscedasticity was reasonable. For vehicle counts, our tests suggested some violations of the normality assumption, because of some skewness in the data, and some heteroscedasticity, as well. To address this finding, we repeated our analyses of vehicle counts on the log scale and found, again, that the only significant predictor was age.

RESULTS

Neuropsychological Test Summary Statistics

A principal component analysis of UFOV, TMT-A, and Pegs scores showed only one eigenvalue greater than 1 (1.98), and it explained 66% of the variability. The first principal component was used as the SOP composite in all analyses. Table 4 shows the descriptive statistics on all three tests as well as the SOP composites for those who were UFOV impaired and unimpaired.

Outcomes Associated With Directing Attention With AR Cuing

Response rate (count). Table 5 shows the effect of AR cuing on response rates (counts) for target objects. A main effect of cuing was observed for pedestrian and warning sign target objects. Participants responded to approximately

TABLE 4: Mean SOP Scores

Group	UFOV	Pegs	TMT-A	SOP
UFOV unimpaired (*n* = 13)	547.46 (162.73)	85.23 (15.55)	29.16 (9.86)	–0.74 (1.07)
UFOV impaired (*n* = 7)	978.57 (300.07)	111.86 (25.93)	39.58 (5.38)	1.43 (1.29)

Note. Higher scores and composites correspond with poorer abilities. Standard deviations appear in parentheses. SOP = speed of processing; UFOV = Useful Field of View Test; Pegs = Grooved Pegboard Test; TMT-A = Trail Making Test Part A.

TABLE 5: Augmented Reality Effects on Pedestrian Count, Vehicle Count, and Warning Sign Count

Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	Pedestrian Count		Vehicle Count		Warning Sign Count	
			F	*p*	*F*	*p*	*F*	*p*
Cuing	1	89	21.77	<.01	0.86	.36	25.64	<.01
Instance	2	89	9.73	<.01	0.90	.41	0.91	.40
Cuing × Instance	2	89	1.42	.25	0.15	.86	1.59	.21
Age	1	15	1.72	.21	6.52	.02	1.89	.19
Gender	1	15	0.32	.58	0.15	.71	6.98	.02
SOP[a]	1	15	1.59	.23	1.40	.25	4.85	.04
SOP × Cuing	1	89	0.92	.34	0.73	.40	1.03	.31
SOP × Instance	2	89	1.37	.26	0.46	.63	1.58	.21

Note. SOP = speed of processing.
[a]In contrast, for overall count (includes all targets), the 95% confidence interval for SOP was [–0.55, 0.42].

25% more pedestrians (difference calculated as cued mean response percentage of 91.13% minus uncued mean response percentage of 66.10%) and 5% more warning signs (cued mean response percentage of 96.10% minus uncued mean response percentage of 91.10%) throughout the study when cued (Figure 3). A main effect of cuing was not found for vehicle target objects.

A main effect of instance was observed for detecting pedestrian targets. Participants responded more frequently to pedestrians as the instance number increased (Table 6). A main effect of gender was observed for warning sign targets in which male participants (least square mean [LSM] = 3.99, *SE* = 0.05) responded to more warning signs than females (LSM = 3.76, *SE* = 0.07, *p* = .02). As age increased, participants had more difficulty responding to vehicle targets (slope = –0.041, *SE* = 0.016). Similarly, as SOP composite increased, participants responded to fewer warning signs (slope = –0.086, *SE* = 0.039).

Time to collision at response (TCR). Table 7 shows the effect of AR cuing on TCR for target objects. Figure 4A presents LSMs and standard errors of each condition of cuing. There was a main effect of cuing for warning sign TCR. Participants responded 0.35 s sooner on average in cued conditions than in uncued conditions (*p* = .02). There was also a main effect of instance for both pedestrian and warning sign TCR. Participants responded to pedestrians fastest during the final instance (Table 6). In contrast, for warning signs, participants responded faster in earlier instances (Table 6).

A main effect of gender was observed for all target categories. Figure 4B presents LSMs and standard errors of each target category for differences in gender. On average, females

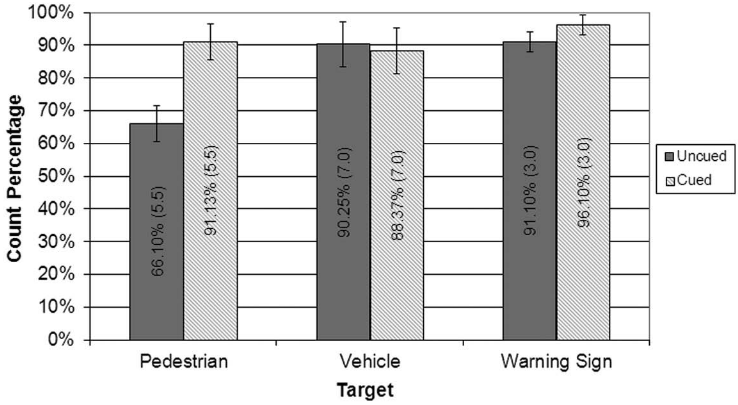

Figure 3. Response rate (count) percentage for targets by cuing.

