Can Collision Warning Systems Mitigate Distraction Due to In-Vehicle Devices?

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Rear-end collisions account for approximately 28% of automotive crashes. Because driver inattention is a contributing factor in more than 60% of these collisions, rear-end collision avoidance systems (RECAS) offer a promising approach to reduce crashes and save lives. A RECAS is a device that uses electronic sensors (e.g. radar) to detect the motion of a lead vehicle, compute whether a collision is likely, and trigger an alarm to alert the driver to the impending collision. This paper presents two experiments that use a high-fidelity driving simulator to compare how well drivers can avoid crashes with and without the aid of a RECAS. The first experiment examined how variations in warning algorithm parameters affect the ability of a RECAS to aid distracted drivers in avoiding an imminent collision. The primary comparison was between algorithms that triggered an early versus late warning. Drivers were distracted with a visually demanding number reading task. The results show that an early warning helps drivers react more quickly and avoid more collisions compared to a late warning or no warning. The second experiment examined the ability of the RECAS to help non-distracted drivers avoid an imminent collision. The results show that the RECAS benefits drivers even when they are not distracted. The magnitude and type of this distraction is compared with cognitive distractions due to speech-based interactions. Potential opportunities and challenges for RECAS to mitigate the effect of in-vehicle distractions are also discussed.

Keywords: Collision warning, behavioral adaptation, Rear-end collision avoidance systems, RECAS, Forward collision warning

INTRODUCTION

Rear-end collisions account for approximately 28% of all collisions and cause approximately 157 million vehicle-hours of delay annually, which is approximately one-third of all crash-caused delays (The National Safety Council, 1996). Driver inattention has been identified as a contributing factor in over 60% of these crashes (Knipling et al., 1993). Compared to driver inattention, environment-related factors have a very small contribution to rear-end collisions. Specifically, poor visibility was identified as a contributing factor in only 2% of the crashes (Knipling et al., 1993). Rear-end collisions are a particularly prevalent crash type for distracted drivers.

In the future, a significant contributor to driver inattention and distraction may be the implementation of increasingly sophisticated in-vehicle technology. Cellular telephones are a frequently cited example of in-vehicle technology, yet many other in-vehicle information systems are possible (Lee, 1997; Lee, Kantowitz, Hulse, & Dingus, 1994). These systems offer valuable services, but may compete with the driving task for drivers' attention. Driving requires attentional resources associated with visual perception (e.g., watching the road) and manual response (e.g., steering and braking). Visual displays for in-vehicle systems require the same resources, and many researchers and designers have recognized the potential of visual displays to distract drivers (Lunenfeld, 1989; Mollenhauer, Hulse, Dingus, Jahns, & Carney, 1997; Srinivasan & Jovanis, 1997). Visual displays pose a *structural distraction* to drivers because they cause drivers to look away from the road. In contrast, speech-based interaction require attentional resources associated with auditory perception and vocal response. Because speech-based interaction (e.g., cellular telephone conversation) requires perceptual and response resources that are different from those required by the driving task; the driver can keep his eyes on the road and hands on the wheel. Speech-based interaction does not pose a structural distraction to the driver; however, speech-based interaction may demand common cognitive resources associated with thinking about the road and the in-vehicle information system, posing a *cognitive distraction* to the driver. Comprehensive reviews of voice communications and driving suggest that speech-based interaction may distract drivers and degrade safety just as visual displays and manual controls can (Goodman, Tijerina, Bents, & Wierwille, 1999; McKnight & McKnight, 1993; Parkes, 1993). These studies show that two major types of distractions are important. The first is *structural distraction*, which occurs when the driver looks away from the road or takes his hands off the steering wheel. The second is *cognitive distraction*, which is less obvious and occurs when the drivers' cognitive activity is directed away from the road as in a complex conversation. Collision warnings may mitigate both the structural and cognitive distraction posed by in-vehicle devices.

