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The Effects of Visual and Cognitive Distractions on Operational and Tactical Driving Behaviors

Yu Zhang, DENSO International America, Southfield, MI, USA, David B. Kaber and Meghan Rogers, North Carolina State University, Raleigh, NC, USA, Yulan Liang, Liberty Mutual Institute for Safety, Hopkinton, MA, USA, and Shruti Gangakhedkar, Boeing Company, Everett, WA, USA

Objective: This study tested the effects of two fundamental forms of distraction, including visual-manual and cognitive-audio distraction, with comparison under both operational and tactical driving. Strategic control remains for future study.

Background: Driving is a complex control task involving operational, tactical, and strategic control. Although operational control, such as lead-car following, has been studied, the influence of in-vehicle distractions on higher levels of control, including tactical and strategic, remains unclear.

Method: Two secondary tasks were designed to independently represent visual-manual and cognitive-audio distractions, based on multiple resource theory. Drivers performed operational vehicle control maneuvers (lead-car following) or tactical control maneuvers (passing) along with the distraction tasks in a driving simulator. Response measures included driving performance and visual behavior.

Results: Results revealed drivers’ ability to accommodate either visual or cognitive distractions in following tasks but not in passing. The simultaneous distraction condition led to the greatest decrement in performance.

Conclusion: Findings support the need to assess the impacts of in-vehicle distraction on different levels of driving control. Future study should investigate driver distraction under strategic control.

Keywords: driver distraction, operational vehicle control, tactical vehicle control, eye tracking, attention resource theory

INTRODUCTION

Understanding how distractions associated with the use of in-vehicle information systems (IVISs) influence driving safety is essential to developing new distraction mitigation countermeasures. One thread of current driving research is aimed at identifying the types of distraction posed by IVISs and assessing the impact on driver cognitive processes and behavior (e.g., Engström, Johansson, & Östlund, 2005). Despite the diversity of in-vehicle devices on the market, the primary modalities of distraction posed by IVISs remain visual, manual, and cognitive in nature. Visual distractions require drivers to look away from the roadway; manual distractions require drivers to take their hands off the steering wheel; cognitive distractions divert drivers’ mental attention away from driving (National Highway Traffic Safety Administration [NHTSA], 2012). Previous driving studies have coupled visual and manual distraction tasks (Horrey, Wickens, & Consalus, 2006) or presented cognitive distraction tasks using auditory cues (Regan, Young, Lee, & Gordon, 2009) as a basis for assessing the impact of different forms of distraction on driver performance.

Multiple resource theory of attention (Wickens, 2002) provides a basis for characterizing the driving task from a cognitive perspective. Driving involves visual perception, spatial coding of information, and manual manipulation (Liang, 2009). The greater the extent to which driver distraction due to an in-vehicle device competes with a driving task in terms of attentional resources, the greater the potential degradation in driving performance (Regan et al., 2009). Visual-manual distraction tasks may
affect driver perception of environment cues and impede driving maneuvers. Cognitive-audio tasks may compete for cognitive resources used in processing spatial information.

The majority of existing studies have typically evaluated one form of distraction (e.g., Horrey et al., 2006) or assessed visual and cognitive distractions separately (e.g., Engström et al., 2005; Muhrer & Vollrath, 2011). These studies have contributed to the understanding of differences between visual-manual distraction and cognitive distraction when the two types of distraction act independently (Engström et al., 2005). However, in real-world driving, competition for attention among IVISs and driving tasks can be multidimensional in nature (Angell et al., 2006). According to other research, visual and cognitive distractions may lead to different or even opposite behavior changes when they occur alone. For instance, although visual distraction tasks commonly lead to dispersed gaze patterns (NHTSA, 2012), cognitive distractions tend to cause visual tunneling (Reimer, 2009). Therefore, based on these studies, it is hard to estimate the compound effects of both visual and cognitive distractions on driving.

Few studies have assessed driver behavior changes under dual-distraction conditions, that is, when both visual and cognitive distractions occur concurrently. However, observations from those studies examining dual-distraction conditions have been mixed. Some research has shown that cognitive and visual distractions may act in an additive manner. Lee, Lee, and Boyle (2007) found that drivers missed more safety-critical events with the presence of both cognitive and visual distractions as compared to visual distraction alone. This study used a dynamic change blindness paradigm as visual distraction, which blocked drivers’ vision from the driving scene periodically. In contrast to this study, others have shown that drivers may adapt to simultaneous distractions to a greater extent than to visual distractions. Liang and Lee (2010) found that drivers produced less steering error under a dual-distraction condition than under a visual-manual-distraction-only condition. One explanation for this finding might be that the two types of distraction do not simultaneously compete with driving for cognitive resources.

