

# Influence of Age and Proximity Warning Devices on Collision Avoidance in Simulated Driving

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**Objective:** We conducted a set of experiments to examine the utility of several different uni- and multimodal collision avoidance systems (CASs) on driving performance of young and older adult drivers in a high-fidelity simulator. **Background:** Although previous research has examined the efficacy of different CASs on collision avoidance, there has been a dearth of studies that have examined such devices in different driving situations with different populations of drivers. **Method:** Several different CAS warnings were examined in varying traffic and collision configurations both without (Experiment 1a) and with (Experiment 2) a distracting in-vehicle task. **Results:** Overall, collision avoidance performance for both potential forward and side object collisions was best for an auditory/visual CAS, which alerted drivers using both modalities. Interestingly, older drivers (60–82 years of age) benefited as much as younger drivers from the CAS, and sometimes they benefited more. **Conclusion:** These data suggest that CASs can be beneficial across a number of different driving scenarios, types of collisions, and driver populations. **Application:** These results have important implications for the design and implementation of CASs for different driver populations and driving conditions.

## INTRODUCTION

There were 42,636 driving-related fatalities in the United States in 2004 (National Highway Traffic Safety Administration, 2004). In an effort to reduce fatalities as well as the severity of injuries experienced in automobile accidents, governments and the motor vehicle industry have implemented a variety of safety features (e.g., front- and side-impact air bags) and research projects (e.g., Fatality Analysis Reporting System, 2002). One relatively recent safety device, currently under development by a number of automotive manufacturers, is a collision avoidance system (CAS) or proximity warning system. A CAS is intended to warn a driver of an impending hazard by way of alarm (e.g., flashing lights, a warning tone, or a vibrating seat). The potential utility of CASs is far-reaching because they can potentially decrease accidents, insurance claims, and property damage.

In a series of four studies conducted under the auspices of the Crash Avoidance Metrics Partnership (CAMP), Kiefer et al. (1999) reported some

interesting and potentially important findings related to forward collision driving behavior, CAS modality, and timing efficacy. These studies examined the timing of three different CAS modalities in a moving vehicle on a test track using a surrogate target. Experimenters compared visual head-up display (HUD), visual head-down display (HDD), auditory speech, auditory nonspeech, and haptic (brake-shaker) warnings. Participants in three different age groups (ages 20–30, 40–51, and 60–71 years) were presented with these alerts under surprise, nonsurprise, attentive, nonattentive, slow relative velocity, and fast relative velocity conditions.

Several important findings were reported: First, relative to the other CAS modality combinations, the use of speech warnings produced less effective avoidance behavior. Second, the visual and auditory nonspeech modalities provided the most useful information to the drivers across all the experimental conditions. Further, although there were no significant performance differences between the HUD and HDD visual modalities, subjective

reports indicated a strong preference for the HDD format. Third, the visual modality was ignored or missed on a substantial number of trials in a variety of situations, relative to the nonspeech auditory warning. Overall, the combination of visual and nonspeech auditory warnings produced more efficient avoidance behavior than the other modalities (see also Kiefer, LeBlanc, & Flannagan, 2005).

Other researchers have examined a variety of different CASs in a number of driving environments. For example, Plet, Domini, Gerbino, and Valarda (2001) investigated the utility of two different dashboard-mounted visual CAS warnings in driving performance with a low-fidelity driving simulator (i.e., small field of view and no driver speed control). Drivers were more successful in completing overtaking maneuvers, with and without a secondary task, when they used the visual warnings. Dingus et al. (1997) studied the relative effectiveness of three types of graduated visual warning displays as well as a combination of auditory and visual warnings using a real-world driving task in which a participant followed a confederate vehicle. Results favored the use of a graduated visual display in conjunction with an auditory warning to increase drivers' following distance.

Lee, McGehee, Brown, and Reyes (2002) investigated the effect of collision avoidance systems on driver performance in rear-end collision situations. Using a driving simulator, they examined the effects of an auditory/visual warning across several factors including initial velocity, situation severity (lead vehicle deceleration rate), and warning algorithm parameter (early vs. late warning). They found that the warning reduced the number and severity of collisions (more so for the earlier than the later warning). These effects were found in both distracted and undistracted drivers.

A number of studies have also examined the utility of haptic/tactile CASs, including brake pulses, force-generating accelerator pedals, vibrating steering wheels, and seat shakers. In general, these systems have been found useful in alerting drivers to forward hazards and have led to increased following distances (Janssen & Nilsson, 1993; Tijerina et al., 2000). However, for the most part, performance with these haptic/tactile devices has not been compared to performance with other uni- and multimodal alerting devices for different types of hazards across drivers who range in age and experience.

The studies reviewed thus far clearly suggest that a CAS can effectively alert drivers to potential collisions, thereby potentially avoiding accidents. However, very few of these studies have asked whether CAS benefits generalize across age and experience as well as across different types of collisions. Indeed, in many of the studies that have examined CAS benefits for older drivers, either age effects were not statistically analyzed (Olson & Sivak, 1986) or "older" adults were actually quite young, often less than 65 years of age (e.g., Dingus et al., 1997; Kiefer et al., 1999; Shinar & Schectman, 2002). Given the increasing age and number of older drivers, along with the increase in accidents at older ages, it is clearly important to examine the performance of drivers over 65 years of age (Hakamies-Blomqvist, 1996; Klavara & Heslegrave, 2002).

What types of collision avoidance differences might one expect between younger and older adult drivers? On one hand, older drivers clearly show deficits on many perceptual, memory, and cognitive abilities (Salthouse, 1996) and therefore might be expected to perform more poorly than young adults with and without CASs. However, given the natural confound between age and driving experience, one might also expect that older adults might be able to capitalize on their wealth of driving experience to compensate for deficits in basic perceptual and cognitive abilities, thereby effectively using a CAS to improve performance and avoid collisions. Indeed, the cognitive aging literature does suggest that age-related experience in real-world domains such as piloting, game playing, and music can reduce performance declines, at least when these skills are well practiced (Kramer & Willis, 2003; but see Salthouse, 2003).

