The Effects of Visual and Cognitive Distraction on Driver Situation Awareness

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Abstract. Driver distraction has become a major concern for transportation safety due to the increasing use of in–vehicle devices. To reduce safety risk, it is crucial to understand how fundamental aspects of distracting activities affect driver cognition in terms of roadway situation awareness. This study used a simulator-based experiment to investigate the effects of visual, cognitive and simultaneous distraction on operational and tactical control of vehicles. Twenty drivers participated in the study and drove in following or passing driving scenarios under four distraction conditions (without, with visual, with cognitive, and with simultaneous distraction). Results revealed visual distraction to affect all aspects of driver situation awareness. Cognitive distraction affected comprehension and projection of roadway and vehicle states. Correlation analyses revealed decrements in driver SA due to distraction to be associated with decreases in performance.

Keywords: Driver Distraction, Situation Awareness.

1 Introduction

The popularity of in-vehicle information systems has raised concerns with driver distraction and safety. In a study of crash and near crash events, driver distraction, due to in-vehicle technology, accounted for approximately 25% [1]. To reduce distraction-related crashes and develop countermeasures, there is a need for a clear understanding of how in-vehicle technologies affect driver cognition and behavior. Many studies [1, 2, 3, 4] have demonstrated that distraction degrades driver performance (e.g., lane maintenance, speed control); however, they do not explain how distraction affects cognitive functions, such as situation awareness (SA), and, in turn, vehicle control.

Previous research [5,6] has developed operational definitions of SA in the driving domain and empirically investigated SA responses under various task and distraction conditions. Results have been used as a basis for developing models of the role of SA in transactions between driving task requirements and operator behaviors. In a lead car following task simulation, Ma and Kaber [5] found driver operational behaviors (braking, accelerating) were primarily dependent on perception and to some extent comprehension of own vehicle states relative to traffic. They also found that use of a

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handheld cell phone (posing both visual and cognitive distraction) degraded driver SA, including perception, comprehension and projection. In a more elaborate driving simulator study, involving operational, tactical (passing) and strategic (navigation) task performance, Jin and Kaber [6] observed tactical tasks to be most dependent on all aspects of driver SA. Strategic tasks required SA but did not load on any one specific aspect. Like Ma and Kaber's [5] results, operational driver behavior was also found to be dependent on perception. In addition, Jin and Kaber [6] found that when roadway hazards were posed to drivers, the importance of SA to performance increased, particularly for operational behavior.

On the basis of this research, the objective of the present study was to identify (or sort-out) the independent and combined effects of visual and cognitive distractions on all aspects of driver SA and to quantify negative effects under normal driving conditions involving operational and tactical behaviors. The research was expected to provide a more complete understanding of a cycle of distraction, SA and performance in driving.

2 Methods

2.1 Participants

Twenty young drivers (10 females and 10 males), between the ages of 16-21 years (*M*=18.8 yrs, *SD*=1.4), were recruited to participate in a driving simulator experiment. We wanted to assess "high-risk potential drivers", who have been targeted by State legislation in terms of driving privilege restrictions, based on expert opinions regarding susceptibility to distraction. All participants were required to have valid driver's licenses, as well as normal vision without wearing glasses or contacts. Participants were compensated for their time at $15/hour.

2.2 Apparatus

We used a high-fidelity STISIM Drive™ M400 simulator that rendered dynamic images of driving scenarios based on driver control input. The simulator integrated three 38-inch HDTV monitors providing drivers with a 135-degree field of view of the roadway (left, center and right of the simulated vehicle). Simulator controls included a modular steering unit with a full-size wheel and adjustable speed-sensitive force-feedback capability, as well as a modular accelerator and brake pedal unit (see Figure 1 for a picture of the simulator setup). The simulator also provided spatialized auditory feedback through a 5.1 surround sound speaker system. The simulator computer systems recorded driver performance data at 20Hz, including steering angle, lane position and vehicle speed, distance to nearby vehicles, etc.

