

Cross-modal warnings for orienting attention in older drivers with and without attention impairments

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ABSTRACT

Older adults are overrepresented in fatal crashes on a per-mile basis. Those with useful field of view (UFOV) reductions show a particularly elevated crash risk that might be mitigated with vehicle-based warnings. To evaluate cross-modal cues that could be used in these warnings, we applied a variation of Posner's orienting of attention paradigm. Twenty-nine older drivers with UFOV impairments and 32 older drivers without impairments participated. Cues were presented in either a single modality or a combination of modalities (visual, auditory, haptic). Drivers experienced three cue types (valid spatial information, invalid spatial information, neutral) and an uncued baseline. Following each cue, drivers discriminated the direction of a target (a Landolt square with a gap facing up or down) in the visual panorama. Drivers with and without UFOV impairments showed comparable response times (RTs) across the different cue modalities and cue types. Both groups benefited most from auditory and auditory/haptic cues. Redundant visual cues, when paired with auditory cues, undermined performance rather than enhanced it. Overall, drivers responded faster to targets with valid spatial information followed by neutral, invalid, and uncued targets. Cues provide the greatest benefit in alerting rather than orienting the driver. The cue expected to be most effective at orienting attention – the extra-vehicular cue – performs most poorly when the spatial information is either invalid or neutral. Even when the spatial information is valid the extra-vehicular cue underperforms the auditory cues. The results suggest that temporal information dominates spatial information in the ability of cues to speed responses to targets. This study represents a first step in assessing whether combining a cognitive science paradigm and a driving simulator environment can quickly assess how different warning signals alert and orient drivers.

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1. Introduction

Older drivers are overrepresented in fatal traffic crashes on a per-mile basis (Bedard et al., 2002). The proportion of crashes involving older drivers is likely to increase due to demographic shifts including increases in the proportion and annual mileage of older drivers (Lyman et al., 2002; McGwin and Brown, 1999). For example, one estimate suggests that by 2030, fatal crashes for drivers over the age of 65 may increase 155% and account for 25% of all fatal crashes (Lyman et al., 2002).

Several studies have demonstrated an increased crash risk in drivers with age-related reductions in the useful field of view (UFOV) (Ball and Owsley, 1991; Goode et al., 1998; Myers et al., 2000; Owsley et al., 1991). The UFOV, an attention-related construct, represents the area from which visual information can be extracted during a single glance without making eye or head movements (Sanders, 1970). The measure incorporates visual sensory function, processing speed, divided attention, and selective attention (Ball and Owsley, 1993). UFOV reductions associated with age may co-occur with other impairments in vision, cognition, attention and memory. For example, UFOV may be sensitive to cognitive decline associated with mild cognitive impairment or Alzheimer's disease (Petersen, 2004; Rizzo et al., 2001).

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Although some have argued that UFOV impairments reflect a constriction in the field of view (Ball and Owsley, 1993), others have suggested alternative explanations or underlying features. For example, one study found that UFOV starts to deteriorate as early as age 20 and reflects deficits in the ability to extract information from complex or cluttered scenes (Sekuler et al., 2000). Recent work suggests that UFOV may also reflect an inability to disengage attention from a previously attended location (Cosman, et al., Submitted). Although the mechanisms related to UFOV are under investigation, it appears that UFOV provides a useful tool for identifying at risk drivers. For example, UFOV scores have been used to predict driving performance outcomes derived from state crash records, on-road driving tests, and driving simulators (Ball and Owsley, 1993; Goode et al., 1998; Myers et al., 2000; Roenker et al., 2003).

Automobile drivers must rapidly shift their attention to multiple locations to monitor hazards and to extract specific information (e.g., a vehicle merging). Two recent studies have examined hazard perception ability, the ability to recognize and anticipate hazardous roadway situations, in drivers 65 years and older (Horswill et al., 2008, 2009). Drivers aged 75 and older were 560 ms slower in identifying hazards compared to middle-aged drivers and 400 ms slower compared to older drivers aged 65–74 (Horswill et al., 2009). Reduced contrast sensitivity, UFOV loss, and simple reaction time (RT) increases accounted for the age differences in hazard perception response times and accounted for 29.5% of the variance in hazard perception response times in drivers ages 65 years old and older (Horswill et al., 2008). These studies suggest that older drivers with attention impairments may be less efficient in identifying hazardous situations. Such decrements likely contribute to the increased crash risk of these drivers.

Collision warning systems might mitigate these attention impairments and represent a means to aid all older drivers in identifying and responding to hazards (J. D. Lee, 2009). Such systems issue a warning signal (e.g., flashing lights, auditory tone, feedback from the accelerator, seat vibrations) when some threshold is exceeded. Several simulator and on-road studies suggest that such systems can produce several potential benefits, such as reducing RTs to hazardous situations (Ho and Spence, 2005; Kramer et al., 2007; J. D. Lee et al., 2002; Scott and Gray, 2008), reducing collision involvement (Kramer et al., 2007; J. D. Lee et al., 2002), and increasing following distance (Dingus et al., 1997; Ho et al., 2006).