TABLE 6: Least Square Means (LSM) for the Instance Main Effect

Instance Number	Pedestrian Count		Pedestrian TCR		Warning Sign TCR	
	LSM	*p*	LSM	*p*	LSM	*p*
1	2.82 (0.16)	<.01	2.60 (0.22)	<.01	3.98 (0.23)	<.01
2	3.14 (0.16)	<.01	2.15 (0.22)	<.01	3.54 (0.23)	<.01
3	3.76 (0.17)	<.01	2.77 (0.22)	<.01	3.44 (0.23)	<.01
2 – 1[a]	0.32	.14	-0.45	.08	-0.44	.02
3 – 1[a]	0.94	<.01	0.17	.50	-0.54	<.01
3 – 2[a]	0.62	.01	0.62	.02	-0.10	.58

Note. TCR = time to collision at response. The *p* values were derived from follow-up Tukey pairwise comparisons.
[a]Difference between LSMs of specific instances (e.g., Instance 2 – Instance 1 = 3.14 – 2.82 = 0.32).

responded 1.37 s faster than males ($p < .01$) to target objects. Finally, a main effect of SOP was observed for both pedestrian TCR (slope = –0.381, *SE* = 0.185) and warning sign TCR (slope = –0.451, *SE* = 0.202). Overall, as the SOP composite increased, participants responded more slowly to pedestrian and warning sign target objects.

Outcomes Associated With Interference

Accuracy of responses to questions. Table 8 shows the effect of AR cuing on accuracy in identifying target and secondary objects. There was no main effect of cuing, small confidence intervals, and similar mean values for both targets, $F(1, 90) = 0.00$, $p > .05$, uncued 95% confidence interval (CI) [5.28, 5.47], cued 95% CI [5.28, 5.47]; and secondary objects, $F(1, 90) = 0.20$, $p > .05$, uncued 95% CI [5.05, 5.29], cued 95% CI [5.11, 5.35].

A Cuing × Instance interaction was observed for target objects in which participants responded less accurately in cued conditions as instance number increased (Instance 1, mean number correct = 5.58, *SE* = 0.15; Instance 2, mean number correct = 5.40, *SE* = 0.15; Instance 3, mean number correct = 5.12, *SE* = 0.15). A main effect of gender was observed for target objects, as male participants (LSM = 5.64, *SE* = 0.10) responded more accurately to targets than did females (LSM = 5.10, *SE* = 0.13), $p < .01$. As age increased, participants (slope = –0.059, *SE* = 0.019) had more difficulty identifying target objects correctly.

A main effect of instance was observed for secondary objects, as participants responded

TABLE 7: Augmented Reality Effects on Pedestrian TCR, Vehicle TCR, Warning Sign TCR

Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	Pedestrian TCR *F*	Pedestrian TCR *p*	Vehicle TCR *F*	Vehicle TCR *p*	Warning Sign TCR *F*	Warning Sign TCR *p*
Cuing	1	90	2.70	.10	2.61	.11	5.24	.02
Instance	2	90	3.28	.04	0.32	.73	4.90	<.01
Cuing × Instance	2	90	0.11	.90	1.14	.32	0.30	.74
Age	1	16	0.07	.79	0.00	.95	0.30	.59
Gender	1	16	9.92	<.01	6.73	.02	6.47	.02
SOP[a]	1	16	4.35	.05	2.66	.12	6.77	.02
SOP × Cuing	1	90	0.41	.52	0.52	.47	0.00	.99
SOP × Instance	2	90	1.01	.37	0.29	.75	0.15	.86

Note. TCR = time to collision at response; SOP = speed of processing.
[a]The 95% confidence interval for SOP on overall TCR was [–0.94, –0.03].