A 12-inch HP tablet computer with integrated display was placed in front and slightly below the right side of the simulator screen to present mock-ups of an in-vehicle navigation system. This was used to present the visual distraction task. The screen was positioned approximately 15 degrees down and 30 degree right of the natural line of sight of participants in using the simulator.

Fig. 1. The STISIM driving simulator and in-vehicle interface

2.3 Experimental Design and Tasks

The experiment was a 2x2x2 within-subject design with two levels of visual distraction (with and without), two levels of cognitive distraction (with and without), and two primary driving tasks. In total there were eight experimental conditions (see Table 1). A lead-car following task required operational control of the simulated vehicle (no maneuvering in traffic or route planning). A passing task required both tactical and operational control, including negotiating complex, multi-lane traffic patterns at high speed. Additional motivation for studying these two task types was a discrepancy in prior research results concerning driver adaptation of behaviors due to cognitive distraction in car following but not in overtaking [7]. Participants drove in eight 8-minute trials with one experimental condition presented in each trial. The sequence of conditions was randomized.

Table 1. Experimental conditions

Primary task	**Cognitive distraction**	**Visual distraction**	
		Yes	No
Passing	Yes	Passing- Simultaneous	Passing- Cognitive alone
	No	Passing-Visual alone	Passing- No distraction
Following	Yes	Following- Simultaneous	Following – Cognitive alone
	No	Following -Visual alone	Following - No distraction

The simulated driving environment was a four-lane interstate highway divided by a green median; two lanes in each direction. The roadway was populated with traffic signs and trees (see Figure 2 for image of simulation display). The speed limit varied between 55mph and 65mph at six virtual locations. In the following task, participants were instructed to follow and maintain a safe distance (using the 4 second rule) to a lead vehicle that drove at the posted limits throughout the trial. The lead vehicle changed lanes 12 times during each trial with a random interval between changes of 20 to 40 seconds; six lane-changes to the right and six lane-changes to the left. The speed limit did not change during the course of lane changes, and there was no interference from traffic.

Fig. 2. Simulation Display

In the passing task, participants were instructed to first stay in the right-hand lane and follow a lead vehicle. When the speed of the lead vehicle fell 10 mph below the speed limit, participants were directed to pass, return to the right-hand lane, and follow another lead vehicle. Participants were restricted to passing only one vehicle at a time and instructed to avoid collisions. That is, participants decided whether and when they could make passing maneuvers. They were also instructed to comply with all roadway regulations. A total of six passing events were simulated in each experiment trial with a random interval between passes ranging from 45 to 65 seconds.

There were two types of secondary tasks, including a visual distraction task and a cognitive distraction task. The former simulated use of a navigation aid enroute and diverted driver attention from the road for signal detection while requiring little cognitive effort. Drivers had to identify an upward pointing arrow with a “yellow” background on the tablet display among three arrows pointing in different directions with a default background color of gray. The display was refreshed every 10s. Participants were instructed to respond to each display update and to not make a selection when all arrows had a gray background.

The cognitive distraction task simulated drivers listening to auditory instructions from a navigation system without posing any visual demands and required a verbal response. The instructions described the path of a car traveling on a controlled-access highway loop around a city with exits located in the four cardinal directions (south, east, north, west) and the four intermediate directions (southeast, etc). The car was described as entering the loop from a specific exit and traveling clockwise or counterclockwise. Participants were asked to verbally identify the exit the car would reach (by direction) after passing a certain number of exists. A set of 40 different auditory messages were randomly presented during trials. The cognitive task was delivered every 20 seconds: the message was approximately 5 seconds in duration, and participants were given 15 seconds to respond. During the simultaneous distraction condition, participants performed both the visual and cognitive distraction tasks.

2.4 Procedure

Participants received a 45-minute training session on driving in the simulator, following and passing tasks, and performing secondary tasks while driving. Each participant completed trials under all secondary-task conditions without replication. The secondary task(s) started 30 seconds after the beginning of a trial and ended 15 seconds before the end. Situation awareness was assessed using a real-time probe method. An experimenter sat next to the driver, posing as a vehicle passenger, and asked the subject questions to assess their SA. Questions were posed every 20 seconds for a total of 18 questions per trial. Participants were offered a short break every four trials. The total duration of the experiment was approximately 3.5 hours and evidence of driver fatigue was not observed through statistical analysis of trial order effects.