Older drivers, particularly those with age-related declines in UFOV, may derive similar benefits from such systems. A recent study found that auditory/visual warnings reduced RTs and collisions during forward and side object collision situations and that older drivers derived similar benefits from in-vehicle technology as other age groups (Kramer et al., 2007). Very few other studies have examined how such systems might benefit older drivers, and none that we are aware of have considered drivers with diminished UFOV. The benefits would be substantial, if older drivers with attention impairments derive similar benefits from these systems as drivers who demonstrate delays in identifying and responding to hazards caused by distraction. For example, Lee et al. (2002) found that alerts benefit drivers by reducing the time delay associated with distraction by 0.11 s–0.86 s depending on the thresholds used to trigger the warning.

The precise mechanism governing the benefit of collision warnings is unclear, but the benefit seems to accrue from redirecting attention, rather than speeding the braking response (J. D. Lee et al., 2002). A warning might redirect attention by either alerting drivers or orienting their attention to the threat. The distinction between the alerting and orienting effects of a warning are grounded in the fundamental mechanisms governing attention and correspond to different functional networks in the brain.

Alerting corresponds to the arousal systems and orienting corresponds to data processing centers in the ventral occipital region (Posner and Petersen, 1990). The current study considers how warnings redirect attention by alerting or orienting drivers, and how this effect depends on the warning signal modality.

Collision warnings can be presented in a single modality or in combinations of modalities; the question is which implementations are most effective and if this effectiveness is different for drivers with diminished UFOV. Warnings presented using multiple sensory modalities facilitate hazard detection by directing attention to regions of extrapersonal space during simulated driving (Ho et al., 2007; Ho et al., 2006; Kramer et al., 2007; Spence and Ho, 2008). Haptic cues presented alone and in combination with an auditory cue may be particularly beneficial in reducing RTs (Ho et al., 2007; Ho et al., 2005; Ho et al., 2006; Scott and Gray, 2008; Sklar and Sarter, 1999; Spence and Ho, 2008). The auditory modality might also have a particularly strong influence on attention. Discrete auditory cues tend to preempt continuous visual tasks, but discrete visual cues do not (Wickens and Liu, 1988). Auditory preemption could make auditory cues more effective in alerting drivers than visual cues.

Scott and Gray (2008) examined how auditory, visual, and tactile warnings influenced driver responses to rear-end collision situations using two time-to-collision thresholds. Although the presence of a collision warning system did not reduce collision involvement, response times were faster when drivers received auditory and tactile warnings compared to the no warning condition. In the early warning condition, tactile warnings induced drivers to respond 139 ms faster compared to the no warning condition. Auditory warnings reduced response times by 133 ms compared to the no warning condition, visual warnings did not produce a statistically significant effect. Spence and Ho (2008) demonstrated the benefits of warnings relative to a baseline no warning condition: haptic (32.7% reduction), auditory (44.1% reduction) and auditory/haptic (52.2% reduction). In contrast, visual cues can sometimes be effective in orienting attention, but can be difficult to ignore if they convey invalid spatial information (Jones et al., 2008). Overall, these studies suggest that warning modality and combinations of modalities may have a powerful effect on the effectiveness of collision warning systems, with a combination of auditory and haptic cues often being most effective (Ngo and Spence, 2010; Spence, 2010).

To assess the relative benefits of different warning cues in older drivers with and without attention impairments, the current study applied a well-studied cognitive science paradigm. Specifically, we used a variation of Posner (1980) attentional cuing paradigm to assess the ability of unimodal and multimodal attentional cues presented within and outside a test vehicle platform to direct driver attention to targets occurring in the external environment. The attentional cuing paradigm provides a straightforward measure of both the efficiency of alerting and orienting. Importantly, we use a variety of cueing conditions to assess their specific effects. The cues could be directional and direct attention to a particular location (e.g., the left side of the car/external scene), or the cues could be nondirectional and provide temporal information that alerts a driver to an upcoming target. Directional cues could influence allocation of attention in space – orienting the driver's attention; whereas nondirectional cues influence the overall alertness (e.g., Posner and Petersen, 1990) or preparatory state – alerting the driver. Relatively little research has investigated the efficacy of the various cue conditions or cue modalities, and whether these cueing effects depend on drivers' UFOV status.

To address this gap, the current study employed Posner's cueing paradigm to assess the relative benefits of different attentional cues in older drivers with and without attention impairments. Based on the literature the following hypotheses were tested:

- Auditory and haptic cues will produce faster RTs than visual cues, and the combination of cues (auditory/haptic) will produce the fastest RTs.
- Valid cues will produce the fastest RTs, followed by neutral cues, and then invalid cues.
- The benefit of valid cues will be greatest for cues that correspond to the same spatial area as the targets – extra-vehicular cues.
- Older drivers with diminished UFOV will have longer uncued RTs and will benefit more from valid cues than older drivers without impairments.

2. Methods

2.1. Participant selection

UFOV screening, conducted using the Visual Attention Analyzer (Model 3000, Vision Resources, Chicago, IL, [Ball and Owsley, 1993](#)), was used to identify participants with attentional impairments. The Visual Attention Analyzer administers four subtests and performance on each subtest is expressed as the display duration (ms) required for the participant to attain 75% response accuracy. Subtest 1 (processing speed) measures how fast participants perform a two-alternative forced choice task presented in central fixation. Subtest 2 (divided attention) measures how fast participants concurrently identify central and peripheral targets. Subtest 3 (selective attention) resembles subtest 2 but distracters surround the peripheral target. Subtest 4 is similar to subtest 3 but in this case the central task requires a same/different discrimination. Performance on subtests 3 and 4 were used to identify UFOV impaired participants. Participants with a score of greater or equal to 350 on subtest 3 or 500 on subtest 4 were classified as having UFOV impairments. This criterion corresponds to cutoffs previously used ([Edwards et al., 2005](#)) that had a sensitivity of 89% and specificity of 81% for predicting crash involvement ([Ball and Owsley, 1993](#)). One study found that older drivers who failed the UFOV test had approximately 4.2 times more crashes and 15.6 times more intersection crashes than drivers who passed ([Owsley et al., 1991](#)).