The promise of increased driving safety through rear-end collision warning systems (RECAS) has generated a substantial body of research (An & Harris, 1996); (Knipling et al., 1993); (Hirst & Graham, 1997). There are also several systems currently under development by Japanese, European and US automobile manufacturers, in addition to the evaluation efforts sponsored by the National Highway Traffic Safety Administration (NHTSA) (McGehee & Brown, 1998; Tijerina, 1998). These systems use electronic sensors (e.g. radar) to detect the motion of a lead vehicle, compute whether a collision is likely, and trigger warning to alert the driver of the possible collision situation. The goal of these systems is to alert the driver to a potential collision situation, return the driver's attention to the roadway, and promote a response that avoids the collision.

We conducted one experiment to examine the safety benefit of early and late collision warnings for distracted drivers. We followed this with a second experiment to examine the effect of a warning on an undistracted driver. These experiments identify how well a warning can mitigate the distraction caused by a demanding visual task and whether or not the warning can benefit drivers who are not distracted by an in-vehicle device.

METHOD

Both experiments used a high-fidelity simulator to evaluate whether a RECAS could help drivers avoid colliding with a decelerating lead vehicle. The purpose of the first experiment was to investigate how distracted drivers respond to imminent rear-end collision situations. Drivers were placed in imminent collision situations where they responded to an auditory and visual warning triggered by different RECAS algorithm parameters under different conditions of speed, headway, and deceleration. The algorithm parameters controlled whether the driver received the warning early or late in the crash scenario. Measures of reaction time to the braking of the lead vehicle, collision frequency, and velocity at collision were collected. The second experiment investigated the benefit of a RECAS in helping drivers who were not visually distracted, but also not expecting a lead vehicle to brake.

Apparatus

Data were collected using the Iowa Driving Simulator (IDS). The IDS uses complex computer graphics and four multi-synch projectors to create a highly realistic automobile simulator with a 190-degree forward field-of-view and a 60-degree rear view. A fully instrumented 1993 Saturn four-door sedan is mounted inside the simulator dome that rests on a six-degree-of-freedom motion base to give drivers motion cues. Both the vehicle dynamics and the antilock brake system modeled were for a Ford Taurus, a typical mid-sized American car. The Ford Taurus vehicle dynamics model used in this study is one that was developed by NHTSA for use with the National Advanced Driving Simulator (NADS). In addition to the sensor data, four video cameras were used to record the simulator events for analysis of driver behavior, response timing, and reaction to the braking event.

Participants

The first experiment included 120 drivers between the ages of 25 and 55. There were an equal number of male and female drivers. All were licensed drivers and had normal or corrected to normal vision. They were paid $30 for the time they took to complete the experiment. None of the drivers had participated in a crash avoidance study before. The second experiment collected data from 20 additional drivers between the ages of 25 and 55.

Experimental design

A five-factor (2^4X3) mixed between and within subject experimental design contrasted the initial velocity (35 mph rural road and 55 mph freeway); order of initial velocity; first and second exposure to the collision situation; situation severity, composed of lead vehicle deceleration magnitude and the initial headway (two levels); and the warning algorithm, composed of two levels of d_F and a baseline condition (no collision warning device). The warning algorithm and situation severity were introduced as between subject variables, with a within subject replication of the experiment at a different initial velocity. For example, if a driver experienced the first collision situation at 35 mph they would experience another collision situation at 55 mph. The order of presentation was counterbalanced across drivers.

The experimental design for the second experiment was very similar to the first. However, rather than a complete replication of Experiment 1, Experiment 2 focussed on a subset of the experimental conditions. Specifically, only the low level of lead vehicle braking severity and early warning conditions were examined. These conditions were chosen because they generated the lowest variance in Experiment 1 and were expected to provide the basis for the most sensitive statistical comparisons. The data from non-distracted drivers were compared to data from the same conditions from Experiment 1. Ten drivers were included in the baseline condition without distraction and ten drivers were included in the early warning condition without distraction. Data for 20 distracted drivers in the baseline and early warning conditions from Experiment 1 were used for comparison.

Procedure

Upon arriving at the IDS simulation facility, participants completed an informed consent form and were briefed about how to operate the simulator vehicle. Participants then completed a demographic survey. To reduce anticipation of rear-end crashes, a *simulator evaluation ruse* was used to induce an unalerted response. Participants were told that they were to evaluate the fidelity of the simulator and to drive as they normally would. They were instructed to pay particular attention to the feel of the steering, accelerator pedal, brakes, other vehicle controls, and the realism of the traffic. Participants were then escorted to the simulator dome and briefed by the ride-along observer on how to assess simulator fidelity.