Responding to cognitive distractions may cause drivers to be less active in reacting to visual distractions and free up perceptual resources for driving under the dual-distraction condition to a greater extent than under visual-manual distraction only. It is also possible that the small steering variance typically associated with cognitive distraction (He, 2012) counterbalances increased steering variance due to visual-manual distraction. Unfortunately, in Liang and Lee’s (2010) investigation, drivers manually responded to both visual-manual and cognitive distraction tasks and were not able to respond to both tasks concurrently. Consequently, it is difficult to conclude the role of cognitive distractions under the dual-distraction condition from this study. More studies are still needed to understand how visual and cognitive distractions interact with each other in driving.

The existing research on distracted driving is also limited in terms of evaluating different levels of driving control. As suggested by Michon (1985), driving can be classified into three hierarchical levels of control, including operational, tactical, and strategic driving. Operational driving refers to basic vehicle handling (i.e., braking and accelerating). Tactical control involves developing strategies to realize near-term goals, such as turning at an intersection. Strategic control concerns high-level route planning. The perceptual, cognitive, and motor demands of driving vary with the levels of control required by ongoing tasks. As proposed by Matthews, Bryant, Webb, and Harbluk (2001), operational control often involves automatic control actions with the support of both focal vision and peripheral vision (Summala, Nieminen, & Punto, 1996). It poses limited demands in central cognitive possessing. In contrast, tactical and strategic driving invokes complex cognitive processes to combine perceptual cues with knowledge from memory and develop action plans toward either short-term or long-term goals. Since visual-manual and cognitive distractions compete with driving for different cognitive resources, the impact of the two types of distractions on driver performance may vary when the levels of control required by the ongoing driving task change.

In addition to differences in cognitive demands, the time frame for task performance...
under the various levels of control also differs. Strategic control may occur only on a few occasions during a trip, whereas operational or tactical control behaviors may occur every second or millisecond (Matthews et al., 2001). Therefore, operational and tactical driving control may rely more on short-term memory and momentary information from the environment than strategic control. Consequently, operational and tactical driving control may be more susceptible to distraction tasks, which also operate in short time frames. With this in mind, at the very least, driving studies need to investigate driver behavior changes when both operational and tactical actions are required to understand the implications of different distractions.

Unfortunately, as compared with operational driving control (e.g., lane-following tasks), tactical driving control has received less research attention, even though it poses greater central cognitive processing demands than operational control. Horrey and Simons (2007) presented a study of cognitive distractions in tactical and operational driving. They found that drivers adapted their vehicle control behavior for safety (e.g., increased headway distances) when posed with cognitive distractions during steady following tasks (i.e., following a lead vehicle at a relatively constant distance). Such behavior adaptation was not observed when drivers were posed with cognitive distractions while performing passing maneuvers, which is a typical tactical control task. These findings suggest cognitive distraction may lead to performance decrements (i.e., lack of driving behavior adaptation) only when a higher level of driving control is required. However, this study and few similar studies assessed only one distraction modality, either visual or cognitive (e.g., Kujala & Saariluoma, 2011; Reyes & Lee, 2004). Although understanding of operational driving under a single type of distraction is mature, the interaction between visual-manual and cognitive distraction is still unclear. Therefore, there remains a need to assess both visual and cognitive distractions with both tactical and operational driving control to discover any potential interactions.

