The Impact of Distraction Mitigation Strategies on Driving Performance

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Objectives: An experiment was conducted to assess the effects of distraction mitigation strategies on drivers’ performance and productivity while engaged in an in-vehicle information system task. Background: Previous studies show that in-vehicle tasks undermine driver safety and there is a need to mitigate driver distraction. Method: An advising strategy that alerts drivers to potential dangers and a locking strategy that prevents the driver from continuing the distracting task were presented to 16 middle-aged and 12 older drivers in a driving simulator in two modes (auditory, visual) and two road conditions (curves, braking events). Results: Distraction was a problem for both age groups. Visual distractions were more detrimental than auditory ones for curve negotiation, as depicted by more erratic steering, $F(6, 155) = 26.76$, $p < .05$. Drivers did brake more abruptly under auditory distractions, but this effect was mitigated by both the advising, $t(155) = 8.37$, $p < .05$, and locking strategies, $t(155) = 8.49$, $p < .05$. The locking strategy also resulted in longer minimum time to collision for middle-aged drivers engaged in visual distractions, $F(6, 138) = 2.43$, $p < .05$. Conclusions: Adaptive interfaces can reduce abrupt braking on curve entries resulting from auditory distractions and can also improve the braking response for distracted drivers. Application: These strategies can be incorporated into existing in-vehicle systems, thus mitigating the effects of distraction and improving driver performance.

INTRODUCTION

Driver distraction can be defined as the diminished attention of the driver to the driving task. The introduction of in-vehicle information systems (IVISs) raises concerns because the conflict between in-vehicle and driving task demands may increase driver distraction. A driver’s willingness to engage in a nondriving-related task and the attentional demands placed on the driver by that task both contribute to the potential for distraction. In addition to the safety considerations associated with distraction, productivity issues associated with IVIS interactions may also arise. IVIS task performance may degrade as in-vehicle tasks are interrupted by drivers’ need to shift attention back to the road (Dismukes, Young, & Sumwalt, 1998; Latorr ella, 1998; Monk, Boehm-Davis, & Trafton, 2002). Development of design strategies that mitigate driver distraction and preserve productive interactions with IVIS is a critical, but unaddressed, issue (Lee & Strayer, 2004).

Taxonomy of Driver Distraction Mitigation Strategies

Mitigation strategies can be described according to several dimensions. Three particularly important dimensions are (a) the degree of automation (Parasuraman, Sheridan, & Wickens, 2000; Sheridan, 2002), (b) type of initiation (Morris, Rouse, & Sharon, 1998), and (c) type of task (Ranney, Mazzae, Garrott, & Goodman, 2000). The degree of automation can be considered in terms of the technology implemented to reduce driver distraction, and recent reviews of automation and its effect on operator performance provide valuable insights that highlight the advantages and disadvantages of various distraction mitigation strategies (Lee & See, 2004; Parasuraman et al., 2000; Sheridan, 2002). The strategy can be either system or operator initiated, and depending on the task allocation between the system and the operator, this can significantly affect the workload experienced by the driver (Leiser, 1993; Parasuraman...
et al., 2000; Rouse, 1994). A system-initiated mitigation strategy may reduce demand in highly distracting situations; however, it also has the potential to increase demands when the system intervenes unexpectedly (Sarter & Woods, 1994). In contrast, the locus of control is with the driver for driver-initiated strategies, but this can burden the driver with the task of managing the interaction with the IVIS. The third dimension that defines mitigation strategies is the type of task modulated by the strategy (Ranney et al., 2000; Wierwille, 1993). Driving-related and nondriving-related tasks compete for driver attention, and mitigation strategies can be designed to modulate attention to each of these types of task. Table 1 shows a taxonomy of 12 unique mitigation strategies defined by these three dimensions and verified with an extensive literature review that was further validated with focus group studies (Donmez, Boyle, & Lee, 2003).

System-initiated strategies under the category of driving-related tasks aim to enhance safety by directing driver attention back to the roadway as well as by directly intervening to control the vehicle. Driving-related, driver-initiated strategies mitigate distraction by having the driver activate or adjust system controls that relate to the driving task. Nondriving-related, system-initiated strategies build on the idea that when driving performance is significantly deteriorating or is likely to do so, the system will take action and change the nature of the nondriving-related task in which the driver is engaged. Nondriving-related, driver-initiated strategies rely on drivers to modulate their own nondriving tasks according to their perceived degree of distraction.

Previous research has mainly focused on driving-related strategies such as intervening (e.g., automatic braking systems), warning (e.g., collision warning systems), and informing (e.g., speed indicator). In terms of nondriving-related strategies, demand minimizing and prioritizing and filtering have been previously investigated as potential means of reducing distraction (Brown & Hook, 1993; Nunes & Recarte, 2002; Verwey, 1993, 2000). Therefore, the strategies that most merit further investigation include nondriving-related strategies such as locking and interrupting and advising. Locking and interrupting, a high-level automation strategy, discontinues nondriving activities by intervening to halt drivers’ interaction with the system at times when the primary driving task requires attention. Advising, a low-level automation strategy, advises drivers to discontinue their nondriving-related task. These two strategies were chosen for further investigation for several reasons. They represent the extreme points of automation under the nondriving-related, system-initiated mitigation strategies. The nondriving-related strategies are scarce in research when compared with the driving-related strategies but represent an area of growing concern with IVIS. Because the driver-initiated strategies depend highly on the subjective distraction level of the driver and do not promise the same level of effectiveness, they were not considered.