The present study has several goals. First, we examine the relative efficacy of uni- and multimodal proximity warning devices for collision avoidance in a high-fidelity driving simulator. Second, collision avoidance both with and without proximity warning devices will be examined as a function of different driving situations: with (Experiment 2) and without (Experiment 1a) a secondary task that simulates reading information from a HDD (i.e., similar to that experienced with an in-vehicle information system).

Third, previous studies of proximity warning devices have generally examined rear-end collisions. In the present case we examine the efficacy of proximity warning systems for both potential

forward and side object collisions (see also Campbell et al., 1996; Tijerina, Jackson, Pomerleau, Romano, & Peterson, 1995). Finally, given the “aging” of the driving population, we examine potential age-related differences in collision avoidance of both younger and older drivers (to 82 years of age).

## EXPERIMENT 1A

This experiment extends previous research on CASSs in a number of important ways. First, given that previous studies have often focused on a single type of collision, often forward collisions, we were interested in studying collision avoidance to different and temporally unpredictable types of collisions. In this study, potential collisions could occur either in the forward direction or to the side (during a lane change). Second, we were interested in examining the relative efficacy of both uni- and multimodal warnings for these different collision configurations. Different visual, auditory, and tactile warnings provided directional information concerning potential collisions with other vehicles. Finally, we were interested in age-related differences in collision avoidance, with and without alerts.

### Method

*Participants.* Forty individuals 18 to 82 years of age participated in the experiment. (We originally ran 27 older and 23 younger adults in Experiment 1, but 7 older and 3 younger adults could not complete the experiment as a result of motion sickness.) Participants were divided into two age groups: young adults between the ages of 18 and 26 (12 women, 8 men; mean age: 21.5) and older adults between the ages of 61 and 82 (14 women, 6 men; mean age: 70.2). The young adults had an average of 15.0 years of formal education, and older adults averaged 14.2 years. All participants had normal or corrected-to-normal visual acuity of at least 20/25 with no instances of color blindness.

All volunteers passed our screening questionnaire, which assessed the risks of experiencing motion sickness and documented other health issues that could affect performance in the simulator. Additionally, all older volunteers were administered the Modified Mini Mental State questionnaire (Folstein, Folstein, & McHugh, 1975) to exclude those suffering from dementia. Finally, each participant possessed a current and valid driver's license. All participants were paid \$35 and fully

debriefed upon completion of the two-session study.

*Materials.* This research was conducted using the Beckman Institute Driving Simulator at the University of Illinois (GlobalSim, Inc. Vection™ Research Simulator). The fixed-based simulator consists of a 1998 Saturn SL positioned in front of a 135° wraparound forward screen and a 135° rear field. Six Epson PowerLite 703c projectors project the simulation onto separate screens. Seven PCs control the simulator. A two-channel sound system provided traffic and road noise in addition to engine sounds. An eighth PC interfaced with the simulator via a network connection and provided both a sound server and a relay control card. The sound server fed sound to a separate four-channel 3-D sound system, which permitted use of localizable auditory warnings that did not interfere with the simulator's sound generation. The relay card (Sealevel Systems, Inc.) controlled the LEDs and the seat shakers to present the visual and haptic warnings.

The simulator dynamics and environments were coordinated with GlobalSim's Vection™ software Version 1.4.1. Driving environments and scenarios were created on a PC using GlobalSim's HyperDrive™ authoring software Version 1.4.1. Ambient traffic, collision events, and dynamics were controlled through programming scripts. For all driving blocks (practice and experimental) the traffic environment consisted of a six-lane freeway (three lanes in each direction). Occasional road construction (i.e., orange construction barrels) occurred in the right- or left-hand lane, such that drivers had to return to the center lane.

*Potential hazard events.* Two types of hazard events were studied:

Each *forward collision* (FC) event featured a vehicle that suddenly appeared at rest in front of the driver. Time to collision (TTC) was kept at a constant 2.12 s across events and drivers, factoring in the drivers' speed. This short TTC was chosen because it created an urgent yet avoidable road hazard.

For the *side object* (SO) events, throughout each driving block, drivers received auditory commands to change their lane (either to the left or right), presented through the vehicle speakers. On one third of these lane changes a vehicle would suddenly appear in the driver's blind spot (3.5 m from bumper to bumper on the merge side and 4 m behind the simulator vehicle), necessitating a maneuver to

avoid a collision. This event was triggered once the simulator vehicle deviated 0.5 m into the instructed lane.

*Alerting systems.* Three different warning modalities were tested in four different combinations. Additionally, one condition (control) featured no warning.

The *visual* warnings were presented via three sets of four red LEDs arranged horizontally. One set was mounted on top of each side mirror and one was mounted on top of the dashboard at the driver centerline. The LEDs were 7 mm in diameter and 9 mm from one another. When the warning was active, the LEDs flashed at a 4-Hz rate with a 50% duty cycle (i.e., repeated cycle of 125 ms on, 125 ms off) in accordance with the flash rate used in the visual component in the CAMP (Kiefer et al., 1999) report. During FC events the center-mounted LEDs flashed, whereas during the SO events the LEDs flashed on the appropriate side mirror, which helped drivers localize the potential collision.

For the *auditory* warnings, the sound used by the forward auditory system was identical to Sound #8 in the CAMP project (Kiefer et al., 1999). This was a 64-dB 2.1-s broadband tone (measured during vehicle operation) with peaks at 2500, 8000, and 12000 Hz. The ambient noise level during driving in the absence of the warning tone was 53 dB. The sound was played through a sound server attached to a 3-D enhanced sound system added to the simulator. This served to permit sound localization. For the FC events, the sound appeared to be coming from directly in front of the driver. During SO events, the sound appeared to be coming from the appropriate side.

The *auditory/visual* warning presented both the auditory and visual warnings simultaneously.

For the *tactile/visual* warning, the tactile component was generated by two thigh shakers installed in the driver's seat so as to be approximately beneath the left and right thighs. The shakers consisted of small DC motors with an off-center weight mounted on the shaft. When activated, the motors operated at 60 Hz. The FC warning involved activating both shakers simultaneously. Activating only the appropriate shaker on either the left or right side generated the SO warning. The alarms began upon presentation of the warning events and continued until either the driver avoided the potential collision or collided with the vehicle positioned in front of or on the side of their vehicle.

In the *no-alert* condition, no warning was presented to the driver.

