Transportation Research Part F 11 (2008) 391–402

Contents lists available at ScienceDirect

Transportation Research Part F

journal homepage: www.elsevier.com/locate/trf

Effects of cognitive load presence and duration on driver eye movements and event detection performance

Michelle L. Reyes *, John D. Lee

The University of Iowa, Center for Computer-Aided Design, 116 Engineering Research Facility, Iowa City, IA 52242, United States

ARTICLE INFO

Article history:
Received 28 August 2006
Received in revised form 22 August 2007
Accepted 1 March 2008

Keywords:
In-vehicle information systems
Driver distraction
Cognitive distraction
Reaction time

ABSTRACT

This study examined the effects of cognitive load on driving performance for interactions with an in-vehicle information system (IVIS) that varied in duration from 1 to 4 min. Twelve participants drove in a simulator while intermittently performing the IVIS task. There were three IVIS conditions: interacting with the IVIS, non-IVIS periods between IVIS interactions, and baseline driving without the IVIS task. Contrary to our hypothesis, driver response to lead vehicle braking was surprisingly uniform across IVIS conditions. IVIS interaction did undermine driver ability to detect the bicyclist along the side of the road, and some of these performance decrements persisted after the IVIS interaction had ended. Reaction time for bicyclist detection increased from the first to the subsequent minutes of the interaction. Eye movements were influenced by the IVIS conditions but not by task duration. Both ANOVA and factor analyses revealed that some of the changes in eye movements were concurrent with IVIS interaction while others persisted after the driver completed the IVIS interaction. Overall, the findings suggest that two mechanisms might account for the distraction-related performance decrements in this study: competition for processing resources and interference due to activation of competing goals.

1. Introduction

Rapid development of wireless and computer technology has led to an increasingly complex and diverse array of devices that people might use while driving. The visual, manual, and cognitive demands associated with interacting with these devices can distract drivers and undermine performance. Assessing the distraction potential of devices, such as navigation systems, cell phones, and personal music systems, poses an important challenge to designing safe in-vehicle information systems (IVISs). The decrements in driving performance that occur when drivers take their eyes off the road (visual distraction) or their hands off the wheel (manual distraction) are relatively easy to define, understand, and assess. However, a growing body of research demonstrates that, even when drivers have their eyes on the road and hands on the wheel, the cognitive demand associated with in-vehicle devices can undermine driving performance (Horrey & Wickens, 2006; Lee & Strayer, 2004; McCartt, Hellinga, & Bratiman, 2006; Regan, Lee, & Young, 2008).

A meta-analysis of studies that examined the use of cell phones while driving found that conversation and information processing tasks performed in "hands-free" mode affected driver reaction time to targets that were unrelated to the cell phone task (Horrey & Wickens, 2006). With one common target detection paradigm, drivers were asked to detect the illumination of a light while they drove and performed cognitive tasks, such as arithmetic manipulations (Patten, Kircher, Ostlund, & Nilsson, 2004; Recarte & Nunes, 2003), autobiographical recall (Recarte & Nunes, 2003), and interactions with an AutoPC (Ranney, Harbluk, & Noy, 2005). Compared to driving alone, drivers missed more targets and often had slower

* Corresponding author. Tel.: +1 319 384 0514.
E-mail address: mlries@engineering.uiowa.edu (M.L. Reyes).

1369-8478/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.trf.2008.03.004

responses when performing cognitive tasks as they drove. The implication of these results is that cognitive load may also undermine driver response to events related to driving.

Research examining the effect of visual–manual–cognitive tasks shows that distractions do not influence driving in a unitary manner. Young and Angell (2003) collected 15 measures of driver performance, including response time to the illumination of lights located on the vehicle hood and driver side mirror and the percentage of lights that drivers missed, for 79 in-vehicle tasks. The measures of driver performance were analyzed using principal components analysis to identify dimensions of driving performance that reflect driver distraction. Three principal components accounted for 83% of the variability in driver performance. The first component, accounting for 61% of the total variation, was termed "overall driver demand" because the loadings for all of the driver performance measures were positive. The second principal component accounted for 17% of the total variation and was called "low-workload-but-high-inattentiveness". Driver performance measures associated with the detection of the illuminated lights loaded in a direction opposite to all of the other measures, suggesting that some distracting activities cause drivers to be particularly poor in detecting events, even when other elements of driving performance are relatively unaffected. Finally, a component termed "peripheral insensitivity" accounted for 5% of the total variation. For this component, reaction time and miss rate for detection of the light on the hood loaded in the opposite direction of the same measures for the light located on the side mirror. Together, these results show that distractions can undermine different dimensions of driver performance, such as vehicle control, event detection, and peripheral event detection.

The results of Young and Angell (2003), particularly the second and third principal components, align with two manifestations of cognitive distraction in the literature. The first is a failure to consolidate fixated information. In other words, the visual information that falls on the fovea during a fixation is not processed or consolidated to a level required for a response to be made. In the case of the light detection paradigm, consolidation failure occurs when drivers do not respond to a light after they have looked at it. The second manifestation of cognitive distraction is a tendency to concentrate fixations within a limited part of the driving scene that can lead to failure to fixate objects in the periphery.