This study investigated locking and advising strategies for mitigating auditory and visual distraction because previous research has shown that nondriving tasks in these modalities can distract drivers and that they have different effects on driving performance (Cooper & Zheng, 2002; Cooper et al., 2003; Lee, McGehee, Brown, & Reyes, 2002). Visual tasks that induce visual and cognitive distractions (particularly those that require

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<th>Level of Automation</th>
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<td>System Initiated</td>
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<td>High</td>
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<td>Low</td>
<td>Informing</td>
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extensive glances away from the roadway) undermine vehicle control more dramatically as compared with auditory tasks that induce cognitive distractions (Parkes & Coleman, 1990; Wickens, Sandry, & Vidulich, 1983). However, tasks with no visual component, such as speech-based E-mail, can also slow drivers’ response to a lead vehicle’s periodic braking (Lee, Caven, Haake, & Brown, 2001). When compared with a control group, a group that received speech-based E-mail had a 30% (310 ms) higher average reaction time. Strayer and Drews (2004) also showed that drivers took 17% longer to recover the speed that was lost following braking when drivers were engaged in hands-free cell phone conversations (auditory distraction). Lamble, Kauranen, Laakso, and Summala (1999) found that brake reaction time increased by 0.48 s when drivers had to divide their visual attention between the road ahead and a visual distraction task; approximately the same increase was experienced by drivers who divided their attention between driving and performing a memory and addition task.

The purpose of this research was to investigate whether driver distraction mitigation strategies can reduce driver distraction. The primary hypothesis of this research is that the effects of distraction can be mitigated with system-initiated strategies. Based on this hypothesis, two promising strategies (advising and locking) were chosen for evaluation in a driving simulator experiment. As part of the study, an assessment of the influence of different mitigation strategies on in-vehicle task performance was also conducted.

This experiment sought to answer the following questions: How do auditory and visual distractions affect driving performance? Which mitigation strategy most improves driving performance, and does the effect depend on whether the mode is visual or auditory? How do these strategies influence secondary task performance?

**METHOD**

The primary objective of this experiment was to assess the effects of different driver distraction mitigation strategies on driver performance as well as on the productivity of the driver interacting with IVISs. Specifically, the experiment evaluated the effectiveness of a potential IVIS design that adapts to roadway demands and directs the driver’s attention to the driving task when roadway demands peak.

**Participants**

Middle-aged drivers between 35 and 55 years of age typically have the lowest crash risk (Cooper, 1990; McGwin & Brown, 1999) and were included in this study as a baseline. However, it is also important to understand how aging influences the use of distraction mitigation strategies. Therefore, an older group of drivers between 65 and 75 years of age was also included in the study. The sample of older drivers was limited to this age group because studies have shown that there are significant differences in driving performance between drivers 65 to 75 years old and those older than 75 (Cooper, 1990). Because this was one of the first studies to investigate the effects of advising and locking strategies on driving performance, other older driver groups were excluded to reduce confounding effects attributable to driving performance variability. These two age groups (middle aged and older) were investigated because they represent likely buyers of vehicles equipped with advanced IVISs.

Equal numbers of participants were recruited in each age group. However, because of withdrawals from the experiment, 16 drivers in the middle-age group (range 35–55 years, \(M = 45\), standard error = 4.27) and 12 in the older driver group (range 65–75 years, \(M = 69\), standard error = 3.26) completed the study, for a total of 28 participants. All participants possessed a valid U.S. driver’s license, had at least 5 years of driving experience, were native English speakers, and had not participated in a simulation study within the past 2 years. The participants were monetarily compensated for their participation in this experiment, with each driver earning an average of $10/hr.

**Experimental Design**

*Independent variables.* There were two levels for each of the three factors: age (middle aged, older), mitigation strategy (advising, locking), and IVIS demand (visual, auditory). Age was a between-subjects variable, whereas mitigation strategy and IVIS demand were within-subjects variables.

The two levels of distraction mitigation strategies (advising and locking) were implemented to either advise the driver to discontinue the non-driving-related task or to terminate the interaction with the system completely. Both strategies were
mapped to driving events that required a response from the driver, independent of the driver’s IVIS task performance. These two events were lead vehicle braking and curve entry. Curve entry refers to a 5-s road section consisting of a 2-s straight section before the curve and then a 3-s section of the curve itself (assuming 20 m/s vehicle speed). The participants were informed that the system would either advise them or lock them out when the roadway required their attention, specifically when the lead vehicle was braking or there was a curve ahead.

The IVIS demands included visual and auditory secondary tasks. These tasks, which were based on the working memory span task (Baddeley, Logie, & Nimmo-Smith, 1985), were displayed to the participant via a peripheral display for the visual task and by a synthetic voice for the auditory task. The secondary task provided a controlled exposure to the visual, auditory, manual, and cognitive distraction associated with IVIS interaction and was similar to the tasks used in other driver distraction studies (Jamson, Westerman, Hockey, & Carsten, 2004; Radeborg, Briem, & Hedman, 1999; Salvucci, 2002). Although the secondary task was somewhat artificial as compared with actual interactions with in-vehicle systems, it provided precise control over the amount of external demand posed on drivers.