2.5 Dependent Variables

The dependent variables included driver performance and accuracy in responding to SA queries. Performance measures included speed variability and steering error. Steering error describes how smoothly participants maneuver their vehicle while driving, and was calculated as the absolute difference between the second-order Taylor series expansion prediction of steering angle and the observed angle [8]. A smaller value indicates smoother steering wheel control and less aggressive tactical control. Speed variability determines how variable the driver's speed is to the posted speed limit. We calculated the variance in observed speed during lane changes and passing under each specific limit. Smaller values indicated a better ability to maintain speed close to posted limits. Both measures were recorded when participants performed a lane-change or passed another car. Triggering events for data collection included the lead vehicle steering in the direction of the lane change in the following task or the lead vehicle initiating deceleration in the passing task. Data collection ended when the subject's vehicle changed to the target lane in following or had driven 80 ft. after returning to the right-hand lane in passing. Data was collected on six left-lane changes in following trials and six passes.

Situation Awareness queries were categorized according to the levels of SA defined by Endsley [9] including: perception (Level 1), comprehension (Level 2) and projection (Level 3). Subcategories of queries within levels of SA focused on current roadway objects and background, speed maintenance, traffic patterns, recall of previous roadway objects, roadway topography, time estimates, and horizontal and longitudinal distance estimates. Accuracy of driver responses to queries was analyzed by comparison with ground-truth information on the simulation recorded by experimenters at the time a query was delivered. Aggregate measures of SA for each level were determined on a per subject and trial basis.

2.6 Hypotheses

The present investigation focused on the SA effects of the various types of distraction and driving tasks. Correlation analyses were also conducted on driver SA and performance measures in order to provide insight on how distractions might act through SA to influence operational or tactical driving behaviors. On the basis of previous research by Endsley [9], Matthews et al. [10], and Regan et al. [11] it was hypothesized that low level SA (perception) would reveal a greater influence of visual distractions, and high level SA, requiring complex cognitive processing, would be influenced by both distractions. Based on Jin and Kaber's [6] findings, tactical behavior (the passing task) was expected to require support from higher levels of SA compared to operational driving behavior (the lead car following task). Related to Horrey and Simmons' [7] study, cognitive distractions were expected to have greater influence on the passing task compared to following task, in terms of degraded SA.

3 Results

3.1 Statistical Analysis

Prior to statistical modeling, diagnostics were conducted on the SA and performance data sets using normal probability plots, a test of normality (Shapiro-Wilks test) and tests for constant variance. Subsequently, a multivariate analysis of variance (MANOVAs) was conducted on all response measures for which interrelations were expected, as a means of data reduction. Analyses of variance (ANOVAs) were then conducted on any significant main effects and interaction effects revealed by the MANOVAs across response measures. For further analysis of significant effects, multiple comparison procedures (e.g., Tukey's test) were conducted.

3.2 Situation Awareness

The aggregate responses for all levels of SA met the assumption of the ANOVA; however, some required transformation (arcsine was applied to Level 1 SA and a power transformation was applied to Level 3 SA).

ANOVA results revealed significant effects of primary task type ($F(1,133)=8.78$, $p=0.0036$), visual distraction ($F(1,133)=16.61$, $p<0.001$), a two-way interaction of primary task and cognitive distraction ($F(1,133)=3.96$, $p=0.0487$), a two-way interaction of visual and cognitive distraction ($F(1,133)=8.93$, $p=0.0033$), and a three-way interaction (all main effects; $F(1,133)=24$, $p<0.001$) on Level 1 SA. Mean accuracy of driver perception of roadway states was lower during the passing task ($M=0.81$, $SD=0.16$) as compared to following ($M=0.87$, $SD=0.17$). A post-hoc analysis of the three-way interaction using Tukey's test revealed the lowest driver