*Procedure.* Prior to the experimental session, potential participants were prescreened by phone or E-mail. This prescreening process identified and removed individuals who had health-related issues or who may have been susceptible to motion sickness.

At the start of the first session, participants completed an informed consent form and basic demographic questionnaires and were tested for near and far visual acuity and color blindness (Ishihara test). Participants were then seated in the driving simulator and encouraged to make adjustments to the seat and mirrors to suit their size and preference. Participants then drove through three separate practice trials designed to familiarize themselves with the control dynamics of the car, the levels of ambient traffic, the potential hazard events, and the CAS warnings. Each practice trial was 7 min in duration.

Following the practice block, drivers were provided with some general instructions regarding the experimental tasks: (a) to always drive between 60 and 70 mph (~96.5 and 112.6 km/hr) unless slowing was required to avoid a collision; (b) to always follow the lane change commands unless a potential collision or road construction forced a lane change; and (c) to always follow the rules of the road, unless an emergency situation dictated otherwise. As with the construction zones, lane change commands were strategically programmed into each experimental drive to ensure that participants were in the appropriate lane for each event.

Overall, there were five experimental blocks: one for each of the alerting systems, plus a no-alert baseline condition. Each block lasted approximately 13 min. Within each block, drivers encountered eight potential hazard events (four of each type). We note that SO events occurred on only one third of the required lane changes.

In the first session, participants were encouraged to drive as many of the five blocks as they could but were reminded to stop if they were fatigued. After finishing the demographic data acquisition and the practice runs, drivers generally finished between zero and three of the five experimental runs in the first session. The remaining trials were completed in the second session. Upon completion of the experiment, each volunteer was thoroughly debriefed and paid. Both sessions were completed within 1 week, and there was no difference in the amount

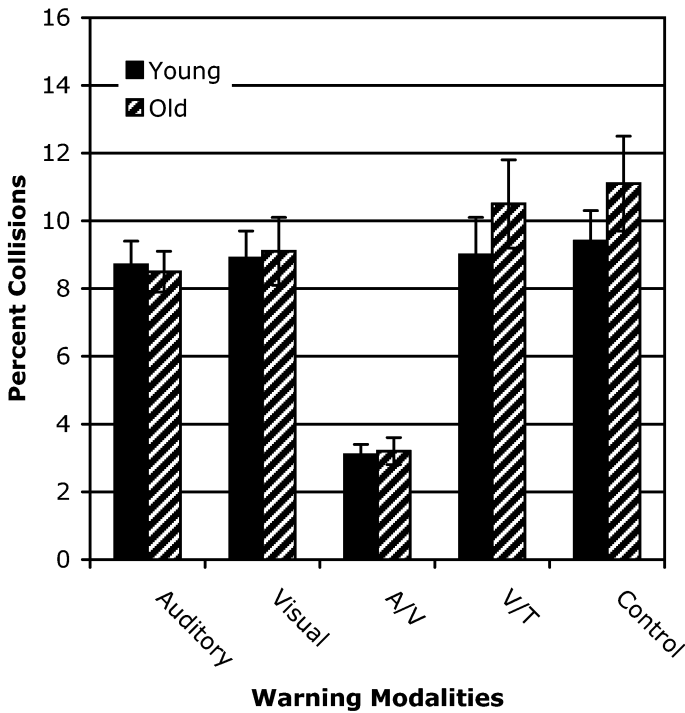
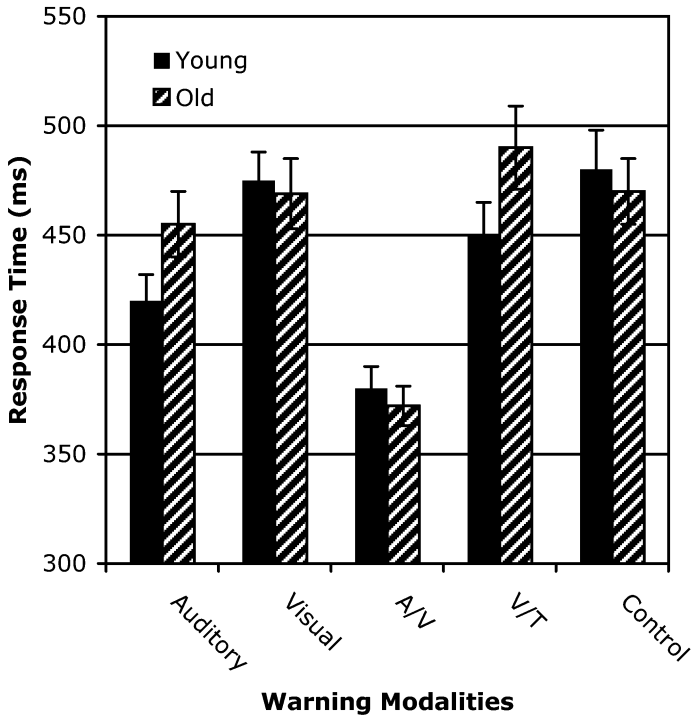


Figure 1. Response times to forward collision events (top panel) and percentage collision (bottom panel) in Experiment 1a as a function of age group and warning conditions. A/V = auditory/visual, V/T = visual/tactile.

of time between sessions for the younger and older or male and female drivers.

*Experimental design.* This experiment featured a  $5 \times 2$  mixed design with warning type (auditory, visual, auditory/visual, tactile/visual, none) as a within-subjects factor and age (older and younger) as a between-subjects factor. Because of the different configurations, we examined FC and SO events separately in subsequent analyses. The five experimental blocks were counterbalanced across drivers with a Latin square design.

## Results and Discussion

Response time (RT) was measured from the time the potential collision vehicle was presented to the time when an avoidance response was detected. After inspecting the steering wheel, brake, and accelerator inputs within a window 5 s before and after an event, we defined a collision avoidance response as the accelerator position reaching zero or the brake position rising above zero at any time within the 5 s following an event. A separate RT was determined for each control input (brake, accelerator), and the faster of the two was taken as the RT for that event. (An examination of the brake, accelerator, and steering wheel responses following the potential collision events indicated that the steering wheel deflections were never the initial response. Therefore, we do not consider them further in the analysis of the collision avoidance RTs.)