In both the visual and auditory conditions, the participant had to respond to the task verbally and by pressing a button located on the steering wheel. Specifically, the secondary task required drivers to determine whether or not a short sentence was meaningful, to respond by pushing steering wheel buttons, and then also to recall the subjects of three consecutive sentences in a verbal response. Participants recalled the three subject words after they were presented with all three sentences. For example, “the policeman ate the apple” is meaningful and its subject is “policeman,” whereas “the apple ate the policeman” is not meaningful and its subject is “apple.” The set of three sentences were presented to participants at 5-s intervals. The participants were also provided with a 10-s pause in which to verbally recall the subject words before a new set of three sentences was presented.

Participants were monetarily rewarded depending on their performance on the secondary task. This part of the design was included to more realistically simulate drivers’ interaction with an IVIS by ensuring that the secondary task was important to the driver. Feedback regarding performance with the secondary task was provided to the participant at the end of each drive.

Driving task. All scenarios took place on two-lane rural roads without any oncoming traffic. A constant level of fog (sight distance: 300 m) was employed during each scenario to diminish the drivers’ ability to anticipate an approaching curve. Before a lead vehicle braking event, the lead vehicle speed was smoothly adjusted to maintain a constant time headway of 1.8 s. Twelve braking events took place in each driving scenario. Half of these braking events were on curves, and the other half were on the straight sections of the drive. In order to make the scenario more realistic, we used different radius curves: Half of the curves had a 400-m radius (three left and three right turns), and the other half had a 200-m radius (three left and three right turns).

There were separate drives for each visual and auditory task and each strategy combination, resulting in a total of six drives (i.e., four drives with a strategy-IVIS demand combination and two baseline drives). For the visual demand, advising was implemented as a red bezel around the screen on which the IVIS task was displayed. The red bezel was illuminated for 5 s whenever there was a lead vehicle braking or curve entry ahead. In the advising condition, the driver was able to continue to interact with the system. The locking strategy blanked the screen and illuminated the red bezel, preventing the driver from interacting with the system. The red bezel and the lockout remained in effect until the triggering condition ended (i.e., the lead vehicle braking or curve entry). For the auditory strategy, advising was implemented with a periodic clicking noise (1 Hz) for 5 s and was also initiated whenever there was a lead vehicle braking or curve entry ahead. In the advising condition, the driver could continue to interact with the system. The locking strategy stopped the message presentation and presented the periodic clicking noise (1 Hz) to the driver. The locking remained in effect until the triggering condition was over.

The two baseline drives were divided into two parts each. During the first half of the drives, participants encountered no secondary task and no mitigation strategy. This represented the no-IVIS-demand condition. In the second half of the baseline drives, participants were presented with either the visual or the auditory secondary task.
This represented one of the two distracted-only scenarios (either visual or auditory).

Dependent variables. The primary dependent measures of driving performance were the response to the lead vehicle braking events and curves and performance on the secondary task. As outlined in Figure 1, some measures have a relatively direct relationship to safety (i.e., minimum time to collision, minimum acceleration, and steering entropy), whereas other measures describe the response process that leads to the safety-relevant outcomes. The response for each roadway event (lead vehicle braking and curve negotiation) can be described in terms of three sets of variables. A pre-event phase defines how the driver adapts and how that adaptation influences initial conditions at the event onset. An event-response phase describes the driver’s closed-loop behavior in accommodating the event. A third set of variables describes the outcome of the response process and defines the safety parameters. The mitigation strategy influences the pre-event adaptation and the closed-loop response to the event.

In the lead vehicle braking events, the pre-event phase is defined by participants’ speed at the onset of the lead vehicle braking, which affects drivers’ response to the braking event. The response process is defined by the accelerator release time from the onset of the braking event, the inverse time to collision at accelerator release, and the transition time from the accelerator to the brake. Time to collision (TTC) is defined as the distance between the participant and lead vehicles divided by the relative velocity (i.e., the time that a collision would occur if the driver were to proceed at constant speed). TTC cannot be used directly at the moment of accelerator release because the participant and lead vehicle velocities at that point may be equal, resulting in infinite TTC values. Based on the instantaneous data, a collision would then never occur. Inverting TTC transforms the data, so that zero represents a noncollision situation and a large inverse TTC represents the need for a faster response to avoid a collision. The transition time from the accelerator to the brake pedal is the time interval between the participant releasing the accelerator and applying the brake.

The primary safety measure is defined by the

![Figure 1. The interrelationships among the dependent variables during the pre-event, event (response process), and postevent (or safety outcome) phases.](image-url)
minimum TTC and minimum acceleration. TTC has been proposed and used as a crash-avoidance metric in forward collision avoidance systems (Minderhoud & Bovy, 2001; Vogel, 2003). Minimum TTC is the shortest TTC during a braking event if the participant were to continue in the same path at the same velocity. Thus, an increase in this variable would indicate a safety benefit. Minimum acceleration is defined as the lowest acceleration (or highest deceleration) value reached by the participant, indicating the braking intensity. An increase in the minimum acceleration would also indicate a safety benefit. More severe braking associated with a greater maximum deceleration increases the probability of being struck from the rear (Lee et al., 2002).

For evaluating driving performance on curve negotiations, the pre-event adaptation is once again defined by speed in approaching the curve. The response to the curve is measured by average acceleration on curve entry and speed at maximum curvature. Steering entropy was the primary measure of safety for evaluating curve negotiation because it reflects discontinuities in steering behavior associated with degraded control (Nakayama, Futami, Nakamura, & Boer, 1999). In this case, an increase in steering entropy reflects degraded safety.