2.2. Participants

Thirty-one males and 30 females between the ages of 60 and 85 ($M = 74.5$, $SD = 5.5$) participated in the study. Participants were recruited from the Iowa City and Coralville area through newspaper ads, flyers and screening sessions. Twenty-nine participants had UFOV impairments (66–85, $M = 76.6$) and 32 participants did not (62–85, $M = 72.8$). All participants had an active driver's license, had normal to corrected normal vision of at least 20/40, and did not meet the criteria for dementia (Mini Mental State Examination (MMSE) score > 25). Compensation was provided to participants.

There was no significant difference between groups with respect to education level ($p = 0.563$) and near visual acuity ($p = 0.284$). However, there was a significant difference between the two groups with respect to age, contrast sensitivity, and far visual acuity. Specifically, older drivers with UFOV impairments were older ($p = 0.005$), had worse far visual acuity (0.176 vs. 0.102, $p = 0.032$), and lower contrast sensitivity scores (1.49 vs. 1.61; $p = 0.021$).

2.3. Materials

This study was conducted using the Simulator for Interdisciplinary Research in Ergonomics and Neuroscience (SIREN). An Intel® Pentium® D processor-based PC was used to run the Posner task software. Stimuli were projected on a large screen with 50°

forward field of view located in front of a 1994 GM Saturn simulator cab (see [Fig. 1](#)). The Posner task interfaced with equipment in the vehicle used to present warnings and the visual targets were presented on the screen in front of the vehicle. Two Monsoon flat panel speakers (21.59 cm × 11.43 cm), mounted on the far left and right of the vehicle dashboard and positioned upward, presented auditory warnings. Sound level measurements were taken from the position of the driver. The location of the speakers within the vehicle caused the left speaker (which was closer to the driver) to be louder than the right speaker and as such provided drivers with spatial information. Specifically, auditory warnings from the left, right and both speakers were presented at 83 dBA, 74 dBA, and 83 dBA. Tactile warnings were presented using tactors embedded in the driver's seat, which was developed by InSeat Solutions, LLC. Responses were made and recorded with two vertical 'push' buttons (labeled UP and DOWN) encapsulated in a small box the participant held during the experiment. The Posner task program recorded cue parameters, RTs, and accuracy for each trial completed.

2.4. Task overview

The experiment used an adaptation of the [Posner \(1980\)](#) attention of orienting paradigm because it provides a precise measure of cueing effects on attention. The participants' task was to localize and discriminate the direction of the target (a Landolt square with a gap facing up or down) presented on a large screen in front of the vehicle approximately 244 cm from the observer. [Fig. 2](#) shows the sequence of events that occurred during each trial. The fixation point, 3 cm in diameter (visual angle of 0.7°), was presented for 1000 ms prior to the onset of the attentional cue and remained visible throughout the trial. After the cue, the target that was 25 cm × 25 cm (visual angle of 5.8° × 5.8°) with a 12.5 cm gap (visual angle of 2.8°) was presented until the participant made a button response. The outcome measures were RT and accuracy.

2.5. Cue type

This study examined the influence of three different types of cues (valid, invalid, neutral) on attention to regions of extrapersonal space, compared to an uncued baseline condition. "Valid" cues correctly indicated the target location and so provided both spatial and temporal information regarding target presentation. "Invalid" cues misled the participant by indicating the location opposite the actual target location. These cues provide valid temporal information regarding the presentation of the target, but invalid spatial information. "Neutral" cues simultaneously indicated both potential locations prior to target presentation and provided valid temporal but no spatial information. In the uncued condition, no cue was presented, providing a baseline measure of RTs to the target.

2.6. Cue modality

This study examined the ability of eight different cue combinations to direct attention: unimodal extra-vehicular (visual), unimodal in-vehicle (auditory, haptic, or visual) and multimodal cues that combined the in-vehicle unimodal cues (haptic/visual, auditory/visual, auditory/haptic, or auditory/haptic/visual). Cues were presented in the driving simulator cab or on the same screen as the extra-vehicular target (unimodal extra-vehicular). Initial testing was conducted to identify the cue parameters used in this study. The parameters used in this study had the best spatial resolution and resulted in the shortest RTs in a series of pilot tests. Each of the following cues was presented for 200 ms prior to target onset:



Fig. 1. Participants sat in the driver's seat of the SIREN simulator (top left) and viewed targets (bottom left) and either extra-vehicular cues presented on the center screen (bottom right) or in-vehicular cues. The top right image shows the implementation of the LEDs for the in-vehicle visual cues and the flat speakers for the auditory cues placed inside the vehicle cab.