Collisions were detected by the Vection software whenever any part of the participant's vehicle occupied the same space and time as occupied by a simulated vehicle. We analyzed collision data with regard to whether or not a collision occurred on a particular trial. As noted previously, separate analyses are reported for FC and SO events.

*Forward collision events.* The RT and collision data were submitted to two-way ANOVAs with age (young, old) as a between-subjects factor and warning system modality (auditory, visual, auditory/visual, tactile/visual, control) as a within-subjects factor. (Both the RT and percentage collision data in the driving simulator experiments violated assumptions of normality. Therefore, we employed normalizing transformations to these data. A logarithmic transformation was used to normalize the rightward skew of the RT distributions. The percentage collision data were normalized by the arcsine transformation. The transformed data were then submitted to the ANOVAs.)

Mean RTs for FC events are shown in Figure 1

(top panel). A main effect of modality was observed,  $F(4, 152) = 6.9, p < .01$ . Post hoc comparisons indicated that the auditory/visual warning yielded faster reaction times than the control condition ( $p < .01$ ). No other warning modality differed significantly from the no-warning control condition. No other main effect or interaction was significant.

The collision data are presented in the bottom panel of Figure 1. Similar to the response time data, the only significant effect was a main effect of modality,  $F(1, 152) = 8.0, p < .01$ . Drivers had fewer collisions when driving with the auditory/visual warning device as compared with the other warnings and the no-warning control condition ( $p < .01$ ).

*Side object events.* Mean RTs are shown in the top panel of Figure 2. A significant effect of modality was obtained,  $F(4, 152) = 2.4, p < .05$ . Post hoc comparisons revealed faster responses in the auditory and auditory/visual conditions as compared with the control condition ( $p < .05$  and  $p < .01$ , respectively; see Figure 2). No other main effect or interaction was significant for the response time measures.

The collision data for the potential side object collisions are presented in the bottom panel of Figure 2. Similar to the response time data, the only significant effect was a main effect of modality,  $F(1, 152) = 5.7, p < .05$ . Drivers had fewer collisions when driving with the auditory/visual warning device as compared with the other warnings and no-warning control condition ( $p < .05$ ).

A comparison of the RT and collision data in Figures 1 and 2 suggests that detecting potential side objects was more difficult than detecting forward collision events, likely as a result of the side objects (vehicles) appearing in the drivers' blind spots.

The results obtained in the present experiment clearly suggest that redundant warning cues, in particular the auditory/visual warning, are effective in both speeding the detection of a potential collision event and reducing the number of collisions. The superiority of the auditory/visual warning is consistent with previous studies of CASSs, which have also found that this type of redundant cue is superior to unimodal visual or speech signals for avoiding collisions and maintaining sufficient headways when following lead vehicles (Dingus et al., 1997; Kiefer et al., 1999).

Our study extends previous research with auditory/visual warnings from the examination of FC events to both FC and SO events and therefore

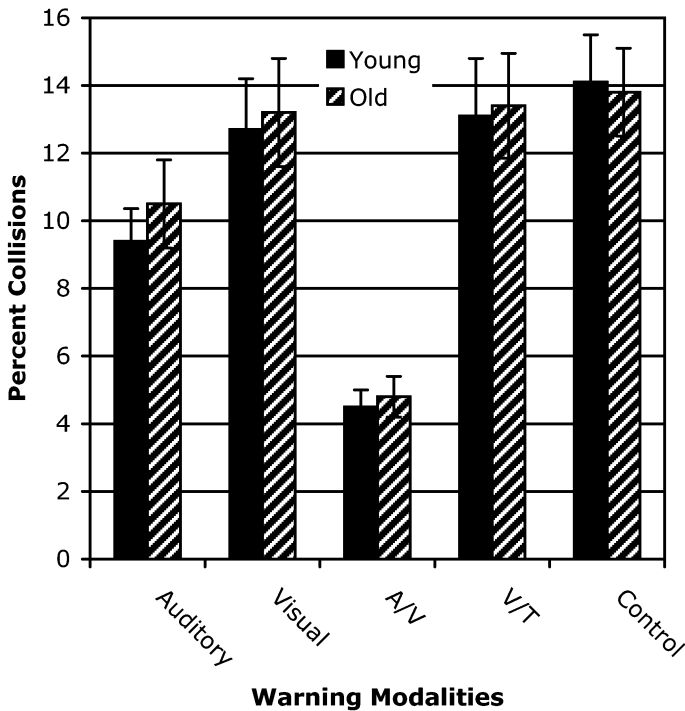
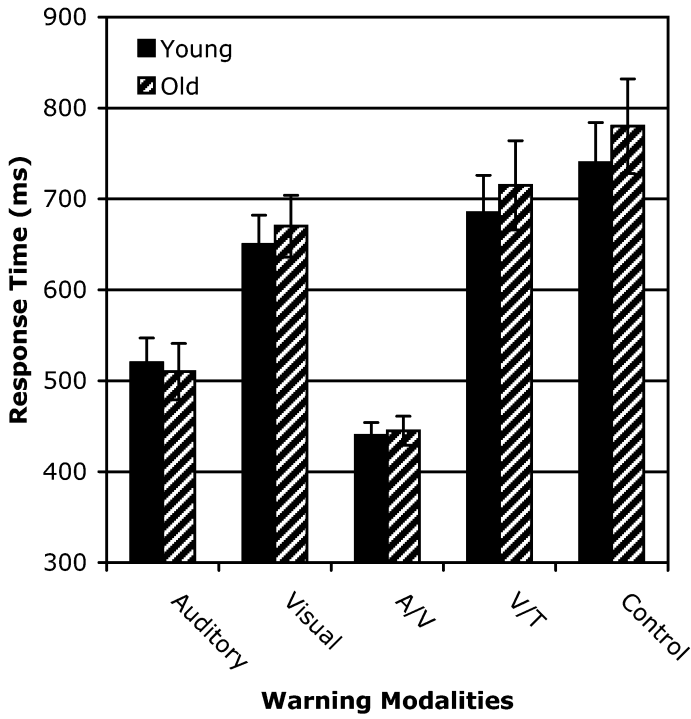


Figure 2. Response times to side collision events (top panel) and percentage collision (bottom panel) in Experiment 1a as a function of age group and warning conditions. A/V = auditory/visual, V/T = visual/tactile.

suggests that these warnings generalize to different types of potential collisions. We suspect that the localized alerts, particularly for the SO events, were an important reason for the effectiveness of these cues (see also Ho & Spence, 2005; Hoshino, Kojima, Uchiyama, & Hongo, 2002). Importantly, the current results also suggest that older drivers are able to respond as quickly as young drivers to the CAS warnings. Experiment 1b was intended to further explore this effect.