The participants began with a five-minute practice drive. During this drive, drivers were told that the vehicle ahead would brake suddenly and they were to brake to a stop behind the vehicle. Following the five-minute practice drive, participants drove two other short road segments, each ending in an imminent collision situation in which the lead vehicle braked suddenly. The drive with the initial velocity of 35 mph began and ended on a rural highway. Another drive began on a rural highway and then drivers merged onto a freeway where the collision situation occurred at a initial velocity of 55 mph. The order of the two drives was counterbalanced across drivers.

A secondary task distracted drivers from the roadway. As they drove, a digitized voice periodically asked them to press a button near the rear view mirror. The button press initiated a display above the rear view mirror to present a series of one digit numbers that changed at a rate of four Hz. The display remained on for 3 seconds. The driver was asked to watch these numbers and report the number of times the digit four appeared. In the imminent collision situation, the drivers' button press initiated the numbers and caused the lead vehicle to begin braking. In this way, the drivers were distracted when the lead car started braking. To prevent drivers from anticipating collision situations associated with the button press, the experiment included several other instances where the drivers were asked to perform the secondary task. Likewise, drivers experienced several lead vehicles that did not brake suddenly and so they were not able to associate a lead vehicle with an imminent collision situation. The procedure in the second experiment was identical to the first, with the exception that, in the second experiment no visual distraction task was used.

RESULTS

The data from each driver were combined to form a database containing 240 imminent collision situations, for Experiment 1 and another 80 imminent collision situations in Experiment 2. Of these data, some data elements were missing for four cases. For example, one driver released the accelerator before the lead vehicle began to brake, making it impossible to calculate a reaction time. A least squares approach was used to estimate the missing data. The data were analyzed using the mixed linear model (MIXED) procedure of SAS. The dependent variables associated with the potential safety benefit of the RECAS are described first, followed by a description of the variables associated with the underlying response process.

Safety benefit for distracted and undistracted drivers

Figure 1 shows the safety benefit of the RECAS by showing that the percentage of imminent collision situations that ended in a collision and the collision velocity both decreased with the RECAS. The warning reduced the percent of collisions $F(2,108)=16.07$ $p<0.0001$. With the late warning only 22.5% of the situations ended in collisions, compared to 45.5% in the baseline condition. The early warning had an even greater benefit, reducing the rate of collisions to 8.8%. Similarly, the warning reduced the collision velocity $F(2,108)=15.51$ $p<0.0001$. The collision velocity without the warning (4.74 m/s) was greater than that with the late warning (1.68 m/s) or the early warning (0.88 m/s). The difference of the collision velocity between the two warning conditions was not statistically significant $t(108)= 1.08$, $p = 0.2808$. These results show that, in some situations, a collision warning system can help mitigate the effects of some distractions.