Several studies of driver distraction suggest that failure to consolidate fixated information contributes to distraction-related decrements in driving performance. For example, Strayer, Drews, and Johnston (2003) found that drivers were less likely to remember a billboard that they had viewed while driving in a simulator and conversing on a hands-free cell phone than the one viewed while they were only driving. Even though drivers looked at the billboards, they failed to "see" them because their attention was focused on the conversation. Similarly, Greenberg et al. (2003) examined cognitive distraction using a realistic and driving-related event detection protocol. Drivers were asked to respond when a vehicle in the forward- or rear-view departed the lane. A failure to consolidate fixated information was reflected in some drivers' failure to detect lane departures of the car ahead while receiving hands-free phone calls, even though they were looking ahead when the lane departures occurred.

Fixation concentration describes a narrowing of the visual field scanned by the observer. Various factors have been shown to affect fixation concentration. Crundall and Underwood (1998) found that scanning of the driving scene was affected by driver experience and type of roadway. The experienced drivers' scanning patterns were sensitive to roadway type, with greater variability in both the vertical and horizontal dimensions on the dual carriageway compared to the rural and suburban roadways. In contrast, the novice drivers' scanning patterns were not sensitive to the different roadways. Recarte and Nunes (2000) found that performing mental tasks while driving led to decreased variability in fixation position, which they termed "spatial gaze concentration", and shorter distances covered during the brief, ballistic eye movements between fixations called saccades. Similarly, Victor, Harbluk, and Engstrom (2005) found that the presence but not the difficulty level of an auditory tone counting task led to a reduction of the standard deviation of gaze position. The implication of these findings is that if driver gaze is concentrated in the center of the driving scene, detection of objects and events in the periphery can suffer.

Recarte and Nunes (2003) investigated the effect of spatial gaze concentration on target detection. Drivers detected lights in various eccentric locations and completed a variety of cognitive tasks while their eye movements were tracked. Although spatial gaze concentration was seen under cognitive load, because target eccentricity and cognitive load did not interact to affect performance of the detection task, Recarte and Nunes concluded that cognitive load undermined detection performance through a general interference effect. They suggested that the general interference reflects the assignment of attentional resources to the non-driving task and is not a result of disrupted scanning due to spatial gaze concentration. The authors attributed the spatial gaze concentration effect to drivers adopting a strategy of directing their visual resources to the area of the visual field that contains the greatest concentration of information needed for driving. Overall, Recarte and Nunes findings suggest that failures to consolidate fixated information rather than gaze concentration is the reason why cognitive load undermines driver performance.

Although it is clear from the previous research that cognitive load can affect both driver eye movements and event detection, no research has studied how such effects may change over time. For example, driver eye movements and detection abilities may differ at the beginning of a cell phone conversation compared to several minutes into the call. A survey of college students found that frequency of cell phone calls rather than duration of calls was linked to being involved in accidents or near-accidents (Seo & Torabi, 2004), but no research has directly studied the effect of task duration on driver performance. In addition, although some have speculated that distraction has carryover effects such that driver performance decrements continue after the secondary task is over (Redelmeier & Tibshirani, 1997), this area has received little direct research.

When drivers perform a secondary task, they must switch between the two tasks, interrupting and resuming each in turn. Analysis of interrupting or subsequently resuming a task shows that the timing of the interruption has substantial influence on how easily the task can be resumed. Interruptions that prevent goal rehearsal or that occur in the middle of the task resulted in longer resumption times (Monk, Boehm-Davis, & Trafton, 2004). These results are consistent with the goal activation model (Altmann & Trafton, 2002) and suggest that increasing task duration may make drivers less able to interrupt IVIS tasks and return to driving tasks. The goal activation model also predicts that the distraction posed by an IVIS interaction may persist even after the immediate interaction with IVIS has been completed.

In summary, past research has demonstrated that cognitive load can undermine event detection. Evidence of gaze concentration and consolidation failure gives some insight into the mechanisms underlying performance decrements. However, the effects of cognitive distraction over time have not been examined. In addition, it may not be valid to generalize from detecting lights and recalling billboards to detecting driving-relevant events. This study considers these issues by evaluating the contribution of consolidation failures and gaze concentration in detecting driving-relevant events.

This study used a driving simulator to investigate the temporal effects of cognitive load on driver performance. Participants interacted with an auditory in-vehicle system that required continuous attention, intermittent manual response, and trend tracking over various periods of time. To assess the effects of the cognitive demands of this task, we measured drivers' response to a braking lead vehicle, ability to detect a target in the driving scene, and eye movements.

Based on the previous research, interaction with the IVIS while driving was expected to degrade driver performance and result in both consolidation failure and gaze concentration. Drivers would respond more slowly to the braking lead vehicle and be less sensitive to detecting the bicyclist. The magnitudes of these effects were expected to increase with the IVIS task duration. Both IVIS task presence and duration were expected to affect driver eye movements. Specifically, more fixations were expected in the center of the roadway, variability of fixation position was expected to decrease, and saccade distances were expected to decrease during IVIS interaction, and these effects would be greatest during long interactions. As with the principal components analysis of Young and Angell (2003), we expected that a factor analysis of eye movement data would suggest that multiple dimensions underlie driver distraction. Finally, we expected that, consistent with the goal activation model of interruptions, the relatively engaging interactions with the IVIS in this study would undermine attention to the road even after the interaction had ended.