It is important to consider how the mitigation strategies may also affect secondary task productivity. Therefore, the performance of the secondary tasks was measured using percentage of verbal recall success, which measured the performance of working memory, and percentage of correct button pushes, which measured performance in judging semantic coherence. These are not indicators of safety but, rather, measures of how the mitigation strategies interfere with the in-vehicle tasks.

**Apparatus**

The experiments were conducted with a medium-fidelity, fixed-based simulator powered by a Global Sim, Inc., DriveSafety™ Research Simulator, a fully integrated, high-performance driving simulation system designed for use in ground vehicle research and training applications. The simulator has a 1992 Mercury Sable vehicle cab with a 50° visual field. The cab was equipped with a force feedback steering wheel, actual gauges, and a rich audio environment. State-of-the-art PC hardware was employed to generate fully textured graphics with 60-Hz frame rate at 1024 × 768 resolution. The driving scenarios were created using HyperDrive™ Authoring Suite. All graphics for roadway layouts, markings, and signage conform to the American Association of State Highway and Transportation Officials and the Manual of Uniform Traffic Control Devices design standards. Driving data were collected at 60 Hz.

A 7-inch (~17.8-cm) LCD (60-Hz frame rate at 640 × 480 resolution) was mounted on the dash above the center instrument panel with a small stand and used for presentation of the visual messages in the secondary task. The display was positioned 15 inches (~40 cm) to the right of the center of the steering wheel and 3 inches (~8 cm) above the center of the speedometer. With respect to the driver, the screen was turned approximately 15° toward the driver and located 32.5° lateral to and 15.4° below the driver’s line of sight. The messages displayed on this LCD were designed using Arial Bold font in 20-point type.

Auditory messages used in the secondary task were converted into .wav audio files through the Ultra Hal Text-to-Speech Reader, Version 1.0, created by Zabaware, Inc. The voice used for conversion is “Sam,” a Microsoft SAP14 Text-to-Speech Synthesis Machine. The “Sam” voice is described as an adult male, low-accented, North American English native voice. Both of the message systems (visual and auditory) were operated on a standard PC in Microsoft Visual Basic.

**Procedure**

Upon arrival, participants read and signed the study consent form and were briefed on the activities to be completed. The total test time was approximately 4 hr. Participants were initially asked to complete two practice drives of 5 min each. These drives were designed to allow participants to become familiar with the simulator, the driving environment, and the visual and auditory secondary tasks. The first half of each practice drive consisted of simulator acclimation. In the second half, participants could practice either the visual task or the auditory task while driving. After completing the practice drives, participants proceeded on to the six experimental drives (four strategies and two baseline drives), each lasting about 20 min. The order was randomized across participants. Participants were instructed to drive at a comfortable speed that did not exceed the speed limit of 45 miles/hr (~72 km/hr) and to follow a lead vehicle that periodically braked at a mild rate of
deceleration (0.2 g) for 5 s. If participants performed well on the secondary task while driving through the scenarios, they received a bonus (of up to $10) in addition to their compensation. This bonus was based on the average of correct button push and correct verbal recall response percentages. Participants also took a short break between drives. At the end of the study, participants were debriefed.

RESULTS

The mitigation strategy and the IVIS demands were collapsed into one factor, called strategy, consisting of seven levels: visual advising, visual locking, visual none, auditory advising, auditory locking, auditory none, and no distraction. “No distraction” indicates the lack of a secondary task and strategy, and “none” indicates the lack of a strategy even though a secondary task was present. Because of missing treatment combinations (e.g., an advising strategy when there is no distraction is not a feasible condition), these levels were collapsed for analysis based on a strategy described by Milliken and Johnson (1992). The resulting experiment is a $2 \times 7$ repeated measures design with age (two levels) as a between-subjects factor and strategy (seven levels) as a within-subjects factor with repeated measures. The mixed linear model used to analyze the data (PROC MIXED statement in SAS 9.0) takes into account an unbalanced design (i.e., different numbers of participants) with missing treatment combinations. A compound symmetry covariance structure was chosen for repeated measures. $F$ tests on main and interaction effects (Table 2) and pairwise comparisons between different levels of the significant effects were performed. The significant pairwise comparisons of the least square means, with the $p$ values adjusted using the Tukey-Kramer procedure (Kramer, 1956), will be discussed further.

The auditory and visual demands affected driving performance differently, and drivers’ response to the mitigation strategies depended on the event (i.e., lead vehicle braking or curve entry). In general, advising and locking strategies improved driver’s performance, but the influence depended on the type of distraction.

Lead Vehicle Braking

Before the lead vehicle began to brake, drivers adopted slower speeds when distracted (i.e., drove more cautiously) as compared with when they were not distracted (Figure 2), visual none versus no distraction: $t(138) = –3.92$, $p < .05$; auditory none versus no distraction: $t(138) = –3.54$, $p < .05$. None of the strategies reversed this tendency ($p > .05$). For visual distractions, drivers maintained higher speeds with the advising strategy than with the locking strategy, $t(138) = 2.00$, $p < .05$. With higher speeds, the headway distance is longer, as a constant headway time was fixed at 1.8 s. Longer separation between vehicles results in smaller visual angles and a less salient braking event. The higher speeds and smaller visual angles influence accelerator release time, inverse TTC, and accelerator-to-brake transition time.