To address the limitations of prior driving distraction research, the present study assessed the impact of uniquely defined visual-manual and cognitive distractions on driver performance under operational and tactical control scenarios. To clearly distinguish the effects of visual-manual distraction and cognitive distraction, the visual distraction task required a manual response and the cognitive distraction task was presented using audio messages and required a verbal response. Due to limited experimental resources, this study did not make assessment of distraction on strategic driving control but focused on operational and tactical driving performance. The influence of visual and cognitive distraction on strategic driving control needs to be explored in future studies. In the following sections, the two types of distractions are referred to as visual-manual and cognitive-audio distraction tasks. Based on the literature review, we hypothesized that visual-manual distraction would attract focal vision and interfere with manual operations, that is, we expected degraded operational and tactical driving control. However, since visual-manual tasks require limited central cognitive processing, drivers may be better able to adapt their behaviors toward safety, particularly under operational control (Hypothesis 1). It was also expected that cognitive-audio tasks would pose greater interference with driving under tactical control than under operational control (Hypothesis 2). Furthermore, occurrence of both visual-manual and cognitive-audio tasks was expected to be the most cognitively demanding condition, as compared to any single distraction condition, and to lead to the greatest performance degradations (Hypothesis 3). The dual-distraction condition was also expected to allow for the least driver behavior adaptation toward safety, particularly when tactical control is required (Hypothesis 4).

**METHODS**

**Participants and Apparatus**

A total of 20 young drivers, between the ages of 16 to 21 years ($M = 18.8, SD = 1.4$) and with driving experience between 0.5 and 4 years ($M = 2.5, SD = 1.6$) participated in a simulator experiment. According to a recent issue of *Injury Facts* (National Safety Council, 2009), drivers younger than 21 years of age are the most vulnerable driving age group. For this reason,
we studied the younger population to make a sensitive assessment of the visual-manual and cognitive-audio distractions on driving performance (i.e., a worst-case scenario in terms of safety). All participants had a valid driver’s license as well as normal vision without wearing glasses or contacts (as required for use of ASL eye-tracking equipment).

A fixed-base STISIM Drive™ M400 simulator was used to present dynamic driving scenarios in response to driver control inputs. The simulator included three 38-inch HDTV monitors, providing a 135° field of view of the roadway. Drivers used a full-size steering wheel, turn indicator, conventional gauges, and accelerator and brake pedals for vehicle control. The simulator recorded performance data at 30 Hz, including steering angle, lane position, and vehicle speed. Previous research has demonstrated driver performance in simulators, including the STISIM Drive simulator, to be highly correlated with performance in actual road tests (de Winter et al., 2009; Wang et al., 2010). This research supports validity of the simulator for assessing driver behavior. In addition to the performance data, an ASL EYE-TRAC® 6 Series head-mounted eye tracker with a head motion tracker (Flock of Birds 6-DOF sensor) was used to record eye movements at a frequency of 60 Hz. A digital video camera was also used to record all experiment sessions.

A 12-inch HP tablet computer was used to present the visual-manual task to drivers. Its position was approximately 15° below and 30° right of the natural line of sight when drivers were sitting in the simulator seat. Therefore, the computer display was within the drivers’ peripheral vision, but out of their focal vision when “driving.”

**Experiment Design and Driving Tasks**

The experiment followed a $2 \times 2 \times 2$ within-participant design with eight trials per participant. Each trial simulated a unique combination of one level of driving control (operational or tactical), a mode of visual-manual task performance (“on” or “off”), and a mode of cognitive-audio task performance (“on” or “off”). When both distraction tasks were off, we referred to this as the “no distraction” condition. When both distraction tasks were on, we referred to this as the “dual-distraction” condition. When only one distraction was present, we referred to the test conditions as “single modality” distraction, or specifically “visual-manual” or “cognitive-audio” distraction.

As in Horrey and Simons’s (2007) study, a lead-car following task was used to simulate operational driving control, whereas a passing task was used to represent tactical control. Both driving tasks were performed on a virtual four-lane interstate highway, with a 36-foot-wide grass median and two lanes of travel in each direction. The highway was populated with conventional traffic signs as well as overhead signs. Speed limits changed between 55 mph and 65 mph at six locations along the 12-mile virtual highway. Traffic was moderately dense in each direction (2-3 cars/lane/min.), based on interstate roadway traffic volumes for North Carolina (North Carolina Department of Transportation, 2011). Trees and curves were used to enhance the realism of the virtual driving environment.

Both driving tasks required similar driver actions, that is, maintaining and changing lanes. However, these two tasks were associated with different internal goals and cognitive processes. In the following task, participants were required to keep a safe distance from a lead vehicle and change lanes whenever the lead vehicle changed lanes. The lead vehicle drove at posted speed limits and made 12 lane changes in a trial at random intervals between 20 to 40 seconds. In the passing task, participants were required to pass a lead vehicle by changing lanes and returning to the original lane, whenever a lead vehicle decelerated to 10 mph below the posted speed limit. There were six passing events in each passing trial occurring at random intervals between 45 to 65 seconds. In addition to having to determine the status of the lead car, participants had to develop a local strategic plan for passing according to the surrounding traffic. In essence, they had to define a field of safe travel without the benefit of a leader.