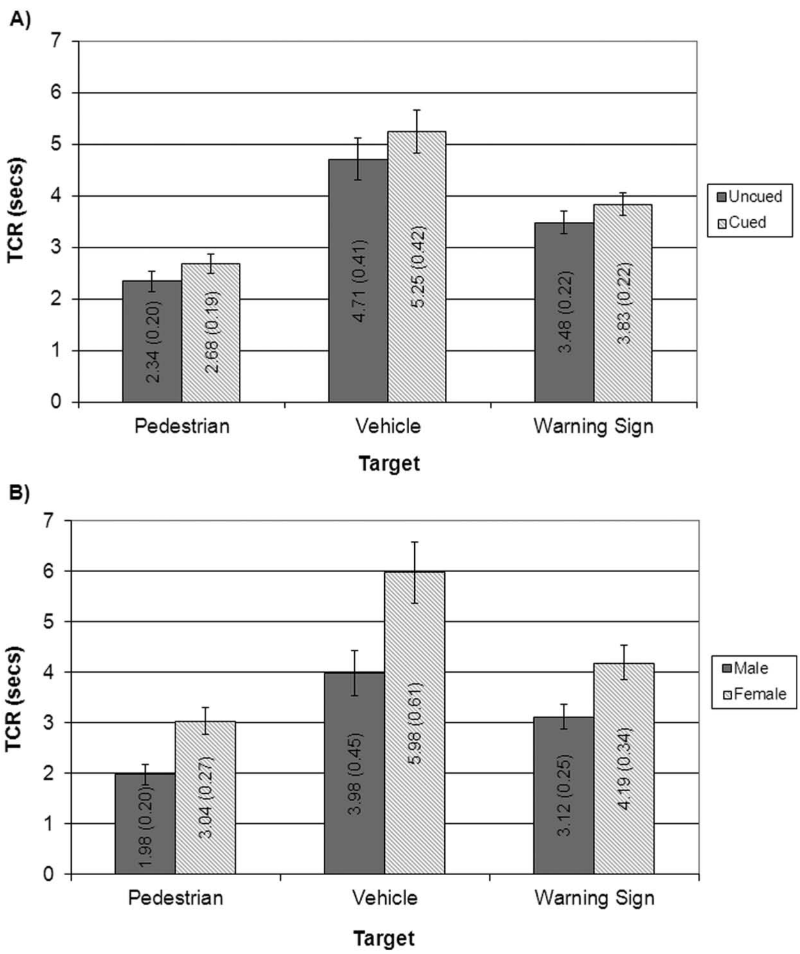

Figure 4. Time to collision at response (TCR) for (A) targets and (B) gender across all target categories.

TABLE 8: Augmented Reality Effects on Accuracy in Identifying Target and Secondary Objects

Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	Target Object QA		Secondary Object QA	
			F	*p*	*F*	*p*
Cuing	1	90	0.00	.95	0.20	.66
Instance	2	90	0.46	.64	11.82	<.01
Cuing × Instance	2	90	9.08	<.01	2.58	.08
Age	1	16	9.56	<.01	1.71	.21
Gender	1	16	11.57	<.01	0.30	.59
SOP	1	16	0.02	.90	9.06	<.01
SOP × Cuing	1	90	1.97	.16	0.49	.48
SOP × Instance	2	90	0.21	.81	1.94	.15

Note. QA = question response accuracy; SOP = speed of processing.

TABLE 9: Augmented Reality Effects on Pedestrian HV, Vehicle HV, and Warning Sign HV

Effect	Numerator Degrees of Freedom	Denominator Degrees of Freedom	Pedestrian HV		Vehicle HV		Warning Sign HV	
			F	*p*	*F*	*p*	*F*	*p*
Cuing	1	90	0.17	.68	0.04	.84	3.11	.08
Instance	2	90	4.67	.01	1.63	.20	1.10	.34
Cuing × Instance	2	90	0.02	.98	1.03	.36	1.09	.34
Age	1	16	0.01	.91	0.00	.95	0.09	.77
Gender	1	16	2.50	.13	2.13	.16	1.75	.20
SOP	1	16	5.99	.03	1.69	.21	3.04	.10
SOP × Cuing	1	90	0.06	.81	7.94	<.01	0.02	.89
SOP × Instance	2	90	0.45	.64	2.22	.11	0.52	.59

Note. HV = headway variation; SOP = speed of processing.

more accurately on average to the six questions asked in each scenario as instance number increased (Instance 1, mean number correct = 4.72, *SE* = 0.14; Instance 2, mean number correct = 5.42, *SE* = 0.14; Instance 3, mean number correct = 5.45, *SE* = 0.14). As SOP composites increased, participants became less accurate in identifying secondary objects correctly (slope = –0.253, *SE* = 0.084).