2. Method

2.1. Participants

Twelve people (balanced for gender) between the ages of 35 and 55 ($M = 45$, SD = 6) who had at least 19 years of driving experience ($M = 30$, SD = 7) and drove at least five times per week participated in this 3-h experiment. They were compensated $15 an hour and earned up to $10 in bonus compensation based on their performance on the IVIS task.

2.2. Design and independent variables

Participants completed four 15-min drives while performing an IVIS task and two 15-min baseline drives without the IVIS task. Each IVIS drive included four interactions with the IVIS, and the duration of each interaction was different: 1, 2, 3, or 4 min. The presentation order of the four durations was counterbalanced for each of the four IVIS drives using a Latin square. One-minute intervals occurred before the first interaction, between interactions, and after the last interaction in each IVIS drive (see Fig. 1). The order in which each participant completed the IVIS drives and baseline drives was randomized using Latin squares.

The independent variables of IVIS condition and IVIS task duration were manipulated as within-subject conditions. The IVIS condition included three levels: IVIS (periods when the driver was performing the IVIS task), non-IVIS (periods in the IVIS drive when the driver was not performing the IVIS task), and baseline (periods from the baseline drive). IVIS task duration reflected how long the driver had interacted with the stock ticker: 1, 2, 3, or 4 min.

2.3. Apparatus

The experiment was conducted with a medium fidelity, fixed-based DriveSafety™ Research Simulator. The simulator has a 1992 Mercury Sable vehicle cab with a 50-degree visual field and generates fully textured graphics at a resolution of

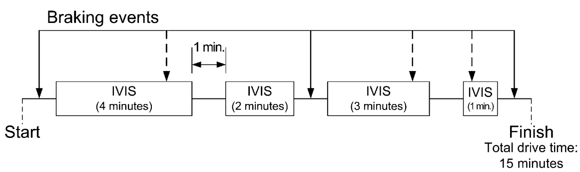

Fig. 1. Sample timeline of IVIS interactions and braking events during an IVIS drive. Braking events during IVIS interactions are indicated with dashed arrows while those between IVIS interactions (non-IVIS condition) are indicated with solid arrows.

1024×768 with a 60 Hz frame rate. Driving data were collected at 60 Hz. The driving environment, shown in Fig. 2, consisted of a straight suburban street with two lanes of traffic traveling in each direction divided by a center turning lane.

Eye movement data were collected at 60 Hz using Seeing Machines' faceLAB™ eye tracking system (version 4.1). The system uses two small video cameras to track head and eye movements and then calculates, among other measures, horizontal and vertical coordinates for a gaze vector that intersects the simulator screen.

2.4. Experimental tasks

2.4.1. Driving tasks

At the beginning of each drive, the subject vehicle (SV) was parked in the right lane of the roadway. Parked directly in front of the SV was a white lead vehicle (LV). The participants were instructed to accelerate to a speed of 20 m/s (45 mph) and follow the lead vehicle. The SV was equipped with a simulated cruise control to ensure uniform speed and distance from the LV across participants and IVIS interactions. The cruise control engaged automatically when the SV velocity reached 20 m/s and held the SV at this velocity at a time distance of 1.8 s behind the LV until the participant pressed the brake. Participants were instructed to use the cruise control as much as possible.

During each drive, participants performed two main driving tasks: responding to a braking lead vehicle and event detection. Participants responded to six LV braking events during each drive. Each braking event began when a vehicle traveling in the passing lane near the LV changed lanes to enter the lane in front of the LV. The LV braked following the lane change at a rate of 0.2 g until the participant pressed the brake pedal at least once and the LV reached a minimum velocity of less than 9 m/s (20 mph). Once both of these conditions were met, the LV continued to brake for a period selected at random from a uniform distribution of 0–5 s. Then the LV accelerated at a rate of 0.25 g until it reached a speed of 11 m/s (25 mph). At this point the LV was again coupled to the SV with a 1.8 s tailway. If participants did not brake in response to the LV, they would collide with the LV at a relative velocity of about 12 m/s (26 mph) approximately 6 s after the LV began to brake. To prevent participants from associating lane changes exclusively with the LV braking events, each drive also included six lane changes without LV braking.

Each participant experienced a total of 36 braking events, six in each of the six drives, and the braking events were balanced across IVIS condition. Fig. 1 shows an example of how braking events and IVIS interactions were distributed during an IVIS drive. Braking events occurred during the last minute of three of the four IVIS interactions (represented in Fig. 1 by the dashed arrows) and during three of the five non-IVIS intervals (solid arrows). The timing of the six braking events for each of the two baseline drives was determined as for the IVIS drives, using two random orderings of the IVIS interaction lengths.

The second driving task was a peripheral event detection task with a realistic target. Participants were instructed to respond to the appearance of a man on a bicycle in the driving scene by pressing a button on the steering wheel. Because the roadway was very wide and the passing traffic occluded the participants' view of the left side of the scene, the bicyclist only appeared to the right of the roadway. In half of the appearances, the bicyclist was stationary; in the other half, he was moving. The participants were told that the bicyclist would never enter the roadway. On average, the bicyclist was visible for 2.85 s (SD = 0.88 s) and appeared 45 times during the 15-min drive. The bicyclist is visible in the driving scene in Fig. 2.