**Distraction Tasks**

The visual-manual task was designed to divert driver focal vision away from the roadway and require manual responses with minimal
cognitive demand. Prior visual distraction studies (Engström et al., 2005; Liang, 2009) and current in-vehicle navigation systems were used as references in designing the task. The task interface presented three arrows pointed in different directions, including left, upward, and right (see Figure 1). Each arrow appeared in the center of a 1.2-inch × 1.2-inch square with 0.3 inches of space between squares. The squares were adjacent to each other in the center of the tablet, which displayed a black background. Participants were instructed to select a yellow highlighted upward-pointing arrow among three gray or highlighted arrows by touching the tablet’s display (see Figure 1a). There were also display states in which all arrows were gray and no action was required by drivers (see Figure 1b). The tablet’s display refreshed every 10 seconds. In each test trial, about 50% of the display states included highlighted arrows. The task software recorded participant responses to the visual-manual task.

The cognitive-audio task was designed to load a driver’s central cognitive processing by requiring them to spatially encode a verbal message and to provide a verbal response. Similar to a task used by Liang (2009), the cognitive-audio task simulated auditory messages from a navigation system. Drivers were required to verbally identify the final orientation of a virtual car traveling along an octagonal loop (see Figure 2). Messages described the location at which the virtual car entered the loop, the direction in which it drove (clockwise or counterclockwise), and the number of exits it passed (with one exit in each segment of the octagon). An example auditory message was, “Starting at north, go clockwise, and pass one exit.” The answer was “East.” The cognitive-audio task was delivered to the participant every 20 seconds: The message was approximately 5 seconds in duration and allowed participants 15 seconds to respond. A JAVA program installed on a stand-alone PC generated and played the audio messages. The program also presented an interface with buttons labeled with the directions of the eight exits for recording driver responses. All driver responses were also verified through retrospective video analysis.

In each single modality distraction condition, the distraction task was presented at 15 seconds into a test trial and continued until 15 seconds before the end of a trial. In the dual-distraction condition, the visual-manual task started 15 seconds into the trial whereas the cognitive-audio task started 22 seconds into the trial. The refresh rates of each task remained consistent across and within test conditions. The offset of the start times in the dual-distraction condition was to minimize overlap in manual and verbal responding to the two distraction tasks.
Dependent Variables

Because the manual actions of lane changing and lane keeping were considerably different, each experiment trial was divided into maneuvering and monitoring phases. Performance measures recorded during maneuvering and monitoring were considered as independent responses. The maneuvering phase began when the lead vehicle decelerated in the passing task or steered right/left in the following task. The phase ended when participants drove for 80 feet after they returned to the center of the origin lane in the passing task or changed to the center of the target lane in the following task. Monitoring phases included all other times in the task when participants monitored the lead car for lane changes or deceleration. Average response values were determined for all driving performance and eye-tracking measures during each phase. To balance the number of data points on the two types of driving tasks for statistical analysis, during the following task, we recorded only observations on monitoring phases before drivers changed to the left lane and on maneuvering phases involving changes to the left. All data recorded during the passing task were analyzed. In addition, response accuracy for both distraction tasks (regardless of the phases of driving) was included as a response measure.

Driving performance measures included steering entropy, speed variance, and completion times for required maneuvers. Steering entropy describes the smoothness of steering actions, which we calculated as the absolute difference between the second-order Taylor series expansion prediction of steering angle and the observed angle (see Nakayama, Futami, Nakamura, & Boer, 1999). A smaller value indicates smoother steering control. Speed variance measured the variability of vehicle speed with respect to the posted speed limit in each section of roadway, which was calculated as the square root of the sum of the squared difference between instantaneous speed and the posted speed limits. We used variance measures of driver performance in this study rather than absolute values of speed and steering control because only deviation measures have been extensively validated across driving simulation and field studies (Wang et al., 2010). The completion time of a passing maneuver was calculated as the duration from when the lead vehicle began to decelerate to the point when the participant’s vehicle returned to the center of the original lane after passing, whereas the completion time of a lane change during the following task was calculated from when the lead vehicle began to change lanes until the participant’s vehicle reached the center of the target lane.