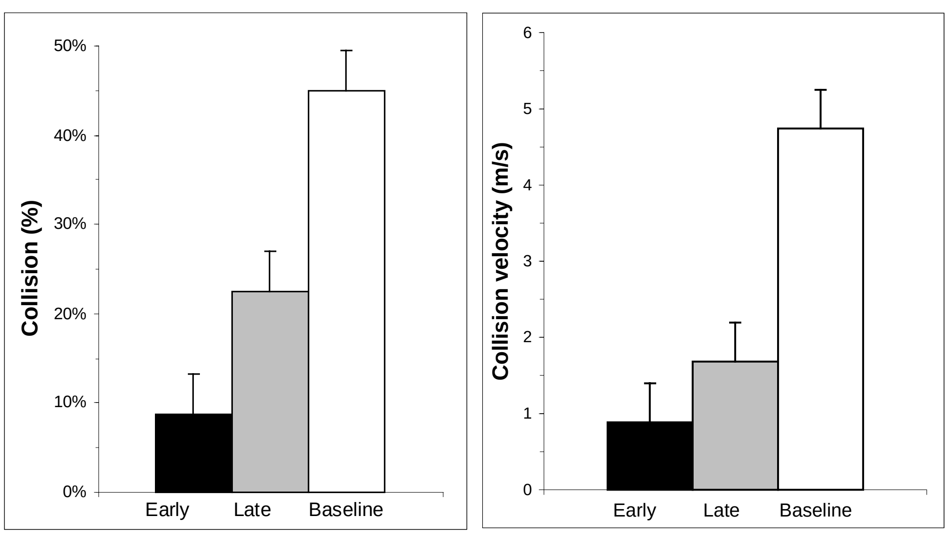

Figure 1. Safety benefit of early warning compared to the late warning and the baseline condition without a warning.

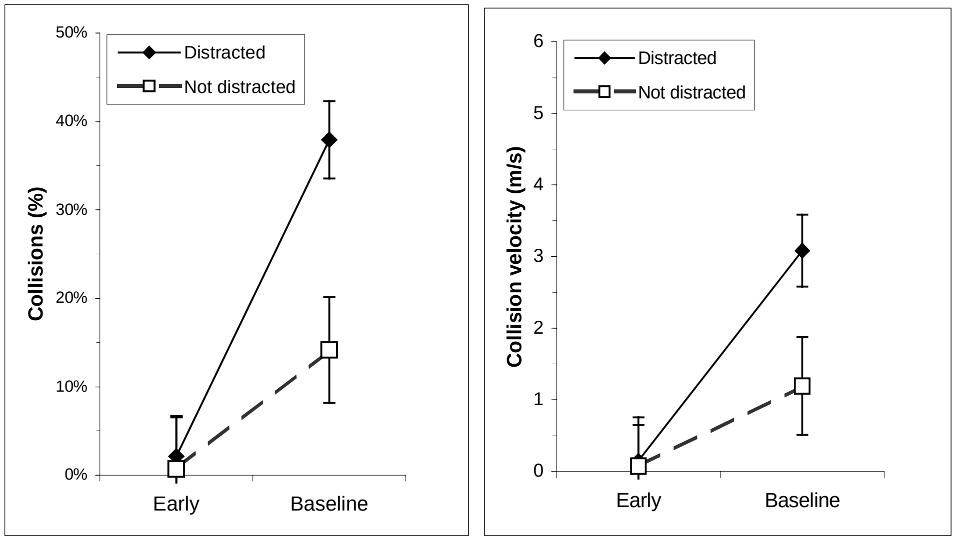

Figure 2. The safety benefit of the early warning for distracted and undistracted drivers.

Figure 2 compares the distracted drivers in Experiment 1 to the undistracted drivers in Experiment 2. The percentage of imminent collision situations that end in a collision and the collision velocity both show that RECAS provides a safety benefit to both distracted and undistracted drivers. The warning reduced the percentage of collisions, $F(1,52)=20.17$, $p<0.001$. With an early warning, drivers collided in only 1.4% of collision situations, compared to 26.0% in the baseline condition. This benefit depends on whether the drivers were distracted. Drivers who received a warning avoided almost all collisions regardless of whether they were distracted or not, $F(1,52)=4.95$, $p<0.05$. Figure 2 shows that undistracted drivers collided 14.2% of the time without a warning and 0.7% of the time with when a warning was given. Distracted drivers collided 37.9% of the time without the warning and 2.1% of the time when a warning was given. Overall, distracted drivers were involved in more collisions than undistracted drivers, $F(1,52)=6.34$, $p<0.05$. Distracted drivers were involved in collisions 20.0% of the time compared to 7.4% for undistracted drivers. These results also show that the visual monitoring task distracted drivers enough to seriously degrade driving safety in imminent collision situations. The warning also reduced the collision velocity, $F(1,52)=11.36$, $p<0.01$. Without a warning, drivers collided at 2.1 m/s compared to 0.1 m/s for drivers who received a warning. For collision velocity, the interaction between distraction and the warning did not reach statistical significance. This suggests the warning benefits undistracted and distracted drivers equally and that there is no direct safety decrement associated with warning undistracted drivers.