## EXPERIMENT 1B

The results reported in Experiment 1a showed that older adults were able to respond to the collision events just as quickly as younger adults. This finding was quite unexpected, particularly in light of the almost universal finding of significant and substantial slowing of responses from the 20s to the 80s (Salthouse, 1996). It is conceivable that the RTs observed in Experiment 1a could have been attributable to either exceptionally fast older adults or particularly slow younger adults. However, an intriguing alternative possibility was that the older adults may have benefited from years of driving experience and that this extensive experience may have offset the often observed slowed responding in laboratory tasks (Kramer & Willis, 2003, Salthouse, 2003; Underwood, Chapman, Brocklehurst, Underwood, & Crundall, 2003).

If these results were indeed an example of experience-related moderation of age-related slowing, we would expect, based on previous research, to observe slowed responding for our older adults on traditional laboratory RT tasks. This follows because transfer of experience is quite narrow and rarely extends to nontrained tasks (or stimuli). In the present study we asked participants from Experiment 1a to come back to the laboratory and perform simple RT tasks with auditory and visual stimuli. A finding of age-related slowing in the laboratory RT tasks would be consistent with the experience hypothesis, whereas an observation of equivalent RTs for the young and older adults in our laboratory tasks would suggest either very fast older adults or slow younger adults.

## Method

*Participants.* Of the original 40 participants, 26 (9 younger and 17 older) returned and participated in this experiment. The ages and other characteristics of this subset of participants were not

significantly different from those of the full set of participants who took part in Experiment 1a.

*Stimuli.* In the simple RT block, the visual stimulus was a capital letter *S* and the auditory stimulus was a 2000-Hz tone. In the choice RT block, the visual stimuli were the capital letters *S* and *X*. The auditory stimuli were tones of 4000 Hz (high tone) and 800 Hz (low tone). Stimuli were presented on an SVGA monitor connected to a PC running Micro Experimental Laboratory software.

*Procedure.* The study consisted of two blocks: simple and choice RT. The order of presentation of the two blocks was counterbalanced between the participants. Both blocks consisted of visual and auditory stimuli. The order of presentation was randomized within blocks.

There were 200 trials in the simple RT time block, 100 trials with the visual stimuli and 100 with the auditory stimuli. Participants were asked to focus at the fixation point in the center of the screen. The duration of the fixation point was randomized between an equal number of trials with the duration of 250, 500, 750, and 1000 ms. This was done to prevent anticipatory responses. Following the presentation of the fixation point, on 80% of the trials a stimulus was presented. Participants were instructed to press a specified key (*O*) if the stimulus was present. No response was required for the trials in which the stimulus was absent.

There were 200 trials in the choice RT block, 100 trials with the visual stimuli and 100 with the auditory stimuli. The fixation point was presented in the center of the screen for 1000 ms, followed by a stimulus. For both visual and auditory stimuli, participants were presented with one of two possible stimuli. They were required to respond to the stimulus by pressing the appropriate key on the keyboard, either *z* or the slash symbol (*/*).

## Results and Discussion

The RT data were analyzed in a three-way mixed-mode ANOVA with age as a between-subjects factor and modality (auditory and visual) and task (simple and choice RT) as within-subjects factors. The RT data are presented in Figure 3. Accuracy rates were very high (>98%) and did not differ as a function of condition.

A significant main effect was obtained for task,  $F(1, 23) = 80.5, p < .01$ . As can be seen in Figure 3, RTs were significantly slower for the choice than for the simple RT task. Importantly, a significant effect was observed for the Task  $\times$  Age Group

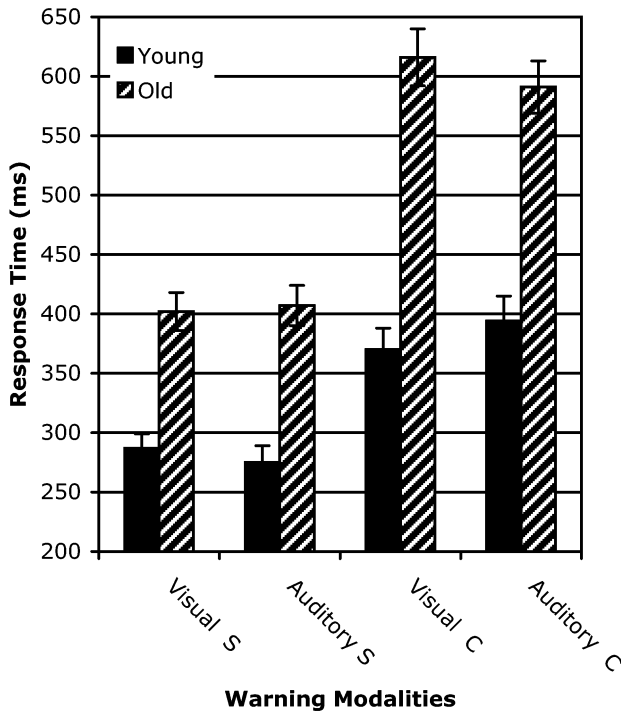


Figure 3. Response times to simple and choice visual and auditory stimuli in Experiment 1b. S = simple, C = choice.

interaction,  $F(1, 23) = 7.6, p < .01$ . The difference in RTs between age groups was significantly larger for the choice (210 ms) than for the simple RT task (124 ms). No other main effects or interactions were significant.

Consistent with the cognition and aging literature, older adults were slower than younger adults for both simple and choice RT tasks, with a larger age-related difference for the choice than for the simple RT tasks (Salthouse, 1996). These data clearly suggest that the older drivers who participated in Experiment 1 were not unusual with respect to their response speed.