- *Unimodal extra-vehicular visual cue* (Fig. 1 bottom right): were red circles presented in extrapersonal space (in the environment isodirectional and coplanar with the potential targets).
- *Unimodal in-vehicular visual cue* (bottom left and right of Fig. 1): were presented within peripersonal space (approximately three feet from the seatback). The display only used the outer left and right light emitting diodes (LEDs) in a display consisting of 12 LEDs placed on the dashboard in front of the windshield. These two LEDs illuminated in red and were in line with the possible target locations.
- *Unimodal in-vehicular auditory cue*: used an abstract auditory alarm presented through the left and/or right speakers of the vehicle (J. D. Lee et al., 2002; Tan and Lerner, 1995). To be consistent with the other cue modalities the auditory cue was shortened from 2.25 s to 200 ms. The peak frequency was 2496 Hz. It should be noted that there was no significant difference between groups with respect to hearing at this range (the average of 2000 and 3000 Hz) for the left ear (mean of 27.7 for impaired group and 33.9 for the unimpaired group; $p = 0.314$) or right ear (25.9 vs. 30.8; $p = 0.365$).
- *Unimodal in-vehicular haptic cue*: used two factors in the back of the seat pan, one on the left and one on the right. The amplitude was 58 dB for the first 80 ms and then increased to 79 dB for the remaining 120 ms.
- *Multimodal in-vehicular cues*: consisted of a combination of unimodal cues. Specifically, this experiment examined the following combination of in-vehicle cues: haptic/visual, auditory/visual, auditory/haptic, or auditory/haptic/visual.

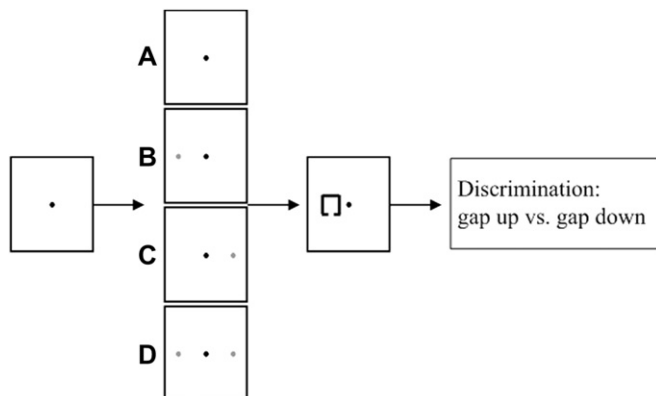


Fig. 2. Overview of the sequence of events drivers were exposed to on each trial. This particular diagram illustrates the onscreen cueing condition. The black fixation point was presented to drivers 1000 ms prior to the cue onset. Four cueing conditions were possible, a) no cue, b) valid cue, c) invalid cue, d) neutral cue. Subsequently a target Landolt C was presented to the left or right of fixation with a gap facing up or down. Each trial was terminated when the driver made a discrimination using a button press.

3. Procedure

Participants completed eight blocks of 214 trials. Each block corresponded to one of the eight cue modalities: extra-vehicular visual, visual, auditory, haptic, haptic/visual, auditory/visual, auditory/haptic, or auditory/haptic/visual. The first 22 trials of each block were practice trials and the remaining 192 trials were experimental trials. Practice trials were not included in the analysis. During each block of experimental trials 50.0% percent (96) of the cues were valid and 16.7% (32) of the cues were invalid, neutral, or uncued. For each of these cue types the trials were balanced so that half the targets appeared on the left and half on the right. The trials were also balanced so that half had a target with the gap facing up and half had the gap facing down. The presentation of the eight blocks was divided into two sets (counterbalanced using a Latin Square), one for unimodal cues and one for multimodal cues. Half the participants started the session with unimodal cues, and half started with multimodal cues. Eight different pre-defined trial orders, generated by random assignment of trials, were used to avoid order effects.

Each participant sat in the driver's seat of the simulator and made seat and steering wheel adjustments so that the LED display was visible. A research assistant explained the task using an instruction sheet. Participants were asked to focus on the fixation point throughout the task. Because we were interested in the ability of the cues to capture attention in a stimulus-driven manner, we stressed that the cues would not be predictive of the target location and that they could be ignored. Participants were informed that the target of interest was a square with a gap at either the top or bottom (the Landolt square) and their objective was to indicate the location of that gap using a box with two buttons positioned vertically, and labeled UP and DOWN. Participants were encouraged to respond as quickly and accurately as possible.

4. Experimental design

The experiment was a $2 \times 8 \times 4$ mixed design: Population (between-subjects: UFOV impaired, UFOV unimpaired), Modality (extra-vehicular visual, visual, auditory, haptic, haptic/visual, auditory/visual, auditory/haptic, or auditory/haptic/visual), and Cue Type (valid, invalid, neutral, uncued). Cue Type and Modality were within-subject variables.

5. Data analysis

The outcomes of interest were accuracy and response time (RT). RT is defined as the elapsed time between the presentation of the target and the participants' discrimination response. The RT data was initially filtered to 1) retain only correct trials, and 2) remove trials with RTs greater than 2500 ms and trials with RTs greater than 2.5 SD above the mean. This filtering eliminated less than 1% of trials. To further reduce the effect of outliers, we based our reaction time analyses on the median RTs for the trials from each modality and cue type combination within-subject, resulting in a total of 1952 ($61 \times 8 \times 4$) data points. Accuracy was calculated as the percent correct for each person within each of the same 32 experimental settings as the RT data.