Warning enhanced responses and distraction delayed responses

Analyzing the components of the drivers' reaction time and examining the drivers' braking profile provides insight into how the RECAS generates the observed safety benefit. The drivers' reaction time consists of the time from braking onset of the lead vehicle to the accelerator release, the movement time from accelerator release to initial brake press, and the time from the initial brake press to maximum deceleration. The RECAS could generate the observed benefits by shortening any one of these components.

Figure 3 shows the effect of the RECAS warning on the distracted drivers' response process for the early, late, and no warning scenarios (Experiment 1), and for the distracted and undistracted drivers (Experiment 2). For Experiment 1, the warning had a strong influence on how quickly drivers released the accelerator in response to the braking of the lead vehicle, $F(2,108)=47.4$, $p<0.0001$. The early warning led drivers to react more quickly (1.35 s), compared to those drivers with late warning (2.10 s) or those in the baseline condition (2.21 s). The difference between the baseline and late warning failed to reach statistical significance. The warning did not enhance any other aspect of the response process. For Experiment 2, the warning again increased the speed of the accelerator release, $F(1,52)=64.22$, $p<0.0001$. Drivers who received a warning released the accelerator in only 1.03 seconds, compared to drivers in the baseline condition who took 1.73 seconds to release the accelerator. Drivers who were distracted released the accelerator more slowly in response to the lead vehicle braking $F(1,52)=24.36$, $p<0.0001$. Distracted drivers took 1.59 seconds to respond to the braking lead vehicle, whereas undistracted drivers took only 1.16 seconds to respond to the lead vehicle. The warning did not interact with driver distraction for any element of the response process, suggesting that, like the safety benefit, the warning enhances the driver's response, independent of whether the driver is distracted or not.

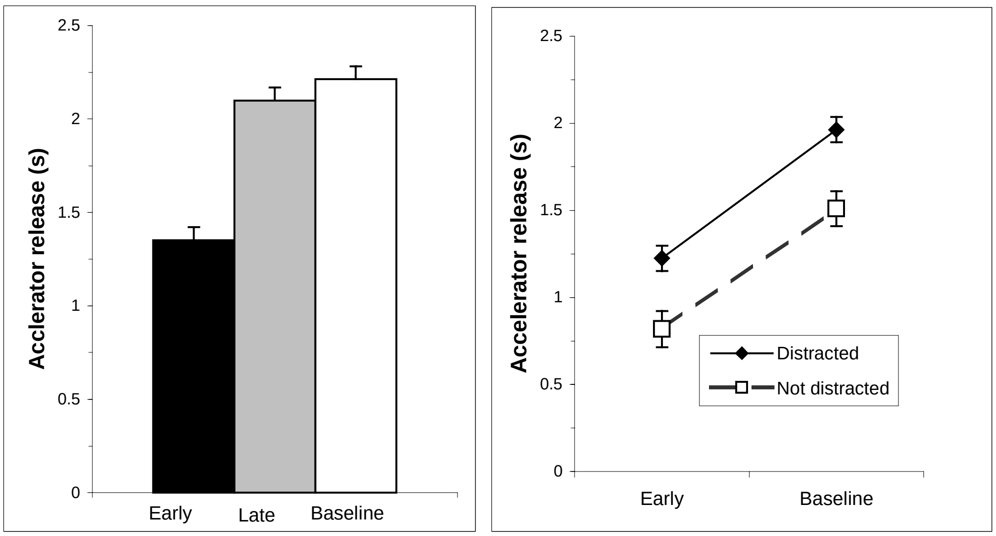

Figure 3. The effect of warnings and distraction on driver reaction time to the braking of the lead vehicle.