Instead, it would appear reasonable to suggest, consistent with a subset of the literature on experience-related moderation of age-related decline in perceptual and cognitive processes (Kramer & Morrow, in press), that the substantial driving experience of the older adults enabled them to maintain high levels of preparation in order to respond quickly when confronted with potential collisions and to take the proper action to avoid them. However, as indicated by the results in the present study, the putative driving-related benefits did not transfer to other RT tasks. This finding of specificity of experience-related benefits is also

consistent with the literature on aging and experience (Kramer & Willis, 2003).

## EXPERIMENT 2

Overall, the driving situation that was simulated in Experiment 1 was relatively easy. That is, participants drove on a straight roadway without any secondary tasks or distractions. Clearly, such a situation is not very representative of many everyday driving situations (Horrey & Wickens, 2004; Stutts et al., in press).

Given these contextual constraints, it seems important to ask whether drivers would benefit to the same degree from the warning alerts under more difficult driving conditions. It is also important to determine whether older drivers will be able to maintain their high level of collision avoidance performance, with and without the collision alerts, under more challenging situations. Indeed, although age-related experience has been found to moderate age-related decline in basic information-processing abilities, some researchers have argued that age-related compensatory strategies may fail under particularly challenging situations (Baltes & Kliegl, 1992; Kramer & Willis, 2003).

Therefore, in the present study, drivers were asked to complete a subset of three experimental blocks from Experiment 1a. In this experiment, however, the driving conditions were more difficult and a secondary, visual in-vehicle task was added. The difficulty of lane keeping and speed control was increased by introducing frequent and unpredictable wind gusts, which pushed the vehicle laterally in its lane or slowed it longitudinally. The occasional in-vehicle task required that drivers divert their eyes from the roadway to access information presented on an HDD located near the vehicle's center console. The in-vehicle task was used to simulate viewing an automotive telematic display, such as a global positioning satellite navigation system or another in-vehicle information system.

The three experimental blocks replicated from Experiment 1a were (a) no warning (control), (b) visual warning condition, and (c) visual/auditory warning condition. The central question addressed in this study was whether the CAS benefits found in Experiment 1a would also be observed for young and older adults under more challenging driving conditions and in the presence of in-vehicle distraction.

## Method

*Participants.* Forty individuals 19 to 82 years of age participated in the experiment. Participants were divided into two age groups: one 19 to 30 years of age (11 women, 9 men; mean age = 21.8) and the other 65 to 82 years of age (9 women, 11 men; mean age = 72.0). All individuals had normal or corrected-to-normal vision of at least 20/25. The young adults had an average of 14.7 years of education, and the old adults had an average of 15.2 years of education. As in Experiment 1a, all participants were screened for color blindness, motion sickness, health issues, and dementia. Each participant possessed a current and valid driver's license. Participants were paid \$8/hr and debriefed upon completion of the experiment.

*Materials.* The simulator hardware and software, driving environments, and collision events (FC and SO) were identical to those used in Experiment 1a. The CAS warnings were also consistent with those used in Experiment 1a; however, we used only the visual, auditory/visual, and no-alert conditions here. Also, for each driving block random wind was introduced, which exerted a lateral force on the vehicle. This wind randomly varied in

strength (1,000–3,000 N), direction (left, right), and duration (1–3 s).

*Procedure.* As for Experiment 1a, participants were prescreened for motion sickness and health issues and tested for visual functioning at the start of the experimental session.

In the simulator, participants were given verbal instructions detailing the nature of the task. Specifically, participants were instructed to (a) maintain a speed of 65 mph (~104.6 km/hr) unless there is a potential collision, (b) always follow the lane change commands unless a potential collision forces a lane change, (c) always follow the rules of the road unless a potential collision dictates otherwise, and (d) complete a secondary (digit-reading) task to the best of their ability while avoiding collisions.

For the secondary task, participants were instructed to read aloud strings of digits presented on a visual display (Horrey & Wickens, 2004). All strings were 10 digits long and were presented on a console-mounted LCD screen (approximately 38° diagonally offset from the center of the horizon line; 34 cm below and 37 cm to the right). This task was more or less continuous, with digit strings presented every 1 to 4 s following the completion of the previous string. Participants were instructed to respond to the digits as quickly as possible but not to compromise safe driving. When the participants noticed the presentation of digits, they were required to press a steering-wheel-mounted button at the beginning of their response. When they finished reading the digits, they pressed the button once again.

Prior to the experimental blocks, drivers were given two separate practice trials designed to acclimatize them to the control dynamics of the car (one without and one with wind). They were also given a 1-min practice block for the digit task alone. Following these practice blocks, participants were administered the three experimental blocks. Each block lasted an average of 13 min, during which drivers encountered eight potential collision events (four of each type: FC and SO). Upon completion of the experiment, each participant was debriefed and remunerated.

Consistent with Experiment 1a, we focus here on RTs and collision data in the potential collision events. However, we also examined the time to complete the secondary digit-reading task.

*Experimental design.* This experiment featured a 3 × 2 mixed design with warning type (visual,

auditory/visual, none) as a within-subjects factors and age (older and younger) as a between-subjects factor. As in Experiment 1a, the performance data for the FC and SO events were analyzed separately.

## Results and Discussion

We first describe the results of the analyses for the hazard RT and percentage collision data and then examine RTs to the secondary (digit-reading) task.

*Forward collision events.* The RT and collision data were submitted to two-way ANOVAs with age (young, old) as a between-subjects factor and warning system modality (visual, auditory/visual, and control) as a within-subjects factor.

Mean RTs for the FC events are shown in Figure 4 (top panel). A main effect of modality was obtained,  $F(2, 76) = 11.8, p < .01$ . Post hoc comparisons indicated that the auditory/visual warning yielded faster reaction times than the control condition ( $p < .01$ ). No other main effect or interaction was significant.

The collision data are presented in the bottom panel of Figure 4. Similar to the response time data, the only significant effect was a main effect of modality,  $F(2, 76) = 9.6, p < .01$ . Drivers had fewer collisions when driving with the auditory/visual warning device as compared with the visual warning and no-warning (control) conditions ( $p < .01$ ).

*Side object events.* Mean RTs are shown in the top panel of Figure 5. A significant effect of modality was obtained,  $F(2, 76) = 7.2, p < .01$ . Post hoc comparisons revealed faster responses in the auditory/visual conditions as compared with the control condition ( $p < .05$ ). No other main effect or interaction was significant for the RT measures.