The drivers’ accelerator release times were generally longer with higher speeds (Pearson correlation coefficient = .15, $p < .05$). One would expect that distractions, in general, would always generate longer accelerator release times. However, given that speed influences the cues that affect drivers’ responses to the braking event, there were no differences between the visual distraction and the no-distraction baseline ($p > .05$), and auditory distractions actually resulted in shorter accelerator release times, $t(138) = –2.08$, $p < .05$ (Figure 3a). Similarly, because drivers maintained faster speeds with visual advising, their accelerator release times were longer with this strategy than with visual locking, $t(138) = 2.23$, $p < .05$. Despite the fact that there were no differences in speed between visual advising and visual none, visual advising resulted in longer accelerator release times, $t(138) = 2.44$, $p < .05$.

The criticality of the situation at the point of accelerator release can be assessed with inverse TTC (Figure 3b). Among all strategies, only visual advising resulted in a more critical situation for the driver when compared with the situation experienced without the mitigation strategy, visual advising versus visual none: $t(138) = 2.99$, $p < .05$; visual advising versus no distraction: $t(138) = 3.50$, $p < .05$; visual advising versus visual locking: $t(138) = 2.02$, $p < .05$. Visual advising seems to induce a higher speed, which may contribute to a longer accelerator release time, which then leads to a high inverse TTC. Despite the fact that distractions did not induce a more critical situation at the point of accelerator release ($p > .05$), they did induce faster transition times from the accelerator to brake pedal (Figure 3c), visual none versus no distraction: $t(138) = –3.35$, $p < .05$; auditory...
## TABLE 2: Overall Statistical Significance of Main and Interaction Effects

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<tr>
<th>Response Variable</th>
<th>Independent Variables</th>
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<tr>
<td><strong>Lead vehicle braking</strong></td>
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<tr>
<td>Pre-event adaptation</td>
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<tr>
<td>Speed at lead vehicle brake onset</td>
<td>( F(1, 26) = 0.43, ) ns</td>
<td>( F(6, 138) = 5.34, p &lt; .05, \eta_p^2 = .19 )</td>
<td>( F(6, 138) = 0.33, ) ns</td>
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<tr>
<td>Response process to event</td>
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<tr>
<td>Accelerator release time</td>
<td>( F(1, 26) = 1.53, ) ns</td>
<td>( F(6, 138) = 2.97, p &lt; .05, \eta_p^2 = .15 )</td>
<td>( F(6, 138) = 0.64, ) ns</td>
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<tr>
<td>Inverse TTC at accelerator release</td>
<td>( F(1, 26) = 1.29, ) ns</td>
<td>( F(6, 138) = 3.87, p &lt; .05, \eta_p^2 = .17 )</td>
<td>( F(6, 138) = 1.03, ) ns</td>
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<tr>
<td>Transition time from accelerator to brake pedal</td>
<td>( F(1, 26) = 0.11, ) ns</td>
<td>( F(6, 138) = 3.78, p &lt; .05, \eta_p^2 = .24 )</td>
<td>( F(6, 138) = 0.27, ) ns</td>
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<td>Safety outcome based on event</td>
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<td>Minimum TTC</td>
<td>( F(1, 26) = 0.40, ) ns</td>
<td>( F(6, 138) = 6.35, p &lt; .05, \eta_p^2 = .24 )</td>
<td>( F(6, 138) = 2.43, p &lt; .05, \eta_p^2 = .10 )</td>
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<td>Minimum acceleration</td>
<td>( F(1, 26) = 1.96, ) ns</td>
<td>( F(6, 138) = 3.90, p &lt; .05, \eta_p^2 = .17 )</td>
<td>( F(6, 138) = 0.44, ) ns</td>
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<td><strong>Curve</strong></td>
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<td>Pre-event adaptation</td>
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<td>Speed approaching a curve</td>
<td>( F(1, 26) = 1.55, ) ns</td>
<td>( F(6, 155) = 6.65, p &lt; .05, \eta_p^2 = .22 )</td>
<td>( F(6, 155) = 1.55, ) ns</td>
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<td>Response process to event</td>
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<tr>
<td>Average acceleration on curve entry</td>
<td>( F(1, 26) = 3.30, ) ns</td>
<td>( F(6, 155) = 23.58, p &lt; .05, \eta_p^2 = .47 )</td>
<td>( F(6, 155) = 0.33, ) ns</td>
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<td>Speed at maximum curvature</td>
<td>( F(1, 26) = 0.76, ) ns</td>
<td>( F(6, 155) = 2.30, p &lt; .05, \eta_p^2 = .08 )</td>
<td>( F(6, 155) = 1.17, ) ns</td>
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<td>Safety outcome based on event</td>
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<td>Steering entropy</td>
<td>( F(1, 26) = 0.00, ) ns</td>
<td>( F(6, 155) = 26.76, p &lt; .05, \eta_p^2 = .51 )</td>
<td>( F(6, 155) = 0.47, ) ns</td>
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<td><strong>Productivity</strong></td>
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<td>Button push %</td>
<td>( F(1, 26) = 7.66, p &lt; .05, \eta_p^2 = .23 )</td>
<td>( F(5, 130) = 8.44, p &lt; .05, \eta_p^2 = .25 )</td>
<td>( F(5, 130) = 0.6, ) ns</td>
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<td>Verbal recall %</td>
<td>( F(1, 26) = 2.84, ) ns</td>
<td>( F(5, 130) = 0.89, ) ns</td>
<td>( F(5, 130) = 0.7, ) ns</td>
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Note: \( \eta_p^2 \) is one measure of effect size and is calculated as \( SS(\text{effect})/(SS(\text{effect}) + SS(\text{error})) \) where SS is the Sum of Squares.
none versus no distraction: \( t(138) = -3.62, p < .05 \). That is, drivers had generally longer transition times when there were no distractions.