The median RTs and accuracy were analyzed in a fully mixed-effect model using the PROC GLM procedure in SAS version 9.1 (SAS Institute Inc., Cary, NC, USA). Fixed effects (Population, Cue Type, and Modality) and their interactions were tested using the mean squares from the appropriate random factor or mixed-effect interaction term. The RT summary data presented are therefore means of medians. Original and logarithmically transformed (not shown) data were analyzed and found to give similar results. Adjusting for age, far visual acuity, and contrast sensitivity did not change the significance of results; therefore, only unadjusted results are presented. Tukey's method was used to make comparisons among the eight modalities within each cue type.

6. Results

Drivers accurately identified the direction of the Landolt square gap in over 90% of the trials. However, accuracy was influenced by cue type, $F(3,177) = 22.26$, $p < 0.0001$. Post-hoc comparisons indicate that accuracy did not differ for valid (94.6%), neutral (94.08%) and uncued (94.3%) trials. Accuracy for all three of these cue types was higher than accuracy for invalid trials (92.9%, $p < 0.001$ in all cases). No other main effects or interaction for accuracy was statistically significant. Invalid cues, regardless of the modality, diminish accuracy in both impaired and unimpaired drivers to such a degree that drivers perform more accurately when no cue is presented.

Figure 3 shows the estimated means for RT and standard errors for each driver population, cue modality, and cue type. Despite the

apparent difference between the UFOV impaired drivers and the unimpaired drivers in Fig. 3, the mean RTs were quite similar: 628.5 ms for unimpaired and 647.0 ms for the impaired drivers, $F < 1$, $p = 0.357$). Population did not interact with cue type ($F < 1$, $p = 0.489$), nor modality, $F(7,413) = 1.02$, $p = 0.417$). Although the failure to reject the null hypothesis does not imply that the means of the groups are equal or even that they are similar, the error bars in Fig. 3 show that statistical tests had the power to identify practically meaningful differences. The standard error of the means in Fig. 3 is approximately 31 ms, with a corresponding 95% confidence interval of approximately 64 ms, suggesting that the effects of most cue type and modality were quite similar for both groups.

To assess the sensitivity of these comparisons, the data from all modalities on all cued trials estimated the mean reaction time to be 20.1 faster for the unimpaired group ($p = 0.298$). A variance component analysis showed that the total variance for between group analyses was 6211 (i.e., a standard deviation deviation of 78.8). Hence, the estimated effect size of UFOV impaired compared to unimpaired was $20.1/78.8 = 0.26$. Based on our sample size of 61 participants, we would have the following power for detecting effects of 20, 30, 40, 50, 60, and 70 ms: (16%, 31%, 50%, 68%, 83%, and 93%). Hence, if the actual difference between the two groups had been 60 ms or more (i.e., an effect size of $60/78.8 = 0.76$), there was sufficient (>80%) power to detect it.

There were significant main effects of cue type ($F(3,177) = 152.64$, $p < 0.0001$) and modality ($F(7,413) = 6.85$, $p < 0.0001$), and there was a significant interaction between these two factors, $F(21,1239) = 12.26$, $p < 0.0001$. Fig. 3 shows temporal information had a strong effect on RTs. Drivers responded fastest to valid cues ($M = 606$ ms), followed by neutral ($M = 626$ ms), invalid cues ($M = 651$), and uncued trials ($M = 668$ ms). Neutral cues conveyed temporal information and reduced RTs by 42 ms relative to uncued trials. Valid cues were more effective at reducing RTs, a reduction of 62 ms as compared to no cues, but the benefit of the spatial information conveyed by valid cues was only 20 ms relative to the neutral cues. Even invalid cues were 17 ms faster than uncued trials, but were 26 ms slower than neutral cues.

Tables 1–3 summarize the post-hoc comparisons across valid, neutral, and invalid cue types. The effect size for the pair-wise comparisons can be estimated by the difference of the respective means divided by the square root of the MSE from the statistical model (28.0). In Table 1, the effect size for the difference between visual and visual/haptic is $(625.1 - 618.0)/28 = 0.25$. To conserve space the effect size of the 28 pair-wise conditions in each table is not shown.

Table 1 shows that for valid cues the visual, haptic/visual, extra-vehicular visual, and haptic modalities perform relatively poorly and were not significantly different than each other, because the Tukey grouping code of "A" spans all of their means. The haptic, auditory/haptic/visual, auditory/visual, and auditory/haptic modalities form another group ("B") of means that were not significantly different. The modalities that produced the shortest RTs included auditory/haptic/visual, auditory/visual, auditory/haptic, and auditory modalities ("C"). These comparisons show that for valid cues those with an auditory component produce the shortest RTs and that adding other cues to the auditory cue, such as a redundant visual or haptic cue provides no benefit.

There are some interesting similarities and differences across Tables 1–3. Most notably, the auditory and auditory/haptic cues were robust, performing better than the other modalities across valid, invalid, and neutral cues. For all three cue types, the auditory/haptic and auditory modalities had shorter RTs than the visual, haptic/visual, and extra-vehicular visual modalities ($p < 0.05$ in all cases). Considering performance across the three cue types, multimodal cues were most beneficial when they included an auditory component. The only exception was the haptic/visual