The collision data for the potential side object collisions are presented in the bottom panel of Figure 5. Similar to the response time data, there was a significant main effect of modality,  $F(2, 76) = 12.8, p < .01$ . Drivers had fewer collisions when driving with the auditory/visual warning device as compared with the other warnings and the no-warning (control) condition ( $p < .01$ ). A significant interaction between age group and modality was also observed,  $F(2, 76) = 4.1, p < .05$ . Older adults had more accidents than younger adults in the no-warning (control) condition.

A comparison of the RT and collision data in Experiment 1a (Figures 1 and 2) with those obtained

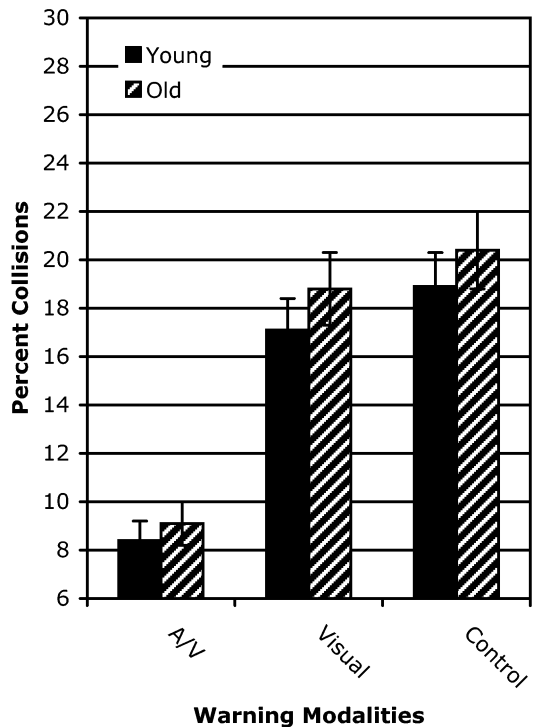
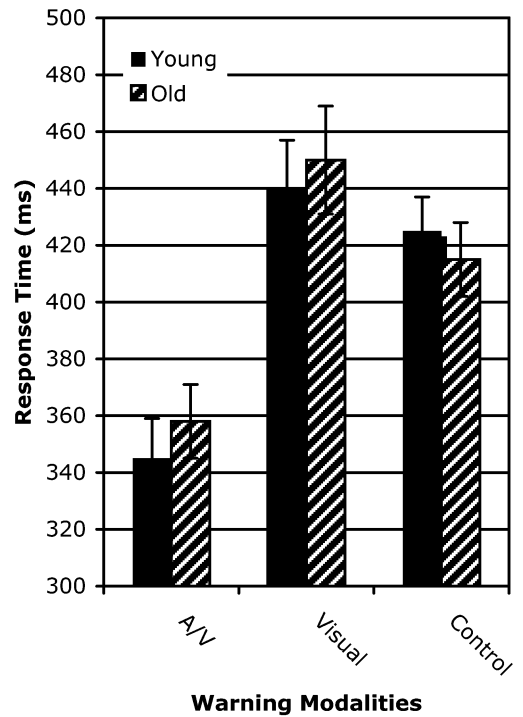


Figure 4. Response times to forward collision events (top panel) and percentage collision (bottom panel) in Experiment 2 as a function of age group and warning conditions. A/V = auditory/visual.

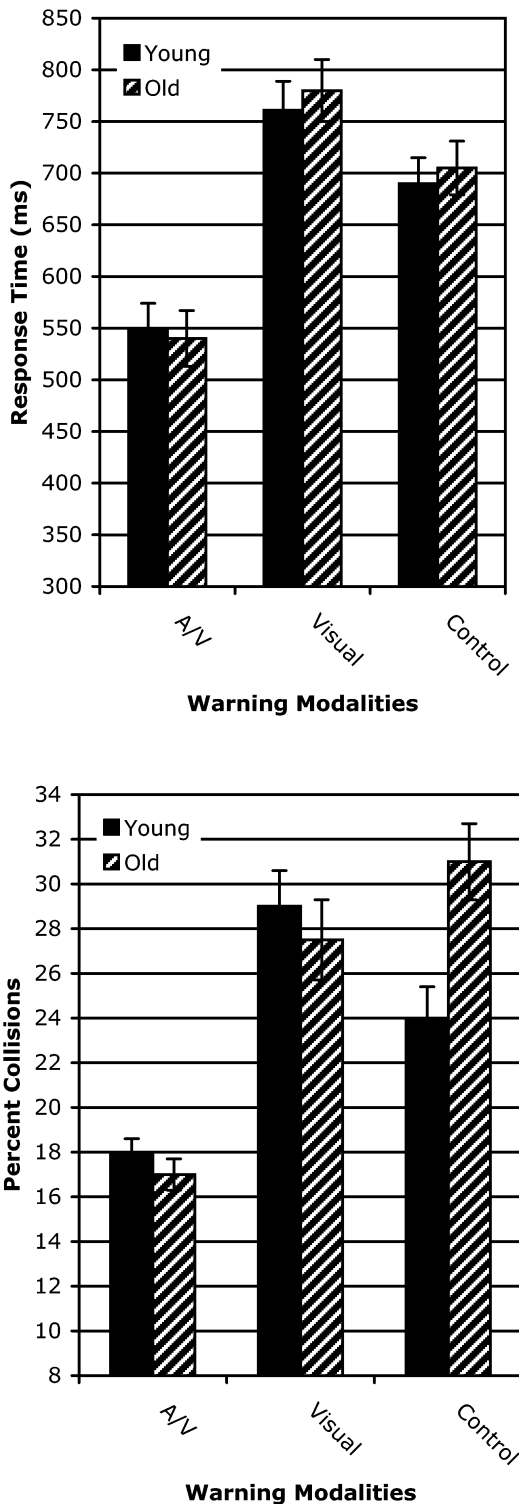


Figure 5. Response times to side collision events (top panel) and percentage collision (bottom panel) in Experiment 2 as a function of age group and warning conditions. A/V = auditory/visual.

in the present experiment (Figures 4 and 5) suggests that our attempts (via increased winds and a secondary task) to increase the difficulty of the present driving conditions were successful.