As expected, both advising and locking strategies during an auditory distraction helped drivers maintain higher minimum TTC values (Figure 4a), auditory advising versus auditory none: \( t(138) = 3.25, p < .05 \); auditory locking versus auditory none: \( t(138) = 3.94, p < .05 \). Therefore, both advising and locking during an auditory distraction have the potential to help drivers maintain a greater safety margin when the lead vehicle brakes. In addition to this benefit, both strategies helped drivers during auditory distractions by increasing the minimum accelerations (or lowering maximum deceleration; Figure 4b), auditory advising versus auditory none: \( t(138) = 3.48, p < .05 \); auditory locking versus auditory none: \( t(138) = 3.34, p < .05 \). Advising and locking for auditory distractions also resulted in higher minimum TTC when compared with the conditions with no distractions, auditory advising versus no distraction: \( t(138) = 4.01, p < .05 \); auditory locking versus no distraction: \( t(138) = 4.79, p < .05 \). A similar effect was observed for minimum acceleration, auditory advising versus no distraction: \( t(138) = 2.40, p < .05 \); auditory locking versus no distraction: \( t(138) = 2.26, p < .05 \). Visual locking also resulted in higher minimum TTC values when compared with the no-distraction condition, \( t(138) = 2.01, p < .05 \). This is consistent with previous results that show collision warnings can benefit both distracted and undistracted drivers (Lee et al., 2002). For visual distractions, advising did not have significant effects on minimum TTC or minimum acceleration. The lack of benefit for visual advising may be explained by the high initial speed, long reaction time, and high inverse TTC when the accelerator was released.

**Curves**

In general, drivers performing secondary tasks, both visual and auditory, approached the curves with lower speeds as compared with drivers with no distractions (Figure 5), visual none versus no distraction: \( t(155) = -6.01, p < .05 \); auditory none versus no distraction: \( t(155) = -3.49, p < .05 \). Visual distraction resulted in speeds that were even slower than those for auditory distractions, visual none versus auditory none: \( t(155) = -2.18, p < .05 \). When a mitigation strategy was introduced during visual distractions, drivers maintained higher speeds and approached curves as if they were not distracted, visual advising versus visual none: \( t(155) = 3.91, p < .05 \); visual locking versus visual none: \( t(155) = 3.36, p < .05 \).
Figure 3. Response process to lead vehicle braking event by age and mitigation strategies: the mean (and standard error) of (a) accelerator release time, (b) the inverse TTC at brake onset, and (c, on the following page) transition time from brake to accelerator pedal.
Drivers still had to brake hard on curve entries during auditory distractions despite the lower speeds (Figure 6a), auditory none versus no distraction: $t(155) = -9.85, p < .05$. In contrast, visual distractions resulted in a slight acceleration on the curve entries, visual none versus no distraction: $t(155) = 2.51, p < .05$. Drivers with auditory distractions entered curves more slowly, but they did not slow down as much as under the visual distraction condition. Nevertheless, drivers under auditory distractions braked strongly, suggesting that they still perceived their speeds to be too fast. With the mitigation strategies, drivers did not brake as hard under auditory distractions, indicating a system benefit, auditory advising versus auditory none: $t(155) = 8.37, p < .05$; auditory locking versus auditory none: $t(155) = 8.49, p < .05$.

Given the higher speeds noted earlier for the visual strategies, drivers had to brake mildly on the curve entries, which was also observed in the no-distraction condition, visual advising versus visual none: $t(155) = -3.44, p < .05$; visual locking versus visual none: $t(155) = 3.80, p < .05$. The two mitigation strategies induced slightly higher curve entry speeds and decelerations through the curve for both auditory and visual distractions. There were no significant differences in speed across conditions at the point of maximum curvature (Figure 6b), $p > .05$.

Steering entropy provides an indicator of safety during curve negotiation, and the analysis shows that drivers were more erratic on curves when they encountered distractions (Figure 7), visual none versus no distraction: $t(155) = 10.01, p < .05$; auditory none versus no distraction: $t(155) = 6.48, p < .05$. This effect was more profound with visual distractions than with auditory distractions, $t(155) = 3.05, p < .05$). The strategies did not significantly mitigate the erratic steering induced by auditory distractions. However, visual locking resulted in less erratic steering when compared with both visual advising, $t(155) = 1.99, p < .05$, and visual none, $t(155) = 2.02, p < .05$.