Headway variation. Table 9 shows the effects of AR cuing on headway variation. There was no main effect of cuing, $F(1, 90) = 0.91$, $p > .05$, uncued 95% CI [0.04, 0.10], cued 95% CI [0.05, 0.11]. A main effect of instance was observed when participants approached pedestrian targets such that participants improved their ability to maintain headway distance better in all later instances (Instance 1, *M* = 0.10, *SE* = 0.16; Instance 2, *M* = 0.06, *SE* = 0.16; Instance 3, *M* = 0.04, *SE* = 0.17). There was a main effect of SOP when participants approached pedestrians (slope = 0.018, *SE* = 0.014) such that participants with higher SOP composites maintained headway distance more precisely. There was also an interaction between SOP and cuing for headway variation when participants were approaching

TABLE 10: Estimated Slopes, Slope Comparisons, Standard Errors, and Comparison Results for SOP × Cuing[a] for Vehicle Headway Variation (HV)

Effect	Vehicle HV		
	Slope	*SE*	*p*
SOP	0.017	.013	.212
SOP × Cuing (cued)	0.002	.014	.867
SOP × Cuing (uncued)	0.031	.014	.036
SOP × Cuing (cued-uncued)	–0.029	.010	.006

Note. SOP = speed of processing.
[a]Effects of SOP, stratified by cuing, with pairwise comparisons of slopes across condition.

vehicles. Table 10 presents estimated slopes, slope comparisons, standard errors, and selected comparisons for this interaction. As SOP composites increased, participants had a harder time maintaining headway in the uncued scenarios (while approaching vehicles) relative to cued scenarios.

In summary, the most important results observed relating to the potential benefits of AR cuing included effects of cuing for detection of pedestrians and warning signs and an effect of cuing for response time (TCR) for warning signs. Concerning interference, there was no statistically significant effect of cuing, small confidence intervals, and similar mean values for both target and secondary objects on question response accuracy and no effect on headway variation. A Cuing × Instance interaction was observed on question response accuracy for target objects: Participants responded less accurately in cued conditions as instance number increased.

DISCUSSION

In this study, we investigated the potential costs and benefits of using AR cues to alert elderly drivers with varying SOP capacity to potential roadside hazards. AR cues improved participant response rates and response times relative to uncued conditions, as predicted. Importantly, the results showed limited evidence that AR cues interfered with performance. Those findings were not moderated by SOP capacity and thus generally held true for those with low and high SOP.

Outcomes Associated With Directing Attention

To the extent that response likelihood, accuracy, and response time to hazards contribute to crash likelihood, then improvement on these measures represents a benefit, and decreased performance represents a cost. We interpret response to potential in this experiment as hazards that have a potential safety consequence, and so the degree to which cuing enhances or degrades response to targets represents a safety benefit or cost. In this study, no main effect of AR cuing was observed for objects (vehicles) of high visibility. Vehicles were generally visible from a greater distance than pedestrian and warning sign targets because of their larger size and color contrast against the rural driving scene. Participants responded to 25% more pedestrians and 5% more warning signs in cued conditions than in uncued conditions, consistent with reports of Yeh and Wickens (2001) and Rusch et al. (in press) in which benefits of cueing were greatest for objects of low visibility.

In addition, AR cues improved participant response time (TCR) to warning signs. Participants responded to these targets 0.35 s faster in cued conditions than in uncued conditions. In this vein, early warnings have been observed to help drivers react more quickly, particularly compared with when no warning is given (Lee et al., 2002). A response initiated 0.35 s sooner could meaningfully reduce braking time, especially since age-related decrements to braking performance have been attributed to longer response times rather than poor response execution (Martin et al., 2010).

The observed benefits of AR cuing are also consistent with findings of Kramer et al. (2007). They showed that collision avoidance systems can effectively alert elderly drivers even when driving is affected by wind gusts or distractions, such as a number-reading task. This study showed benefits of AR cuing when task difficulty was increased with other driving-relevant demands, such as maintaining safe headway and identification of secondary objects.

Outcomes Associated With Interference

In this study, no evidence was observed that AR cues interfered with driver perception of secondary objects, even for participants with cognitive impairment. This finding is important as the goal of the AR cuing in this application was to aid the detection of critical objects, such as pedestrians, without adversely affecting perception of other potential hazards. However, since all drivers were familiarized with both target and secondary objects prior to driving, drivers may have become hypersensitive to the objects and more likely to identify the objects regardless of cue presence. Unexpected or unfamiliar secondary hazards may have led to a different result.