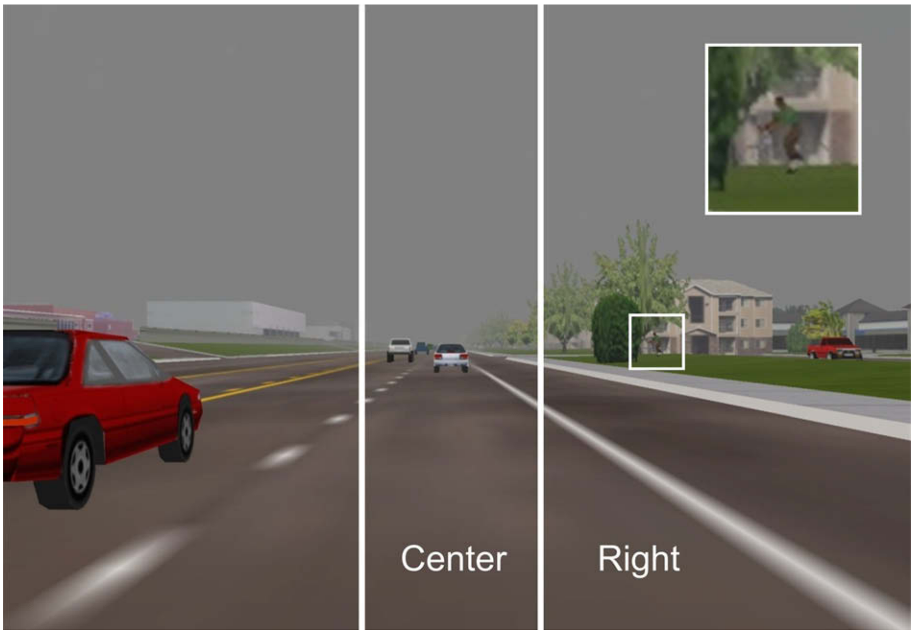

Fig. 2. Driving scene overlaid with areas of interest is used to classify fixation position. The bicyclist is located just to the right of the large bush.

2.4.2. In-vehicle information system (IVIS) task

The in-vehicle information system consisted of an auditory stock ticker that presented three-letter stock symbols (e.g., ADX) and whole number values from 1 to 25. The symbols and values were spoken by a digitized voice and were produced using a text-to-speech system. The symbols were selected randomly from all possible three-letter combinations, and their pronunciation by the text-to-speech system was informally checked for intelligibility by the first author. Each interaction began with a beep. The first two symbols and values presented after the beep were the two target stocks and their starting values. During the rest of the interaction, the two target stocks were randomly intermixed with non-target stocks with the constraint that target stocks could not be presented consecutively. Symbols that were very similar (i.e., CDU and CTU) were not included in the same interaction.

Participants tracked the values of the target stocks as they increased and decreased using buttons on the steering wheel. For example, if the participant identified a symbol as a target stock and then decided that its value had increased since the last time she heard that symbol, she pressed the button on the steering wheel labeled ↑. A new symbol and value were presented approximately every 3 s, and approximately six target stocks were presented during each minute of the interaction. At the end of each interaction, signified with another beep, the participant verbally identified the overall trend each of the target stocks followed during the interaction from four choices: hill, valley, upward or downward. This task was developed to impose a controlled demand that is more representative of potential in-vehicle systems than running memory tasks that are often used in dual-task situations (Hancock, Lesch, & Simmons, 2003; Matthews, Sparkes, & Bygrave, 1996).

2.5. Procedure

Upon arriving at the laboratory, each participant read the informed consent document, was given an opportunity to ask questions about the study, and gave consent. The participant was seated in the simulator and given instructions about how to follow the LV and use the cruise control. Then the participant completed a 10-min drive that included lane changes and braking events to become acclimated to the simulator. During the drive, the experimenters created the head model for the eye tracker. After the acclimation drive, the participant's gaze was calibrated to the simulator screen, and the accuracy of the eye tracker model was verified while the participant drove for 3 min.

Next the participant learned how to perform the IVIS task. The experimenter read instructions describing how the IVIS task was to be performed. Then the participant practiced interacting with the IVIS until s/he was able to perform the task, and the IVIS training concluded with a 5-min drive that included two practice interactions.

Before each experimental drive began, the eye tracker calibration was verified. The participant was reminded of the driving tasks, and if the next drive was an IVIS drive, the participant was reminded of IVIS task instructions. After the sixth drive, the participant was debriefed, given the opportunity to ask questions, and compensated for their time.

2.6. Dependent variables

Dependent variables were recorded for each driving task and the IVIS task conditions. For the lead vehicle braking events, the dependent variables were accelerator release reaction time and brake reaction time. Accelerator release reaction time is defined as the interval from when the lead vehicle began to brake until the participant removed his foot from the accelerator. Brake reaction time is the interval from when the LV began to brake until the participant depressed the brake pedal at least 9% of the brake pedal range.