Eye-tracking measures were used to describe changes in driver gaze behavior by following the methods described in ISO 15007-1 (2002). Glances were determined with respect to two areas of interest (AOIs), including an on-road AOI and off-road AOI. The visual-manual task interface belonged to the off-road AOI. Driver eye behavior metrics included average off-road glance duration and the percentage of off-road glances. The percentage of off-road glances was calculated by dividing the summation of the off-road glance durations during an experiment (monitoring or maneuvering) phase by the experiment phase duration.

RESULTS

Analyses of variance (ANOVAs) were applied to those response measures that conformed to tests for normality (Shapiro–Wilks) and constant variance (Bartlett). A Friedman-type nonparametric test (Mack & Skillings, 1980) was used to analyze data on measures that violated parametric test assumptions.

Analyses Across Driving Task Types

Results of an ANOVA (2 types of primary driving tasks × 2 modes of cognitive-audio task performance) revealed a significant effect of the primary task on the arcsine transformed response accuracy for the visual-manual task, $F(1, 59) = 5.3, p = .025$. Drivers responded to visual-manual tasks more accurately when following than when passing ($M = 97.1\%, SD = 6.2\%$ vs. $M = 94.7\%, SD = 6.6\%$). However, according to another ANOVA (2 types of primary driving tasks × 2 modes of visual-manual task performance), drivers maintained a similar response accuracy to the cognitive-audio task regardless of the primary driving task type ($M = 76.4\%, SD = 17.1\%$). Related to this, there was no significant effect of cognitive-audio
Only steering entropy during the maneuvering phase revealed constant variances for all three experiment manipulations. Therefore, an ANOVA model including all three independent variables (2 types of primary driving tasks × 2 modes of visual-manual task performance × 2 modes of cognitive-audio task performance) was applied to this response. Results revealed significant main effects of the primary driving task, $F(1, 901) = 29.94$, $p < .001$, and visual-manual distraction, $F(1, 901) = 31.72$, $p < .001$, as well as a significant interaction effect of visual-manual and cognitive-audio distraction, $F(1, 901) = 9.67$, $p = .002$. Drivers showed larger steering entropy when performing passing maneuvers compared to following ($M = 0.71°$, $SD = 0.49°$ vs. $M = 0.63°$, $SD = 0.35°$). As shown in Figure 3, post hoc analysis on the two-way interaction indicated a significant decrement in steering smoothness under the dual-distraction condition. Drivers showed the smallest steering entropy when the cognitive-audio distraction was present, which was significantly lower than visual-manual distraction only or dual-distraction conditions. However, the smoothness of steering under cognitive-audio distraction conditions was not significantly different from driving in the absence of any distraction.

Nonparametric tests revealed a significant main effect of the type of driving task on speed variance during monitoring ($MS = 121.95$, $p < .001$). There was also a significant main effect of this independent variable on the three eye-tracking measures, including percentage of off-road glances during monitoring ($MS = 3.88$, $p = .049$) and maneuvering ($MS = 42.16$, $p < .001$), as well as average glance duration during maneuvering ($MS = 58.47$, $p < .001$). Because Friedman nonparametric tests provide limited capability to explore interaction effects, the two types of primary driving tasks were analyzed separately. Results are presented in the subsections following.

**Analyses on Operational Driving Control**

Nonparametric analysis revealed a significant effect of visual-manual distraction on steering entropy during monitoring ($MS = 72.45$, $p < .001$) and on speed variance during monitoring ($MS = 4.60$, $p = .032$). Steering entropy was significantly higher under the visual-manual distraction condition than the no visual-manual distraction conditions ($M = 0.29°$, $SD = 0.19°$ vs. $M = 0.19°$, $SD = 0.12°$). Drivers also showed increased speed variance under the visual-manual distraction condition while monitoring compared to the no visual-manual distraction conditions ($M = 14.54$ mph, $SD = 3.89$ mph vs. $M = 13.90$ mph, $SD = 3.29$ mph).