Few results suggest interference of AR cuing with perception of target objects. There was a lone effect (of a Cuing × Instance interaction on question response accuracy for target objects) in which participants responded less accurately in cued conditions with successive instances. However, the least square means of this effect showed that participants responded, on average, only less than half a question worse from beginning of the testing to the end when discriminating target objects. This difference may have reflected increasing emphasis on response rate and response time than on accuracy of perception of target objects.

Driving performance decrements, such as increased headway variation, is another potential adverse outcome of AR cuing. Participants' headway maintenance was not degraded in this study. In fact, as SOP composites increased (worsened), participants displayed superior headway maintenance in the cued scenarios relative to the uncued scenarios. Although it is possible that this effect was not present for those participants with the lowest (best) SOP composites because there may not have been substantial room for improvement, these effects suggest that AR aided rather than harmed elderly drivers with impairments in maintaining safer headway distance. These findings of AR cuing differ from those of in-vehicle displays, which have been reported to impair driver performance in closing headway situations (Lamble, Laakso, & Summala, 1999).

Limitations, Implications, and Future Research

This study showed similar effects of AR cuing in drivers with lower and higher SOP abilities. In three out of four outcome measures, the interaction effect between SOP and cuing was not significant. These findings may reflect a limited range on SOP abilities in this sample or small sample size. Also, benefits of AR cues for impaired elderly drivers may be specific to a subset of performance measures. In the future, researchers should investigate benefits of AR cuing in drivers with a range of SOP abilities as measured by various performance metrics.

System reliability has the potential to affect user trust (Bliss, 1997; Sorkin, 1988). Our AR system included FAs and misses to represent possible errors of a real-world application. The system had an overall reliability of at least 85% in all driving scenarios and was greater than the estimated 70% "crossover point" below which unreliable automation appears to be worse than no automation at all (Wickens & Dixon, 2007). Further research is needed to more accurately estimate this crossover point and to determine how AR system reliability and alert context (e.g., frequency or severity of the events being highlighted, familiarity with the system) affects user trust, performance, and resource allocation.

This study simulated an austere rural environment where benefits of AR cuing may be positively or negatively influenced by the low level of distraction inherent to the setting. For example, drivers may have been more likely to detect a hazard in the scenarios because of the small number of buildings and oncoming vehicles present. Other driving environments with more commotion, such as an urban scene, may contain many driving hazards that accentuate the benefits of AR cuing. However, such a setting may also make deployment of AR cues unsafe, as a driver may place too much attention on the warning stimuli. Researchers should assess a multitude of contexts for deploying AR cues in response to expected and unexpected hazards in simulated and real-world settings. In addition, further research should be conducted to investigate the feasibility of implementing AR cues into real-world motor vehicles. Studies are also needed to determine whether AR cuing may assist other at-risk drivers, such as younger, inexperienced drivers whose neglect of hazards places them at risk (Pollatsek, Fisher, & Pradhan, 2006; Pradhan et al., 2005).

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KEY POINTS

- Augmented reality (AR) cuing aided in the detection of targets of low visibility (e.g., pedestrians, warning signs).
- Response times improved for targets of low visibility (e.g., warning signs) with cuing.
- AR cuing did not impair discrimination of secondary objects.
- AR cuing did not impair driver ability to maintain consistent distance behind a lead vehicle.

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Mark C. Schall Jr. is a PhD student in the Mechanical and Industrial Engineering Department at the University of Iowa. He received his MS in industrial engineering from the University of Iowa in 2011.

Michelle L. Rusch is a postdoctoral fellow in the Departments of Neurology and Mechanical and Industrial Engineering at the University of Iowa. She received her PhD in human computer interaction from Iowa State University in 2008.

John D. Lee is a professor of industrial and systems engineering and the director of the Cognitive Systems Laboratory at the University of Wisconsin–Madison. He received his PhD in mechanical engineering in 1992 from the University of Illinois at Urbana-Champaign.

Jeffrey D. Dawson is a professor, the associate dean for faculty affairs, and the director of graduate studies in the Department of Biostatistics at the University of Iowa. He received his ScD in biostatistics from Harvard University in 1991.

Geb Thomas is an associate professor of industrial engineering and the director of the Graphical Representation of Knowledge Laboratory at the University of Iowa. He received his PhD in industrial engineering in 1996 from Pennsylvania State University.

Nazan Aksan is a research scientist in the department of neurology at the University of Iowa. She received her PhD in psychology from the University of Wisconsin–Madison in 2001.

Matthew Rizzo is a professor of neurology, engineering, and public policy at the University of Iowa, where he directs the Division of Neuroergonomics. He received his MD in 1979 from Johns Hopkins University School of Medicine.

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