Level 1 SA in passing with cognitive distraction (*M*=0.71, *SD*=0.14), which was significantly different from roadway perception during following with cognitive distraction (*M*=0.93, *SD*=0.14). Passing with cognitive distraction was also significantly worse than driving with visual distraction in either task (following, *M*=0.97, *SD*=0.07; passing, *M*= 0.87, *SD*=0.16), and passing with simultaneous visual and cognitive distraction (*M*=0.86, *SD*=0.15). This latter comparison was surprising as we expected the cognitive demands of the dual-distraction condition to have the greatest implications for driver SA in either task.

Beyond the aggregate measures of accuracy for the general level of SA, it is important to note that certain subcategories of queries revealed SA decrements while others appeared robust to distraction. Regarding the main effect of visual distraction, SA was lower under distraction for queries on traffic pattern (*M*=0.792), recall of previous roadway objects (*M*= 0.825), and horizontal distance estimates (*M*=0.85) as compared to SA on current roadway objects and background (*M*=0.913), speed maintenance (*M*=1) and roadway topography (*M*=0.975).

ANOVA results on Level 2 SA revealed a significant main effect of cognitive distraction (F(1,133)=6.05, p=0.0152) with decrements only occurring for specific types of queries. Accuracy of responses to time and longitudinal distance estimates (*M*=0.35 and *M*=0.3, respectively) were severely degraded compared to no distraction. However, SA on traffic (*M*=0.835), speed maintenance (*M*=0.85), and current roadway objects and background (*M*=0.975) were robust to cognitive distraction. Visual distraction also had a significant effect on Level 2 SA (F(1,133) = 12.06, p=0.0007) with mean accuracy under distraction (*M*= 0.725, *SD*=0.18) being lower than without (*M*=0.813, *SD*=0.16). Results also revealed a significant two-way interaction of primary task type and visual distraction (F(1,133)=15.73, p=0.0001), and a significant two-way interaction of visual and cognitive distractions (F(1,133) = 4.64, p=0.033) on Level 2 SA. In regard to the primary task and visual distraction interaction, during following the distraction did not make a difference; however, driver roadway state comprehension was significantly degraded in passing with visual distraction (*M*=0.68, *SD*=0.17) than during tactical behavior without distraction (*M*=0.87, *SD*=0.15). With respect to the visual and cognitive distraction interaction, vehicle state comprehension relative to the roadway environment was significantly degraded by visual distraction (*M*=0.67, *SD*=0.18) compared to all other conditions [no distraction (*M*=0.81, *SD*=0.15), cognitive distraction (*M*=0.82, *SD*=0.18), and simultaneous distraction (*M*= 0.78, *SD*=0.15)].

Driver accuracy in Level 3 SA (projection of future roadway states) also revealed a significant main effect of cognitive distraction (F(1,133)=16.78, p<0.0001) with worse projection occurring under distraction (*M*=0.72, *SD*=0.21) versus none (*M*=0.83, *SD*=0.15). Visual distraction also had a significant main effect on Level 3 SA accuracy (F(1,133)=6.45, p=0.0123). However, only queries concerning time estimates (*M*=0.6315) and speed maintenance (*M*=0.75) revealed decrements under distraction. SA on traffic (*M*=0.913) and road scenery (*M*=1) were not impacted by the secondary task.

ANOVA results on a Total SA response revealed a significant two-way interaction of primary task type and visual distraction (F(1,133)= 4.3, p=0.0401), and a significant three-way interaction of all three main effects (F(1,133)=5.11, p=0.0254). Post-hoc results on the two-way interaction showed significantly lower total SA for passing with visual distraction (*M*=0.78, *SD*=0.11) versus following (*M*=0.83, *SD*=0.1). Regarding the three-way interaction, it appeared that cognitive distraction during passing was significantly worse for overall SA (*M*=0.77, *SD*=0.10) than visual distraction during following (*M*=0.86, *SD*=0.07).