Beyond steering and speed control performance, an ANOVA model (2 modes of visual-manual task performance × 2 modes of
cognitive-audio task performance) revealed a significant effect of visual-manual distraction, $F(1, 451) = 7.11, p = .008$, and a two-way interaction of visual-manual and cognitive-audio distraction, $F(1, 451) = 4.54, p = .034$, on lane-change completion times. Compared to driving under only cognitive-audio distraction, the presence of visual-manual distraction increased the pace of driver lane-changing maneuvers (see Figure 4).

A nonparametric analysis of gaze pattern data during the following task revealed significant effects of visual-manual distraction on average off-road glance duration during both the monitoring ($MS = 317.27, p < .001$) and maneuvering ($MS = 56.79, p < .001$) phases. The percentage of off-road glances during monitoring ($MS = 319.37, p < .001$) and maneuvering ($MS = 56.2, p < .001$) was also significantly influenced by visual-manual distraction. Compared to under the no visual-manual task conditions, participants showed a substantial increase in average off-road glance duration during the monitoring ($M = 0.46$ s, $SD = 0.18$ s vs. $M = 0.28$ s, $SD = 0.17$ s) and maneuvering ($M = 0.38$ s, $SD = 0.27$ s vs. $M = 0.08$ s, $SD = 0.03$ s) phases, along with an increased percentage of off-road glances in both phases (during monitoring phases: $M = 8.57\%$, $SD = 4.29\%$ vs. $M = 0.08\%$, $SD = 0.30\%$; during maneuvering phases: $M = 4.43\%$, $SD = 6.64\%$ vs. $M = 0.035\%$, $SD = 0.32\%$) under the visual-manual distraction condition.

No significant effect of cognitive-audio distraction on eye-tracking measures was identified through the nonparametric analyses.

**Analyses on Tactical Driving Control**

A nonparametric test demonstrated a significant effect of visual-manual distraction on steering entropy during monitoring ($MS = 20.3, p < .001$). Participants exhibited increased steering entropy under the visual-manual distraction condition versus the no visual manual distraction conditions during the monitoring phases of passing tasks ($M = 0.27^\circ, SD = 0.22^\circ$ vs. $M = 0.19^\circ, SD = 0.14^\circ$). In addition, nonparametric tests revealed significant effects of visual-manual distraction ($MS = 17.12, p < .001$) and cognitive-audio distraction ($MS = 12.44, p < .001$) on speed variance during the monitoring phase of the passing task. Increased speed variance was observed under the visual-manual distraction condition as compared to the no visual-manual distraction conditions ($M = 12.51$ mph, $SD = 6.89$ mph vs. $M = 10.0$ mph, $SD = 5.0$ mph). Similarly, greater speed variance was observed under the cognitive-audio distraction condition than under the no cognitive-audio distraction conditions ($M = 12.23$ mph, $SD = 6.5$ mph vs. $M = 10.3$ mph, $SD = 5.7$ mph). An ANOVA model (2 modes of visual-manual task performance × 2 modes of cognitive-audio task performance) revealed a significant effect of visual-manual distraction on passing completion times.

![Figure 4. Lane-change completion time in the following task as affected by visual-manual and cognitive-audio distractions. Note: different alphabetic characters denote statistically significant differences among condition means. Error bars represent standard deviations.](image-url)
Generally associated with higher speed variance due to distraction. Visual-manual distraction was also shown to result in higher average off-road glance duration as compared with no cognitive-audio distraction (Horrey & Engström, 2005), visual-manual distraction (Liang, 2009; Victor, Harbluk, & Engström, 2005) to the various distraction conditions under operational control. In line with previous research (Liang, 2009; Victor, Harbluk, & Engström, 2005), visual-manual distraction resulted in higher average off-road glance durations and more frequent off-road glances across levels of driving control as compared with no distraction. Visual-manual distraction was also shown to result in higher average off-road glance duration as compared with no cognitive-audio distraction (Horrey & Engström, 2005). Interestingly, the cognitive-audio distraction condition resulted in higher average off-road glance durations and more frequent off-road glances across levels of driving control as compared with no distraction. Visual-manual distraction was also shown to have a significant influence on driver off-road glance percentages (MS = 6.48%, SD = 3.72% vs. M = 0.10%, SD = 0.35%).

As a reference for this section, Table 1 summarizes the experimental results according to the various distraction conditions under operational or tactical control. In line with previous research (Liang, 2009; Victor, Harbluk, & Engström, 2005), visual-manual distraction resulted in higher average off-road glance durations and more frequent off-road glances across levels of driving control as compared with no distraction. Visual-manual distraction was also shown to have a significant influence on driver off-road glance percentages (MS = 6.48%, SD = 3.72% vs. M = 0.10%, SD = 0.35%).