Dependent variables for the bicyclist detection task included driver reaction time, driver sensitivity (d') to the presence of the bicyclist, and driver response bias (β). Driver reaction time is the time in seconds from the appearance of the bicyclist until the driver pressed the steering wheel button. Sensitivity and response bias are associated with signal detection theory, and the calculation of these variables will be described with the results.

For the eye tracking data, each drive was divided into intervals approximately 1 min long and each interval contained only one type of IVIS condition. Mean and standard deviation were calculated for each of the following eye movement variables for each interval: fixation duration, horizontal position, and vertical position; and saccade duration, distance, and speed. In addition, the standard deviations of both horizontal and vertical fixation positions were multiplied as a measure of spatial gaze concentration (Recarte & Nunes, 2000, 2003).

Finally, two binary variables were defined. The first assessed failure to consolidate fixated information. Each bicyclist event in which the participant made at least one fixation to the right while the bicyclist was visible was coded 1 if drivers reported the bicyclist and 0 if they did not. The second binary variable categorized each failure to respond the bicyclist with respect to fixation position. Each bicyclist event in which the participant failed to respond to the presence of the bicyclist was coded 1 if the participant made at least one fixation to the right and 0 for all others.

3. Results

The brake response, bicyclist detection, and eye movement variables were analyzed using repeated-measures ANOVAs. The statistical models used a composite symmetry covariance structure, and subject was specified as the repeated measure. The two independent variables, IVIS condition and IVIS duration, were evaluated in separate models. Post hoc comparisons were conducted and p-values were adjusted for multiple comparisons using the Tukey–Kramer method. Binary dependent variables were analyzed using generalized linear models with a logit link function, and a binomial distribution was specified. Subject was specified as the repeated measure and the correlation matrix had an independent structure. Statistics for type 3 contrasts were computed using generalized estimating equations.

3.1. Brake and accelerator release reaction times

Driver response to the lead vehicle braking events was largely unaffected by the IVIS task. There were no significant differences in brake and accelerator release reaction times for IVIS, non-IVIS, and baseline lead vehicle braking events (see Table 1). Similarly, reaction times were not significantly affected by IVIS task duration.

3.2. Bicyclist event detection performance

Inspection of bicyclist detection performance showed that some bicyclist events were very conspicuous, whereas others were seemingly undetectable. Bicyclist events with detection rates greater than 95% or less than 5% were excluded from analysis. In addition, despite efforts to prevent such situations, five bicyclist events followed the preceding bicyclist event too quickly for the participant to have adequate time to respond, and these events were also omitted from analysis. Overall, 683 events were omitted across all participants. For the remaining 2314 bicyclist detection events, the following analyses were performed.

The first response made during the "acceptance window", defined as the time the bicyclist was visible plus an additional 3 s, was counted as a "hit". Any subsequent responses during the acceptance window were discarded. Any response after the acceptance window had expired was classified as a "false alarm". Since the intervals outside the acceptance windows (M = 21.0 s, SD = 15.0 s) were much longer than the acceptance windows (M = 5.9 s, SD = 0.9 s), resulting in more opportunities for false alarms than for hits, the false alarm rate was adjusted by the ratio of the average acceptance window time to the average non-acceptance window time. Thus, false alarm rate is the number of false alarms recorded multiplied by the average acceptance window size divided by the total non-acceptance window time. The hit rate is the total number of hits over the number of events. If the hit rate was 1, it was replaced with a value slightly less than 1, $1 - (2 \times \text{number of events})^{-1}$. Similarly, a small positive value $(2 \times \text{number of events})^{-1}$, was used when the false alarm rate was zero. Stanislaw and Todorov (1999) present formulas for calculating sensitivity and response bias, where F is the false alarm rate, H is the hit rate, and Φ^{-1} yields z scores for the rates. Driver sensitivity to the bicyclist events was calculated using

$$d' = \Phi^{-1}(H) - \Phi^{-1}(F) \quad (1)$$

Response bias was calculated using

$$\beta = e^{\left\{\frac{[\Phi^{-1}(F)]^2 - [\Phi^{-1}(H)]^2}{2}\right\}} \quad (2)$$

Interaction with the IVIS strongly affected bicyclist event detection performance (see Table 1). When drivers were interacting with the IVIS, they took about 270 ms longer to detect the bicyclist compared to the non-IVIS condition and about 290 ms longer compared to the baseline condition. The reaction times for the non-IVIS and baseline conditions were not significantly different from one another.

Driver sensitivity and response bias were calculated for each baseline drive and for the IVIS and non-IVIS portions of each IVIS drive. Perfect detection of the bicyclist with no false alarms would result in a d' value of approximately 4.4 while detecting half of the bicyclist appearances with no false alarms would result in a d' of 2.2. As shown in Table 1, the IVIS condition affected driver sensitivity. Drivers were more sensitive to the bicyclist during the baseline drives relative to the IVIS and non-IVIS portions of the IVIS drives. This contrasts with the effect on the reaction time, which was significantly higher only when drivers were interacting with the IVIS.