3.3 Relation of SA and Performance

Correlation analyses were conducted to assess any relation of driver SA with performance, including steering error and speed variability. During lead-car following under visual distraction, results revealed a significant negative correlation between Level 1 SA and steering error (r=-0.5318, p=0.0158) as well as between Total SA and steering error (r=-0.5806, p=0.0073). As SA increased, steering error decreased, suggesting drivers with heightened perception of the roadway demonstrated more stable vehicle control. Similar observations were made on Level 2 SA with steering error (r=-0.2862, p=0.0101) during the passing primary task. Under cognitive distraction during both following and passing tasks, Level 1 SA (perception of roadway states) was negatively correlated with speed variability [(r=-0.458, p=.0488) and (r=-0.4903, p=0.0282), respectively]. This indicated that as SA improved, drivers exhibited more stable vehicle control.

4 Discussion

The two types of driving tasks and two types of distractions significantly interacted in effect on overall driver SA and perception and comprehension of the roadway environment, in specific. The demands of tactical driving behavior in passing led to worse SA than in the following task. Furthermore, the greatest decrements in driver SA due to distraction occurred during the passing task and involved perception and comprehension of the roadway. These findings are in line with Jin and Kaber's [6] results that indicated tactical task performance placed the greatest demands on driver SA.

Visual distraction had a significant effect on all three levels of driver SA while cognitive distraction was only significant for the higher levels of SA (comprehension and projection). These results supported our hypotheses. Most interestingly, we found that for all levels of SA, there were certain driver information requirements that were more sensitive than others to visual and/or cognitive distraction. Highly sensitive aspects of SA in both passing and following tasks included temporal and spatial judgments of roadway events and objects, respectively. The negative effects of visual and cognitive distraction on these SA elements amounted to, on average, a 43% decrease in accuracy in time estimates and a 50% decrease in spatial position estimates. It is possible that certain SA requirements, which we anticipated to be critical to task performance, did not demand cognitive resources to the extent of competition with the visual and/or cognitive distractions.

The relationship between SA and driving performance was in line with expectation. As SA improved, steering error and speed variability decreased, suggesting drivers with heightened awareness of the roadway were more stable in vehicle control. Results on steering error and speed variability served to validate the SA measurement approach, as the general construct of performance was positively associated with SA. This supports the notion of a cycle of driver distraction acting through SA to influence performance. Consequently, the impacts of driver distraction on SA need to be considered in design of new in-vehicle technologies.

5 Conclusion

The findings of this study demonstrate that visual and cognitive distractions impact driver performance by degrading SA. Higher levels of SA are sensitive to cognitive distraction, in particular time estimates and longitudinal distance estimates. Visual distraction appears to affect low level situation awareness, as well as comprehension and projection. This is likely due to perception being a ‘building block’ for higher level SA, as Endsley [9] described in her theory. In specific, perception of traffic patterns, roadway objects, and horizontal vehicle separation distances were all sensitive to driver visual distraction; whereas, driver projection ability was most sensitive to visual distraction in terms of the timing of roadway events and the need for speed control. Correlation results revealed in-vehicle distractions further impaired drivers’ safety by increasing their steering error and speed variability due to a lack of situation awareness.

It should be noted that this study used young drivers (16-21 years old), who have been observed to be more vulnerable to the influence of distraction because of their inexperience and interest in the use of new technologies while driving. Previous research has noted that young drivers represent the highest crash risk population among all drivers [12]. The results of this study provide insight for high-risk drivers, but at the same time may be somewhat exaggerated relative to, for example, the adult experienced driver population. A broader sample population should be investigated in future research. In addition, because no actual threats to safety were posed by driving in the simulated environment, drivers might have engaged in more liberal operational and tactical behaviors, as compared to real-world driving. Beyond this, the secondary tasks used in the study were not directly related to the primary driving task goals or the daily life goals of subjects. Therefore, subjects may not have been motivated to fully engage in the tasks as they would in using an actual cell phone or GPS device.

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