**Age**

There was a significant interaction between system strategies and age for minimum TTC. For auditory distractions, older drivers had higher minimum TTC with the locking strategy than with the advising strategy, $t(138) = 2.13, p < .05$. Moreover, auditory advising resulted in higher minimum TTC for middle-aged drivers than for older drivers, $t(138) = 2.07, p < .05$. There were no significant
Figure 4. Safety outcome based on lead vehicle braking event by age and mitigation strategies: the mean (and standard error) of (a) minimum TTC and (b) minimum acceleration.
differences for auditory locking between the two age groups or between auditory advising and auditory locking for middle-aged drivers ($p > .05$). Therefore, under auditory distractions, both advising and locking strategies were beneficial for older and middle-aged drivers. However, older drivers benefited more from the locking strategy. For visual distractions, middle-aged drivers had longer minimum TTC with the locking strategy when compared with their visually distracted and nondistracted baselines, visual locking versus visual none: $t(138) = 2.56, p < .05$; visual locking versus no distraction: $t(138) = 3.50, p < .05$.

Secondary Task Performance

Understanding how to design in-vehicle systems to mitigate distraction is critical. However, even if the main objective of distraction mitigation strategies is to enhance safety, these strategies should also aim to enhance the productivity of the driver interacting with an IVIS or at least protect it from deteriorating. Otherwise, mitigation strategies may frustrate drivers, which may in turn cause more distractions. Performance of the secondary task was measured in terms of button push accuracy (i.e., how well drivers were able to determine the meaningfulness of the sentence; Figure 8a) and verbal recall (i.e., how well they remembered the subject words; Figure 8b). Middle-aged drivers did better on the tasks than did older drivers as measured by button push accuracy (Figure 8a), $t(26) = 2.77, p < .05$. Drivers had greater button push accuracy with the visual secondary task than with the auditory task (Figure 8a), $t(130) = 4.46, p < .05$. This may have been attributable in part to the difficulty of comprehending the synthetic voice used in the experiment. Another potential reason is the longer availability of the visual task as compared with the auditory task (Wickens & Hollands, 1999). When drivers were exposed to the mitigation strategies, driving performance improved and the secondary task performance did not significantly deteriorate ($p > .05$). Therefore, the strategies tested allowed drivers to time-share better, and that benefit was observed in their driving performance.

DISCUSSION

The purpose of this study was to assess the efficacy of two distraction mitigation strategies in addressing the effects of auditory and visual distraction. Consistent with previous studies, distracting tasks affected driver response to curves and braking lead vehicles (Lamble et al., 1999; Lee et al., 2002). On the curves, steering entropy was
Figure 6. The mean (and standard error) of (a) average acceleration on curve entry and (b) speed at maximum curvature by age and mitigation strategies.
higher when drivers encountered distractions, indicating that visual and auditory tasks caused more erratic steering behavior. Visual distractions were more detrimental to steering stability than were auditory distractions. On curve entries, auditory distractions led to more abrupt braking than that found in the baseline and visual distraction conditions. Although studies have shown that visual tasks undermine vehicle control more than auditory tasks do (Parkes & Coleman, 1990; Wickens et al., 1983), this result shows that the consequences of auditory distractions and visual distractions differ not only in magnitude but also in type (Young & Angell, 2003).

Braking behavior is a closed loop response, and drivers modulate their behavior according to evolving situations (Lee et al., 2002). Thus, when investigating driver response to a lead vehicle braking event, one needs to consider the interaction among multiple variables. For the two primary safety measures, minimum TTC and minimum acceleration, no significant differences were observed between the undistracted and distracted cases. The speeds, however, were clearly slower when a distraction (auditory or visual) was present, indicating that drivers did adjust their car-following behavior. Distractions also caused drivers to transition more quickly from the accelerator to the brake. The slower transition times in the undistracted conditions suggest more controlled braking responses. The faster transition time in the distracted conditions can explain the lack of significance for the effects of distractions on overall safety outcome measures (minimum TTC and minimum acceleration). Drivers in our study compensated and maintained performance even if components of the response process were degraded (e.g., slower speeds). Similar findings were shown by Boyle and Mannering (2004), who found that the net safety outcome was not observed across different driver information systems but that differences in behavior within varying time intervals influenced the long-term benefits of the system. Thus, even though safety outcomes may not reveal differences between distracted and nondistracted baseline cases, the pre-event and response process events show systematic differences.

The mitigation strategies had a generally positive effect on driver performance. However, the benefit of these strategies was not the same for the two types of distractions and for the two age groups. For auditory distractions, both advising and locking resulted in higher minimum TTC for braking responses and in milder braking on the curves. For older drivers, the locking strategy was more beneficial than the advising strategy. The
Figure 8. Productivity with the secondary task: the mean (and standard error) of (a) percentage button push performance and (b) percentage verbal recall success.
auditory strategies provided the best benefits during lead vehicle braking events. These systems may also decrease the likelihood of being rear-ended by inducing a smoother deceleration. These results suggest that the benefits of mitigation strategies depend on the type of in-vehicle system and the system demands.

The mitigation strategies influenced drivers’ immediate response to events as well as their more general adaptation to the driving and IVIS tasks, such as speed selection. Drivers tended to compensate for distractions by slowing down on curve entries; speeds were relatively low when drivers were engaged in a distracting task with no mitigation strategies. However, with auditory distractions this adaptation was not sufficient, and drivers felt the need to slow even more and to brake abruptly on curve entries. This behavior was mitigated by both mitigation strategies for the auditory distractions and by the locking strategy for the visual distractions. With the visual advising strategy, as compared with the locking strategy, drivers tended to increase their speed substantially in car-following situations, and this resulted in longer accelerator release times. This response may undermine driver safety. However, drivers compensated for this with faster transition times. The visual mitigation strategies also led drivers to approach curves at speeds similar to those adopted when they were not distracted, indicating that the mitigation strategy actually led to more rather than less risky behavior in some situations (Lee & Strayer, 2004; Poysti, Rajalin, & Summala, 2005). These results show that the effects of distraction mitigation strategies are complex and that they may induce both positive and negative adaptations that merit further investigations.