Response bias was highly sensitive to IVIS condition. All two-way comparisons of IVIS conditions differed significantly (all adjusted $ps \leqslant 0.001$). Drivers were most conservative during the baseline and least conservative during the non-IVIS condition. Interestingly, the IVIS condition rather than the non-IVIS condition was the intermediate. Compared to the baseline,

Table 1
Omnibus F-tests and least squares means of the driving performance variables for IVIS conditions

Dependent measure	Omnibus test		IVIS condition least squares means (SE)		
	$F(2,22)$	p-Value	IVIS	Non-IVIS	Baseline
Accelerator reaction time	1.17	0.328	1.16 (0.13)	1.21 (0.13)	1.09 (0.13)
Brake reaction time	0.26	0.776	1.82 (0.16)	1.87 (0.16)	1.84 (0.16)
Bike response time	12.98	0.0002	2.83 (0.08)A	2.56 (0.09)B	2.54 (0.08)B
Sensitivity (d')	6.12	0.0077	2.58 (0.13)A	2.70 (0.13)A	3.02 (0.15)B
Response bias (β)	72.9	<0.0001	16.9 (0.82)A	8.43 (0.82)B	23.1 (1.1)C

Means that have a letter in common are not significantly different from one another (α = 0.05).

drivers were more likely to report seeing the bicyclist but were less sensitive to its appearance during the non-IVIS portions of the IVIS drive.

The reaction time to respond to the bicyclist was sensitive to the duration of IVIS task, $F(3,33) = 4.38$, $p = 0.011$. Post hoc comparisons show that the reaction times during the second, third, and fourth minutes of the IVIS interactions were, respectively, 310 ms ($t(33) = 3.0$, adjusted $p = 0.028$), 330 ms ($t(33) = 2.7$, adjusted $p = 0.048$), and 360 ms (not significant) longer than the 2.64 s required to respond to the bicyclist during the first minute. (Because there were fewer observations as the duration of the interactions increased, standard error increased with duration.) Sensitivity and response bias could not be calculated for IVIS duration because the moderately conservative response bias during the IVIS interactions led to only 13 false alarms.

3.3. Eye movements

The eye tracking system generated a series of coordinates that specify the location of the drivers′ gaze over time. These were translated into fixations, saccades, and smooth pursuit eye movements (see Liang, Reyes, & Lee, 2007 for details of eye movement classification), but pursuit movements were not considered in these analyses. Eye data from three participants were excluded from analysis because of poor tracking quality.

Fixations within 5° on either direction of the modal horizontal fixation position were classified as center fixations. This boundary was selected to create an area of interest around the lead vehicle (see Fig. 2). Fixations that were 5° of visual angle or more to the right of the mode horizontal fixation position were classified as fixations to the right side of the driving scene where the bicyclist appeared.

To assess the degree to which a failure to consolidate fixated information contributed to detection performance, the probability of detecting the bicyclist given that the right side of the scene was fixated was compared for the IVIS conditions. This variable was sensitive to IVIS condition, $\chi^2(2) = 7.14$, $p = 0.028$. The probability of drivers detecting the bicyclist given that they had fixated the right side of the driving scene was 0.69 when they were interacting with the IVIS. This was significantly lower than both non-IVIS (probability = 0.79, $\chi^2(1) = 13.42$, $p = 0.0002$) and baseline (probability = 0.77, $\chi^2(1) = 8.60$, $p = 0.0034$), which were not significantly different. These results show that interaction with the IVIS impaired the drivers' ability to detect the bicyclist even when they looked at the right side of the scene. This variable was insensitive to the duration of the IVIS interaction, $\chi^2(3) = 2.65$, $p = 0.45$; therefore, the impairment associated with looking to the right but not seeing the cyclist appears to be immediate and not cumulative as the task progresses over time.

Overall, drivers missed 558 bicyclist appearances. Nearly half of these misses (270) occurred even though drivers looked to the right side of the driving scene while the bicyclist was visible. The remaining misses occurred when drivers failed to look towards the right side of the driving scene while the bicyclist was visible. The IVIS conditions did not have a significant effect on the proportion of missed events associated with looks to the right, $\chi^2(2) = 0.2$, $p = 0.91$.

Average duration and variability of duration of all fixations were only marginally affected by the IVIS conditions (see Table 2). However, these dependent variables were significantly affected when the fixations were grouped by location. Fixations to the center of the driving scene were significantly shorter during the IVIS interactions compared to those during baseline. The duration of central fixations were also less variable during IVIS compared to both non-IVIS and baseline. Fixations to the right side of the driving scene were longer during the baseline compared to both IVIS and non-IVIS conditions. The duration of fixations on the right was more variable for baseline than for IVIS conditions.

Average horizontal fixation position shifted to the right slightly (by about 0.4°) during the baseline condition compared to the IVIS condition. Surprisingly, variability of horizontal fixation position was greater during IVIS than during baseline, though this difference was very small (less than 0.3°). Probability density plots of horizontal fixation position for each IVIS condition were created for each participant. Inspection of the plots revealed that the distributions of horizontal fixations were very individualized, but a general pattern emerged in which the peak of the IVIS distribution was taller than the peaks for the non-IVIS and baseline conditions. This observation signified a greater concentration of fixations in the center of the driving scene. Kurtosis is the fourth moment of a distribution about the mean and measures the "peakedness" of a distribution. Higher values of kurtosis indicate that the variance depends on a few relatively extreme values. Kurtosis was calculated for the horizontal fixation position over each 1-min period and was found to be sensitive to IVIS condition, $F(2,16) = 37.52$, $p < 0.0001$. Kurtosis was greatest during the IVIS interactions (4.21), least for baseline (0.945), and intermediate for the non-IVIS condition (2.56). All three conditions were significantly different from one another (largest adjusted p-value = 0.0052).