*Secondary task performance.* Figure 6 presents the times required to complete reading out the 10-digit numbers from the LCD panel. Other measures, such as initial RT to the presentation of the digits, were also obtained for this secondary task; these measures were highly correlated, however, so we present the data from the completion time measure.

The completion time data obtained from the secondary task were submitted to a two-way ANOVA with age group as the between-groups factor and warning modality as the within-subject factor. In addition to the collision measures, we had another level of the modality factor: a no-drive control condition in which participants performed the digit-reading task without driving. A significant effect was obtained for age group, with older adults completing the digit-reading task more slowly than younger adults,  $F(1, 38) = 20.7, p < .01$ . There was also a significant interaction between age group and modality,  $F(3, 114) = 7.3, p < .01$ . Post hoc comparisons indicated that the no-drive control was responded to more quickly than the other warning modality conditions for the old but not for the younger adults ( $p < .01$ ).

The data obtained in Experiment 2 were similar in a number of ways to those obtained in Experiment 1a. In both experiments, performance (RTs to collision events and the percentage of collisions) was best in the visual/auditory alert condition. These data are similar to those in previous studies that have found superior performance for redundant cues and, more specifically, auditory/visual cues (Dingus et al., 1997; Kiefer et al., 1999).

Second, both young and older adults displayed similar performance benefits when using the auditory/visual warning in Experiments 1a and 2. This was true for both potential forward and side object collisions. Indeed, older adults showed an even larger benefit from the auditory/visual warning under challenging driving conditions than did younger adults (see bottom panel of Figure 5).

Third, it is interesting to note that although older and younger adults displayed similar RTs in response to the potential collision events, older adults showed substantially slower RTs to the secondary task stimuli (see Figure 6). Thus, these data do suggest age-related slowing consistent with the

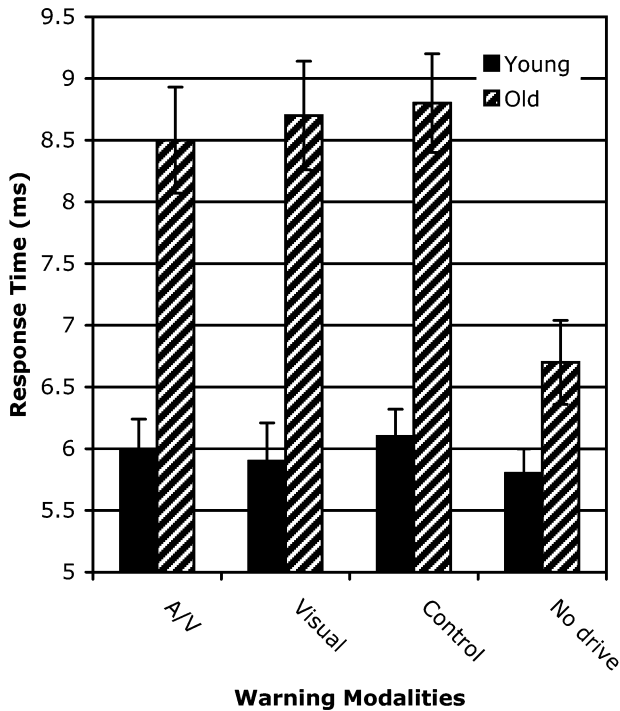


Figure 6. Times to complete readout of the 10-digit number in Experiment 2.

extant literature (Salthouse, 1996). However, the data also suggest that older adults do a good job of prioritizing task components to ensure safety.

Finally, the beneficial results of the auditory/visual warning were observed both across different driving scenarios and for different potential collisions. Such a finding suggests that CASs may have wide applicability. Of course, assessments of CAS devices will need to be validated on the roadway with an even larger variety of individuals and driving scenarios.

## GENERAL DISCUSSION

The results obtained in the present study extend previous research on CASs in several ways. First, our results suggest that the beneficial effects of a CAS extend across driver populations that differ in age and experience. Second, the results suggest that redundant cues and, more specifically, auditory/visual warning cues lead to the best collision avoidance performance.

The failure to observe redundancy benefits from the visual/tactile cue in Experiment 1a was disappointing but not particularly surprising. With current-day systems, people have little experience

interpreting and responding to tactile cues. Thus, additional training and practice with such cues and perhaps placements of the tactile stimulators on different locations of the body may lead to improved performance (Ho, Tane, & Spence, 2005).

A caution is also in order for the auditory component of the visual/auditory warning. Although auditory alerts are clearly useful when drivers' eyes are not directed to the location of a potential visual warning, additional research will be necessary to ensure that auditory warnings are not masked by other auditory information in the automobile (radio, other warnings and alerts, passenger conversation, etc.). We did simulate engine and road noise (e.g., the sound of other vehicles passing the driver's vehicle). However, we did not include other auditory information and noise in our simulations.

In recent years a number of investigators have found that drivers who were exposed to a forward CAS for limited periods of time modified their driving behavior such that they maintained increased headways for up to 6 months (Ben-Yaacov, Maltz, & Shinar, 2002; Shinar & Schechtman, 2002). The participants in these studies were relatively young and were exposed to CAS for a limited period of

time, and the CAS systems were designed to avoid only forward collisions. Whether these promising benefits extend to drivers with a broader age and experience range, beyond forward collisions, and in situations in which the CAS is continuously available is an interesting and important topic for future research.

There are a number of potential limitations associated with the present study. First, the unpredictable and sudden manner in which we introduced the forward and side object vehicles was meant to ensure that drivers would be attentive to their surroundings. The relatively rapid RTs to collision events seem to have achieved this goal. However, it will be important in future studies to determine whether the present results generalize to less-engaged drivers. The results obtained in Experiment 2 speak to this question, in part, as a similar pattern of collision avoidance results were obtained when drivers were distracted by the secondary task.

A second issue concerns the breadth of the visual displays used in the present experiments. Roadway displays covered 135° in the front and the rear of vehicle. Therefore, drivers were missing 45° on both the left and right of the vehicle. Although this arrangement was clearly adequate in most situations (see the relatively low collision rate for the side objects in Figure 2), it remains to be determined in future studies if performance will be equivalent with a larger field of view.

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