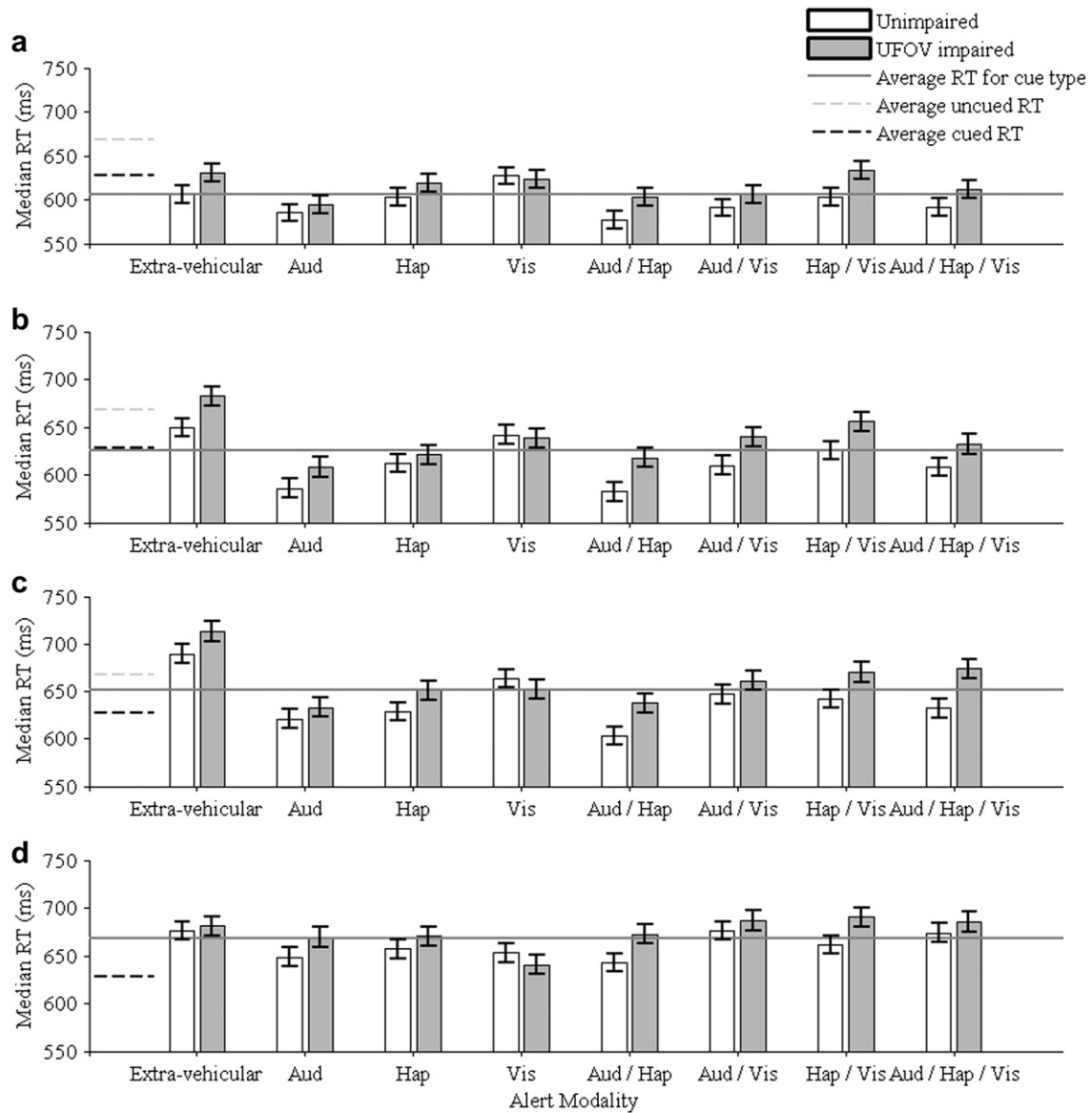


Fig. 3. Estimated means and SE intervals for RT for each cue type, modality, and population: a) valid cues, b) neutral cues, c) invalid cues, and d) no cues. Solid black lines represent the average RT (ms) for the cue type. Black solid lines represent the average RT for cue type (valid, neutral, invalid, uncued) across the different cue modalities. Black dashed lines represent the average uncued RT (ms), and the gray dashed line represents average cued RT (ms) across valid, invalid and neutral trials.

modality in invalid trials, which did not differ significantly from the auditory/visual or auditory/haptic/visual modalities. Cues that include an auditory component provide a consistent benefit whether the cue was valid, invalid, or neutral.

In contrast, the effect of the extra-vehicular cue was not consistent, performing particularly poorly with neutral or invalid cues. Comparing visual vs. extra-vehicular visual modalities, no significant difference was found for valid cues, but the extra-vehicular cues led to longer RTs when paired with neutral or invalid cues (Tables 2 and 3). Table 3 shows that invalid spatial information conveyed by cues that include the visual modality produced the longest RTs. These results suggest that auditory cues do not benefit from the addition of redundant modes and that adding a redundant visual cue led to longer RTs, particularly when it failed to convey valid spatial information.

As with the comparison of UFOV drivers, the failure to reject the null hypothesis does not imply that the means of the groups are equal or even that they are similar; however, the error bars in Fig. 3

show the statistical tests had the power to identify practically meaningful differences.

As expected, there were no statistically significant differences among modalities for uncued trials. To assess whether the inclusion of these uncued trials were the primary cause of the significance of

Table 1
Summary of pair-wise comparisons among modality for RTs on validly cued trials. Means with the same letter were not significantly different.

Modality	Mean median RT (ms)	Tukey grouping
Visual	625.1	A
Visual/Haptic	618.0	A
Extra-Vehicular Visual	617.9	A
Haptic	611.3	A
Visual/Haptic/Auditory	601.6	B
Visual/Auditory	598.2	B
Haptic/Auditory	589.8	C
Auditory	589.7	C

Table 2

Summary of pair-wise comparisons among modality for RTs on neutrally cued trials. Means with the same letter were not significantly different.