This study found no statistically significant effects of the mitigation strategies on the productivity of the driver. This finding is important because mitigation strategies that severely undermine productivity may not be accepted by drivers. Productivity is just one factor that might undermine driver acceptance of distraction mitigation strategies, however. Other factors that should be further explored include annoyance, increased effort, error rate, and trust (Kantowitz et al., 1997; Lee & See, 2004).

Another important result was that no significant main effect for age was observed. Using a within-subjects design resulted in increased power for the within-subjects variable, Strategy, and the interaction term, Strategy × Age (Bradley & Russell, 1998). However, as the between-subjects variable age, repeats the within-subject conditions, the error term for the between-subjects effect increases and thereby degrades the power for this main effect. For example, analysis of the main safety measure, minimum TTC, revealed that the power for the within-subjects effects and the interaction were quite high (1 – β = .99, and 1 – β = .77, respectively). However, for the main age effect, power was only .05 (calculated based on Cohen, 1988). This was a trade-off in power that was considered necessary based on the objectives of this study.

Differences in driving performance attributable specifically to age have already been demonstrated in other studies (Cooper, 1990; McGwin & Brown, 1999) and were not the main focus of this study. The emphasis of this research was on assessing how different driver distraction mitigation strategies affect different driver age groups (i.e., the interaction term). The results show that the main safety measure, minimum TTC, was significantly different and varied for each age group (middle-aged and older drivers) based on the mitigation strategies used. As previously mentioned, older drivers did not benefit from the mitigation strategies as much as middle-aged drivers did. Further studies are therefore needed to assess possible age-related differences in how drivers might respond to other types of distractions and mitigation strategies. It is also important to note that our study focused on only two age populations. The advantages of mitigation strategies should be evaluated for all age groups. Because younger drivers have an increased crash risk due to distracting activities and have different driving patterns, they should be evaluated in future studies (Ferguson, 2003; Olsen, Lerner, Perel, & Simmons-Morton, 2005).

Any mitigation strategy must take into consideration drivers’ inherent ability to adapt to the demands of the driving environment. It is important to note that drivers’ adaptations go beyond the moment-to-moment perturbations that affect vehicle control. Drivers also adapt by selecting faster or slower speeds or deciding not to engage in distracting activities. Distraction-related decrements in driving performance can be described as breakdowns in the multilevel control process involved in safe driving (Lee & Strayer, 2004; Sheridan, 2004). The system-initiated distraction mitigation
strategies investigated in this study represent an initial attempt to avoid breakdowns in the control process by adapting the in-vehicle system to the evolving driving situation. Such a system can enhance the vehicle control process by helping drivers detect and respond to changes in the roadway situation. The system can also enhance drivers’ ability to adapt to the general demands of the IVIS device and respond to potential driving demands in a feed-forward manner. This study demonstrated that this is indeed possible. Given the strategies, visually distracted drivers maintained speeds close to their nondistracted speeds while approaching a curve.

Distraction mitigation strategies can enhance the control process, but they also have the potential to disrupt it. Strategies with higher levels of automation may also increase distraction if drivers try to continue an IVIS task that has been interrupted or locked. The IVIS task used in this experiment involved a series of short, discrete interactions. As revealed in other studies, longer tasks may be more vulnerable to disruptions associated with locking strategies (Ballas, Heitmeyer, & Perez, 1992; McFarlane, 2002). However, as pointed out by Verwey (2000), drivers cannot always properly judge a potentially unsafe situation and so postpone a nondriving-related task. Therefore, the advising and locking strategies discussed in this study could be incorporated into a single system that would adopt the appropriate strategy based on the distraction level of the driver. It is important to note that the reliability of adaptation (Parasuraman, Hancock, & Olofinboba, 1997) and ramifications of workload transition (Huey & Wickens, 1993) are two of many factors that may influence the benefits of an adaptive system. For example, such systems may annoy the driver if they are prone to engaging erroneously. This study also did not include events that overlap or events that impose greater demand, such as braking events that occur on the curve entry. Such overlapping events might require different mitigation strategies.

In designing and evaluating mitigation strategies, one should consider strategies and drivers as mutually adaptive systems. The effect of a mitigation strategy cannot be assessed with the assumption that drivers will not adapt to the technology. The issue of mutual adaptation becomes particularly critical when the mitigation strategy adapts to the drivers’ state as well as to the roadway situation. This process of mutual adaptation makes it difficult to anticipate the effects of distraction mitigation strategies. To address this challenge, a process model is needed to describe the relationship between drivers’ adaptation to the mitigation strategy before and during roadway events and to describe how these interactions affect drivers’ willingness to engage in distracting activities.

**CONCLUSION**

This study showed that distractions undermined driving performance. Drivers compensated by slowing down when following a lead vehicle and when entering a curve. System-initiated, nondriving-related strategies mitigated driver distraction, but the benefits observed depended on the presentation modality. A system that can dynamically adapt to the roadway state is a promising approach to reduce distraction-related crashes, but this approach can also lead drivers to adapt in unforeseen ways. Future research should investigate other modalities for driver distraction mitigation strategies and how these strategies are influenced by the performance differences among driver groups.

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