Vertical fixation position followed a similar pattern. The mean shifted upward about 1.4° during the baseline condition compared to both the IVIS and non-IVIS conditions. Variability of vertical position was also significantly different for all three IVIS conditions with vertical position being most variable during IVIS interactions and least variable during baseline. Spatial gaze concentration was also highly sensitive to IVIS task. However, concentration was seen during the baseline condition rather than during the IVIS interactions. Contrary to the effects of IVIS interaction on kurtosis for the horizontal distribution of fixations, IVIS interaction did not have a strong effect of the kurtosis of vertical fixation position, $F(2,16) = 1.53$, $p = 0.25$.

All six saccadic dependent variables were sensitive to IVIS condition (see Table 2). In addition, all post hoc comparisons of the three IVIS conditions were significant for five of the six variables, the exception being saccade duration variability. Saccade duration was longest during the IVIS intervals and shortest during the baseline. Saccade duration was less variable during baseline compared to both the IVIS and non-IVIS conditions. Saccade speeds were fastest and most variable during IVIS

Table 2
Omnibus *F*-tests and least squares means of the eye movement variables for IVIS conditions

Dependent measure	Units		Omnibus test		IVIS condition least squares means (SE)		
			$F(2,16)$	p-Value	IVIS	Non-IVIS	Baseline
Fixation duration	s	Mean	2.9	0.08	0.284 (0.02)	0.289 (0.02)	0.297 (0.02)
		SD	3.2	0.068	0.201 (0.02)	0.216 (0.02)	0.214(0.02)
Center fixation duration	s	Mean	4.5	0.028	0.301 (0.02)A	0.312 (0.02)A,B	0.320 (0.02)B
		SD	5.8	0.013	0.213 (0.02)A	0.235 (0.02)B	0.234 (0.02)B
Right fixation duration	s	Mean	19.5	<0.0001	0.226 (0.008)A	0.231 (0.009)A	0.247 (0.008)B
		SD	17.1	0.0001	0.120 (0.005)A	0.129 (0.006)A,B	0.138 (0.005)B
Horizontal fixation position	deg	Mean	4.0	0.038	10.64 (0.18)A	11.00 (0.16)A,B	11.05 (0.19)B
		SD	4.9	0.022	4.89 (0.28)A	4.85 (0.29)A,B	4.62 (0.28)B
Vertical fixation position	deg	Mean	24.1	<0.0001	5.72 (2.4)A	5.72 (2.4)A	7.09 (2.4)B
		SD	97.8	<0.0001	5.32 (0.51)A	4.49 (0.52)B	2.97 (0.51)C
Gaze concentration	deg^2		69.0	<0.0001	29.3 (3.7)A	23.0 (3.8)B	14.1 (3.7)C
Saccade duration	s	Mean	60.0	<0.0001	0.102 (0.002)A	0.098 (0.002)B	0.093 (0.002)C
		SD	52.1	<0.0001	0.053 (0.004)A	0.049 (0.004)A	0.036 (0.004)B
Saccade speed	deg/s	Mean	64.1	<0.0001	77.6 (4.1)A	70.9 (4.1)B	67.2 (4.1)C
		SD	103.9	<0.0001	58.7 (3.7)A	51.5 (3.7)B	45.4 (3.7)C
Saccade distance	deg	Mean	132.8	<0.0001	8.38 (0.52)A	6.91 (0.53)B	6.16 (0.53)C
		SD	175.8	<0.0001	8.14 (0.62)A	5.98 (0.64)B	4.56 (0.63)C

Means that have a letter in common are not significantly different from one another ($\alpha = 0.05$). deg = degrees of visual angle.

and slowest and least variable during baseline. Saccades covered greater distances that were more variable during IVIS interaction and shorter, less variable distances during baseline. Overall the saccadic variables were very sensitive and were highly differentiated between the three IVIS conditions.

None of the eye movement variables were sensitive to the length of IVIS interaction. That is, eye movements during the first minute of the IVIS interaction were not different from those in the second, third, or fourth minutes. The same analysis was completed with the IVIS interactions divided into 30-s segments. For all eye movement variables, the first 30 s of IVIS interaction was not found to be significantly different from any other segment. These results suggest that the changes in eye movements associated with IVIS interaction occurred with the onset of the task and did not cumulate over time.

Although the initiation of the IVIS task rapidly affected eye movements, the results suggest that many of the variables did not return to their pre-IVIS pattern as quickly. As shown in Table 2, some changes in eye movements during IVIS interaction were carried over to the non-IVIS periods following the completion of the IVIS interactions; the IVIS means were significantly different than the baseline means, and the non-IVIS means were intermediate.