Modality	Mean median RT (ms)	Tukey grouping
Extra-Vehicular Visual	665.7	A
Visual/Haptic	640.6	B
Visual	640.2	B
Visual/Auditory	624.8	C
Visual/Haptic/Auditory	620.0	C
Haptic	616.5	C
Haptic/Auditory	599.9	D
Auditory	597.0	D

the cue type by modality interaction, we refit the mixed model using only the median RTs for the cued trials ($n = 1464 = 61 \times 8 \times 3$). In the resulting model, there was still a significant interaction between cue type and modality, $F(14, 826) = 8.67, p < 0.0001$. Hence, there is strong statistical evidence that the modality effects vary across cue types, as seen in Tables 1–3. Because Auditory and Auditory/Haptic cues performed the best for the cued trials, the analyses were repeated to assess the effect of UFOV within just those trials. Similar to the broader analyses there was still no effect of UFOV (mean reaction time of 23.3 ms faster for unimpaired group; $p = 0.173$). There was also no evidence of an interaction between UFOV status and modality ($p = 0.259$), nor between UFOV status and cue type ($p = 0.179$). Hence, even under optimal conditions, we saw no effect of UFOV status, nor any interaction involving UFOV status.

7. Discussion

Collision warning technology represents a promising means to reduce crashes, injuries, and fatalities in older drivers (Kramer et al., 2007). Effective warnings might either alert or orient drivers' attention and elicit an appropriate and timely response. Very few studies have examined the benefit of warnings for older drivers, and none that we are aware of have considered older drivers with attention impairments. This study considered the alerting and orienting effect of eight different cue modality combinations for older drivers with and without UFOV impairment.

Contrary to our hypothesis, drivers with attention impairments showed RTs across the different cue types and modalities that were comparable to drivers without impairment. These findings resemble those of Kramer et al. (2007), who found that the efficacy of multimodal cues was similar for younger and older adults. Together, these results suggest that multimodal cues provide an effective means of orienting attention to critical events for drivers, including older drivers with attention impairments.

7.1. Drivers benefit most from auditory and auditory/haptic cues

Several studies have demonstrated the benefits of deploying auditory and auditory/haptic cues to warn drivers of hazards

Table 3

Summary of pair-wise comparisons among modality for RTs on invalidly cued trials. Means with the same letter were not significantly different.

Modality	Mean median RT (ms)	Tukey grouping
Extra-Vehicular Visual	701.4	A
Visual	658.0	B
Visual/Haptic	655.8	B
Visual/Auditory	653.9	B
Visual/Haptic/Auditory	653.0	B C
Haptic	639.8	C D
Auditory	626.9	D E
Haptic/Auditory	620.4	E

arising in complex driving environments (Ho et al., 2007; Ho et al., 2005, 2006; Scott and Gray, 2008; Sklar and Sarter, 1999; Spence and Ho, 2008). This study also found that auditory or auditory/haptic cue modalities provided the greatest RT benefits for older drivers, regardless of UFOV status. Compared to the average RT on uncued trials ($M = 667$ ms), drivers responded between 43 ms (visual cues) to 78 ms (auditory and auditory/haptic cues) faster when provided with a valid cue (RTs for each modality for valid cues are presented in Table 1). This benefit is similar to the benefits observed in the Kramer et al. (2007) study for auditory warnings, but only half of that observed by Scott and Gray (2008)—possibly due to differences in the experimental setup, evaluation method, specific detection task, and warning algorithm.

In this study, auditory cues and multimodal cues with an auditory component were more efficient at speeding responses than warnings without an auditory component. The demonstrated benefits of using auditory/haptic cues in this and other studies (Ho et al., 2007; Scott and Gray, 2008) suggests that drivers benefit from the redundancy of multimodal cues (Ho et al., 2007; Ho et al., 2006; Kramer et al., 2007; Spence and Ho, 2008). In contrast, the visual cues were less effective and when paired with auditory cues undermined the benefit of auditory cues. These results are consistent with the finding that discrete auditory cues tend to preempt continuous visual tasks, but discrete visual cues do not (Wickens and Liu, 1988). In the context of rear-end collisions, distraction associated with looking away from the road often contributes to the crash and so auditory or haptic warnings that do not depend on the direction of the drivers' gaze might be particularly effective (Scott and Gray, 2008). The superiority of the auditory cues is also consistent with research demonstrating that auditory cues are more effective in alerting attention compared to visual cues, and that combining visual and auditory cues can undermine the benefit of the auditory cue (Fernandez-Duque and Posner, 1997).

The poor performance extra-vehicular cues is particularly notable. These cues were expected to orient drivers' attention more effectively than those cues that did not share the same spatial location as the target. Not only did these cues underperform the other cue modalities when the cues contained valid spatial information, they performed particularly poorly with neutral or invalid spatial information. Visual cues, particularly those superimposed on the visual scene, may be hard to ignore (Ngo and Spence, 2010). Furthermore, the orienting effect of visual cues may operate over a longer time course, making them effective for events in which drivers have several seconds to respond—the visual alerting effect takes over 400 ms to develop (Fernandez-Duque and Posner, 1997). These results suggest that information superimposed on the driving scene (e.g., head up displays) may not benefit older drivers in time-critical situations, especially in more complex, realistic environments where spatial information might be inaccurate. Visual information superimposed on the driving scene might be more useful when such information functions less as a warning and more as an information source that the driver interprets and integrates with other information, such as with navigation information.