**DISCUSSION**

As expected, cognitive-audio tasks showed a limited influence on driver behavior during the following (operational control) versus passing (tactical control) task (Hypothesis 2). In the following task, cognitive-audio tasks led to no change in steering entropy, speed variance, or the eye-tracking measures as compared to no distraction. In contrast, drivers showed increased speed variance yet reduced gaze dispersion (i.e., fewer off-road glances) when performing the passing task. This is in line with Victor et al. (2005) findings. That is, drivers showed degraded steering control even though they kept their visual attention on the road. In addition, drivers did not slow down in passing maneuvers when only posed with the cognitive-audio distraction (i.e., less adaptive behavior toward safety). These findings are partially in line with the findings of previous research on operational tasks suggesting that drivers may adapt to cognitive distractions and maintain driving safety by increasing their headway time (Strayer, Drews, & Johnston, 2003). However, such adaptation may fail when drivers engage in tactical control of a vehicle, wherein they adopt similar headway times, as is the absence of distraction (Horrey & Simons, 2007). Therefore, even if an in-vehicle task is cognitively competitive only with driving,
TABLE 1: Summary of Results of Statistical Analyses Under Operational and Tactical Driving Control

<table>
<thead>
<tr>
<th></th>
<th>Operational Driving Control</th>
<th>Tactical Driving Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed variance (SV) during monitoring</td>
<td>Larger SV</td>
<td>No change</td>
</tr>
<tr>
<td>Steering entropy (SE) during monitor phase</td>
<td>Increased SE</td>
<td>No change</td>
</tr>
<tr>
<td>SE during maneuver phase</td>
<td>Comparable to no distraction but larger SE than cognitive-audio distraction condition</td>
<td>Comparable to no distraction and smaller SE than visual-manual only and dual distraction conditions</td>
</tr>
<tr>
<td>Completion time for lane changing or passing</td>
<td>Comparable to no distraction but quicker than cognitive-audio distraction condition</td>
<td>Slower than visual-manual and dual distraction condition</td>
</tr>
<tr>
<td>Off-road glance percentage</td>
<td>Increased</td>
<td>No change</td>
</tr>
<tr>
<td>Average glance duration</td>
<td>Increased</td>
<td>No change</td>
</tr>
</tbody>
</table>

performing such a task may be unacceptable when drivers are simultaneously making tactical maneuvers.

Drivers showed similar gaze patterns, including increased off-road glances, under the visual-manual distraction condition as in the dual-distraction condition for both tactical and operational driving. This suggests that visual-manual distraction may dominate any impact on driver eye behavior relative to cognitive-audio tasks. Related to this, the findings on steering entropy during vehicle maneuvering were different from Liang and Lee’s (2010) findings. They claimed that cognitive distraction caused decrements in steering smoothness, but improvements in lane maintenance, as a result of greater driver visual...
focus on the roadway. Consequently, they also claimed that the dual-distraction condition might be less detrimental than visual distraction alone. However, in their experiment, participants pressed a button in response to the cognitive distraction task. Hence, reduced steering control would be expected when drivers performed such a manual response, which was also required by their visual distraction task. Opposite to this, the cognitive-audio task we used in the present study only required a verbal response. In this way, we observed that cognitive-audio distraction alone did not degrade steering smoothness (He, 2012) in the following task; however, the simultaneous distraction condition led to the worst steering performance (Hypothesis 3). Therefore, cognitive distraction may not alleviate the observed influences of visual distraction on driver performance as suggested by Liang and Lee (2010). There was also some evidence that the dual-distraction condition led to a lower degree of driver behavior adaptation toward safety, as the greatest steering error occurred when tactical control was required (Hypothesis 4). This hypothesis was not supported by the completion time for a lane change in the passing task.

In general, experiment results support Lee et al.’s (2007) finding that the impact of visual and cognitive distraction on driver performance may be additive in nature. This also implies that even if an IVIS can meet the independent requirements for both visual and cognitive distraction, it may still compromise driving safety.