DISCUSSION AND CONCLUSIONS

Degrees and types of distraction

One measure of the degree of distraction is how much it increases drivers' reaction time to a driving relevant event. Specifically, several on-road and simulator studies have shown substantial increases in driver response times during telephone conversations (Alm & Nilsson, 1995; Brown, Tickner, & Simmonds, 1969). A recent study directly compared the visual demands of entering numbers into a keypad to the cognitive demands of a memory and addition task. The results showed that both tasks impaired drivers' ability to detect braking vehicles by 500 ms (Lamble, Kauranen, Laakso, & Summala, 1999). A recent study of driver interaction with a speech-based computer while driving shows a 310 ms increase in reaction time to a periodically braking lead vehicle (Lee, Caven, Haake & Brown, these proceedings). Interestingly, these delays are similar to the 430 ms delay observed in this experiment. The relatively consistent degree of distraction across these studies is somewhat surprising and suggests that *cognitive distractions* may be as important as the more obvious *structural distractions*. The highly demanding visual task used in this experiment increased the drivers' reaction time only slightly more than a speech-based interface. This was true even though the speech-based interaction did not pose any *structural distraction* due to manual control demands (e.g., there was no button pressing and drivers kept their hands on the steering wheel) or visual demands (e.g., the drivers were able to keep their eyes on the road at all times). These results suggest the cognitive demands that in-vehicle devices place on drivers are critically important. The safety benefit of the warning observed for the undistracted drivers suggests RECAS warnings can effectively focus drivers' attention and may benefit drivers facing *cognitive distractions*. Thus, a collision warning system is likely to mitigate the distraction associated with speech-based interactions with in-vehicle computers and cellular telephone conversations, as well as the *structural distractions* associated with visually demanding tasks. However, this conclusion must be tempered by considering the challenges and opportunities associated with integrating warning systems into the vehicle.

Potential benefits and challenges for mitigating distraction using collision warning systems

These experiments demonstrate a clear benefit of collision warnings for distracted and undistracted drivers. The consistent effect of *cognitive* and *structural distractions* on driver reaction time suggests that the benefit seen in these experiments may generalize to types of distractions beyond the demanding visual distraction used in these experiments. The validity of this claim depends on how the system is designed and how drivers respond and adapt to the combination of the collision warning system, the in-vehicle information systems, and the driving environment. Design strategies could enhance the benefit of the warning, but driver adaptation could undermine the benefit.

One design strategy for in-vehicle information systems builds on the assumption that certain in-vehicle systems will distract attention away from the road and others can direct attention back to the road. Coordinating potentially distracting systems with collision warning systems could further enhance the ability of the collision warning system to mitigate distraction. Currently, most in-vehicle information systems are designed independently and are not integrated. A design approach that integrates the in-vehicle functions could greatly enhance the collision warning system by dynamically adjusting the collision warning threshold according to whether the driver is engaged with a potentially distracting device. For example, the collision warning system could generate a warning earlier if it detects that the driver is involved in a cellular telephone conversation.

Integrating potentially distracting systems with collision warning systems may be a particularly powerful strategy to mitigate driver distraction; however, behavioral adaptation may increase drivers' reliance on the warning system, undermining the joint performance of the human and the collision warning system. Trust in the capabilities of technological aids has been shown to underlie reliance on automation and information systems (Lee & Moray, 1994; Muir, 1987) and in-vehicle information systems in particular (Kantowitz, Hanowski, & Kantowitz, 1997). Effective use of RECAS depends on the calibration of trust. If a driver's trust exceeds RECAS capabilities then the warnings may be relied upon excessively and drivers' attention to the roadway may decline. Several recent studies show that decision aids can have negative consequences if trust is not properly calibrated with the capabilities of the aid. An aid used by inexperienced decision makers led to seemingly mechanistic responses to the aid's guidance and decision makers failed to become actively involved in the task or judgement (Glover, Prawitt, & Spilker, 1997). Thus, the aid enhances performance when the aid provides valid advice, but undermines performance when its advice is not valid. Similarly, cueing (e.g., highlighted) targets in a visual detection task can enhance detection for expected targets, but cueing can undermine detection of uncued targets (Yeh, Wickens, & Seagull, 1998). Falsely cued targets can also lead people to incorrectly identify targets and react inappropriately (Conejo & Wickens, 1998). It is possible that the demands of in-vehicle information systems could encourage drivers to rely on the collision warning system as their primary alert to collision situations, rather than as a backup to their ability to detect collision situations. The experiments presented here were not long enough for drivers to adapt to the system and did not explore the potential for drivers to develop biases in their trust of the warning system. If such adaptation occurs, the warning system could have the unintended consequence of encouraging greater use of potentially distracting systems and ultimately degrading driving safety.

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