7.2. Temporal information provides the greatest benefit to drivers

Although our task did not allow for a purely spatial cue (because all spatial precues also convey temporal information), our data indicates that spatial information can either improve or degrade the effect of the temporal information. Both groups (UFOV impaired and unimpaired) benefited most when the cues combined valid spatial and temporal information. As hypothesized, the descending order of benefit was valid, neutral, invalid, and uncued suggesting the possibility that spatial information provides relatively little

value beyond the temporal information in reducing RTs. Drivers maintained a high level of accuracy (>90%) across the different cue types, but invalid cues did lead to slightly lower accuracy than the valid or neutral cues. These results are consistent with the finding that a master (general temporal) warning provided the greatest RT benefit to drivers and that warnings with spatial information provided relatively little additional RT benefit (Cummings et al., 2007).

These findings have two primary implications for RT benefits for both attention impaired and unimpaired drivers: 1) providing drivers with no spatial information may be better than providing inaccurate spatial information and 2) providing inaccurate spatial information may be better than not cueing the driver, at least under low load conditions such as those used in our task. Invalid spatial cues may degrade performance because the driver may need additional time to reorient his or her attention to the correct location. Future research should incorporate more variable warning timings to examine the relative benefit of spatial versus temporal information more thoroughly. The accumulated effect of invalid warnings should also be considered because drivers' attitudes could dominate drivers' responses to unreliable warning systems (Bliss and Acton, 2003; Lees and Lee, 2007).

7.3. Cognitive science paradigms might help evaluate vehicle warnings

This paper used a well-established cognitive science paradigm to assess the ability of unimodal and multimodal warnings to orient attention in older adults with and without UFOV impairments. Posner's attentional orienting paradigm assesses basic attentional mechanisms associated with drivers' initial response to warnings: alerting and orienting. It offers a standard method to evaluate how different warning parameters influence these basic attentional processes. Compared to other types of methods of evaluation (e.g., simulator, on-road evaluation), using cognitive science tasks may offer increased controllability, precision, and efficiency. An important issue for future consideration concerns the degree to which the results from these paradigms generalize to actual driving situations (Lees et al., 2010).

Research suggests that cross-modal cueing depends in part on the complexity of the environment (Y. C. Lee et al., 2007). For example, one study examined links between visual, auditory, and tactile cues and targets in a complex battlefield environment and found that cueing effects depend upon the cross-modal pairings (Ferris and Sarter, 2008). For auditory cues, ipsilateral cues enhanced visual target detection. Contrary to our results, for haptic cues, only contralateral cues enhanced target detection. Future research is needed to examine how spatial cues alert and orient older drivers in more complex driving environments with a greater degree of contextual information. Although this study found similar benefits for older drivers with and without UFOV, future research should also assess whether auditory/haptic warnings aid these driver populations to the same degree in more complex driving settings, such as part-task simulators, driving simulators, and instrumented vehicles.

The simplicity of the Posner paradigm may limit the ability of the results to generalize to more complex driving situations (Lees et al., 2010). Of particular interest is the apparent dominance of temporal information in reducing RTs. The validity of this conclusion depends on how representative the temporal and spatial uncertainty in the current experiment is relative to the uncertainty resolved by the warning system in a complex driving environment. It seems likely that temporal uncertainty is much greater in actual collision warning situations. The RTs observed in more realistic driving situations, such as rear-end collision scenarios examined by

Lee et al. (2002), are substantially longer than in this experiment – averaging 2.2 s. Likewise, uncued RTs to unexpected events – a barrel rolling down an embankment – averaged 1.5 s (Lerner, 1993). More generally, expectations have a dominant influence on RT (Green, 2000). These findings suggest that warning modalities that effectively resolve temporal uncertainty and alert drivers may be more beneficial than those that resolve spatial uncertainty and orient drivers. If this is the case, then the benefit of auditory cues relative to external-vehicular cues might be even greater than what was observed in this study. Modifications to the current cognitive science paradigm, such as using variable SOAs that would increase uncertainty about target onset, might increase the generalizability of the results.

To the extent that basic attentional processes, such as those captured in the Posner paradigm, dominate the response we would expect our results to predict driver response on the road, and for this paradigm to provide an efficient means of assessing collision warnings. Accordingly, auditory and auditory combined with haptic cues appear most promising as a means of alerting drivers' attention. Extending this paradigm to evaluate warning and information systems might proceed by describing the situation to be warned in terms of its spatial and temporal uncertainty, as well as its time constants. Using these parameters to match the Posner paradigm to the specific characteristics of the warning situation is likely to provide more generalizable results. Specifically, situations with high spatial uncertainty and long time constants, such as navigation instructions, are more likely to benefit from cues that orient attention, such as visual cues that overlay the driving environment. Such information systems should be tested using a Posner paradigm with a long SOA and high cue validity. In contrast, situations with high temporal uncertainty and short time constants, such as imminent collision warnings, are likely to benefit from auditory cues. Such warning systems should be tested using a Posner paradigm with a short SOA and relatively low cue validity. Both warning design and warning evaluation can benefit from understanding the underlying neuropsychological processes associated with alerting and orienting attention.

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