CONCLUSION

The current study investigated two primary types of driver distraction (visual-manual and cognitive-audio) in IVISs use by implementing two artificial distraction tasks posing unique requirements on driver cognition according to multiple resource theory. The study demonstrated that changes in driving performance and visual behavior resulting from the distractions were different for tactical versus operational vehicle control, which was simulated through following and passing tasks.

This study adds to previous driving research by identifying the potential safety threats of two basic forms of distraction, especially when tactical driving control is required. Such research on tactical driving tasks is critical when assessing the potential distraction of new IVISs. This study also contributes to characterizing drivers’ capability for behavior adaptation toward safety in the presence of visual-manual and/or cognitive-audio distractions. In addition, the cognitive-audio task in this study may be used as a reference for developing and benchmarking tasks that directly compete for spatial coding processes with driving. This study also suggests drivers may take regulatory measures in driving when they are visually distracted. That is, drivers changed lanes quickly when visual-manual distraction was present during the following task but were slower when the same distraction was presented during the passing task. Unfortunately, due to the design of the visual secondary task (i.e., no time tags on data entries), driver regulatory behavior in relation to secondary task performance could not be confirmed by this study.

The research was also limited to a younger driver population. Middle aged (22–65) and older drivers (65 or older) may show different behavior changes when they interact with in-vehicle technologies (Chaparro & Alton, 2000; McPhee, Scialfa, Dennis, Ho, & Caird, 2004; Merat, Anttila, & Luoma, 2005). Related to this, although older drivers may be equally or more susceptible to distractions than young drivers due to cognitive effects of aging, they may be more aware of their own cognitive limits and tend to compensate by adapting or altering driving behaviors to safety, based on task experience (Zhang, Jin, Garner, Mosaly, & Kaber, 2009). Therefore, they may be less likely to be involved in distraction-related accidents. Hence, there is a need to extend the current research to a broader segment of the driver population.

Beyond this limitation, only one level of visual-manual distraction and one level of cognitive-audio distraction were investigated in this study; visual-manual and cognitive-audio distraction tasks were simply presented together for a dual-distraction condition. Furthermore, this study and other prior work have not investigated the effects of various modalities of driver distraction under strategic vehicle control. Therefore, future research may extend the present work by developing methods to assess various
levels of visual and cognitive demands of IVISs under operational, tactical, and strategic control and to quantitatively relate such demands to driver behaviors.

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KEY POINTS

- Independent and combined effects of visual-manual and cognitive-audio distraction on driver performance were assessed while drivers engaged in different modes of control.
- Operational and tactical driving control were simulated via lead-car following and passing tasks.
- Results revealed visual-manual distraction to lead to longer and more frequent off-road glances versus none, whereas cognitive-audio distraction resulted in reduced gaze dispersion during passing.
- Drivers showed adaptive behaviors to both types of distractions in following but degraded performance due to distractions in passing.

REFERENCES


Yu Zhang was a research assistant in the Human Factors and Ergonomics (HFE) Area at North Carolina State University. She earned her PhD from North Carolina State University in 2011. She worked as a research scientist at the General Motors Technical Center and is now a design engineer at DENSO Corporation. Her major research interests include human–computer interaction and driver behavior modeling.

David B. Kaber is a professor of industrial and systems engineering at North Carolina State University and associate faculty in biomedical engineering and psychology. He earned his PhD in industrial engineering from Texas Tech University in 1996. His current research interests include driver situation awareness under distraction and hazardous driving conditions as well as models of driver behavior as bases for in-vehicle hazard alerting system design.

Meghan Rogers was a NIOSH trainee in the Department of Industrial & Systems Engineering at North Carolina State University. As a graduate research assistant she worked on human factors/ergonomics projects through the Ergonomics Lab and the Ergonomics Center of North Carolina. Meghan earned her master’s degree from North Carolina State University in 2011. She currently is a usability researcher at Delta Airlines.

Yulan Liang was a postdoc researcher in the Department of Industrial & Systems Engineering at North Carolina State University. She earned her PhD from the Department of Industrial Engineering at the University of Iowa in 2009. She currently is a research scientist at the Liberty Mutual Research Institute for Safety. Her research interests include driver distraction and distraction state classification.

Shruti Gangakhedkar was a teaching assistant in the Department of Industrial & Systems Engineering at North Carolina State University. She earned her master’s degree from North Carolina State University in 2011. She currently is a site ergonomist at Boeing.

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