To examine how drivers "recovered" from the IVIS interaction and then transitioned into the next IVIS interaction, the eye movements were summarized for each of these periods: the last 30 s of the IVIS interaction, the first 30 seconds of the 1-min non-IVIS period, the last 30 s of the non-IVIS period, and the first 30 s of the next IVIS interaction. A repeated-measures ANOVA examined both transition period, duration of the IVIS interaction preceding the transition, and interaction of these two factors. Duration of the IVIS interaction significantly affected only the mean horizontal fixation position, $F(3,24) = 3.25$, $p = 0.040$, with horizontal position shifted to the right about 1° of visual angle if the previous IVIS interaction was 4 min long compared to 3 min, $t(24) = -3.12$, adjusted $p = 0.023$. No dependent variables were sensitive to an interaction of transition period and duration of the preceding IVIS. The omnibus *F*-test and the post hoc comparisons for transition period are shown in Table 3.

The pattern of results for fixation duration in the center of the driving scene shows that the effect of transitioning to the non-IVIS period was short-lived. Drivers made shorter fixations to the center of the driving scene during the first 30 s of the non-IVIS period than during the end of the IVIS interaction; however, fixation duration returned to the end-of-IVIS level by the second half of the non-IVIS period. Mean and variability of both saccade speed and distance decreased significantly during the transition from the IVIS interaction to the non-IVIS period, and this change was maintained throughout the non-IVIS period. Variability of vertical fixation position, gaze concentration, and mean and variability of saccade duration reflected a more gradual recovery from the demands of the IVIS interaction, with the beginning of the non-IVIS period being statistically similar to both the end of the IVIS period and the second half of the non-IVIS period. Finally, the results of this analysis confirm the rapid change of eye movement patterns with the onset of the IVIS task. All dependent variables that were affected by the IVIS transition, with the exception of center fixation duration, changed significantly between the second half of the non-IVIS period and the first 30 s of the IVIS interaction.

3.4. Factor analysis

The ANOVA results show that cognitive load does not influence the various measures of scanning behavior in a uniform manner. A factor analysis was used to assess how cognitive load influenced the various dependent variables and to identify

Table 3
Omnibus *F*-tests and least squares means of the eye movement variables for IVIS transition periods

Dependent measure	Units		Omnibus test		IVIS condition least squares means (SE)			
			$F(3,24)$	*p*-Value	Last 30 s IVIS	First 30 s non-IVIS	Last 30 s non-IVIS	First 30 s IVIS
Fixation duration	s	Mean	4.62	0.011	0.290 (0.02)A	0.266 (0.02)B	0.290 (0.02)A	0.275 (0.02)A,B
		SD	2.87	0.057	0.209 (0.02)	0.189 (0.02)	0.210 (0.02)	0.193 (0.02)
Center fixation duration	s	Mean	4.83	0.009	0.309 (0.02)A	0.283 (0.02)B	0.310 (0.02)A	0.289 (0.02)A,B
		SD	3.47	0.032	0.222 (0.02)	0.201 (0.02)	0.225 (0.02)	0.202 (0.02)
Right fixation duration	s	Mean	2.08	0.129	0.225 (0.008)	0.220 (0.008)	0.233 (0.008)	0.217 (0.009)
		SD	1.24	0.316	0.115 (0.006)	0.123 (0.006)	0.126 (0.006)	0.119 (0.007)
Horizontal fixation position	deg	Mean	1.54	0.230	10.6 (0.77)	11.2 (0.77)	11.1 (0.77)	10.7 (0.78)
		SD	2.19	0.115	4.68 (0.38)	5.01 (0.38)	4.63 (0.38)	5.04 (0.39)
Vertical fixation position	deg	Mean	2.63	0.073	5.68 (2.7)	5.28 (2.7)	6.27 (2.7)	5.48 (2.7)
		SD	11.8	<0.0001	5.18 (0.61)A,B	4.64 (0.61)A,C	3.79 (0.61)C	5.67 (0.62)B
Gaze concentration	deg^2		9.98	0.0002	28.1 (4.7)A,B	25.3 (4.7)A,C	18.6 (4.7)C	33.6 (4.8)B
Saccade duration	s	Mean	6.43	0.002	0.104 (0.003)A	0.101 (0.003)A,B	0.097 (0.003)B	0.104 (0.003)A
		SD	5.78	0.004	0.054 (0.006)A	0.054 (0.006)A	0.043 (0.006)B	0.057 (0.006)A
Saccade speed	deg/s	Mean	10.8	0.0001	78.1 (4.8)A	71.3 (4.8)B,C	69.1 (4.8)B	75.5 (4.8)A,C
		SD	13.1	<0.0001	57.6 (4.5)A	51.4 (4.5)B	48.3 (4.5)B	57.7 (4.5)A
Saccade distance	deg	Mean	25.6	<0.0001	8.56 (0.62)A	7.07 (0.62)B	6.60 (0.62)B	8.25 (0.63)A
		SD	32.9	<0.0001	7.96 (0.76)A	6.30 (0.76)B	5.16 (0.76)C	8.27 (0.77)A

Means that have a letter in common are not significantly different from one another ($\alpha = 0.05$). deg = degrees of visual angle.

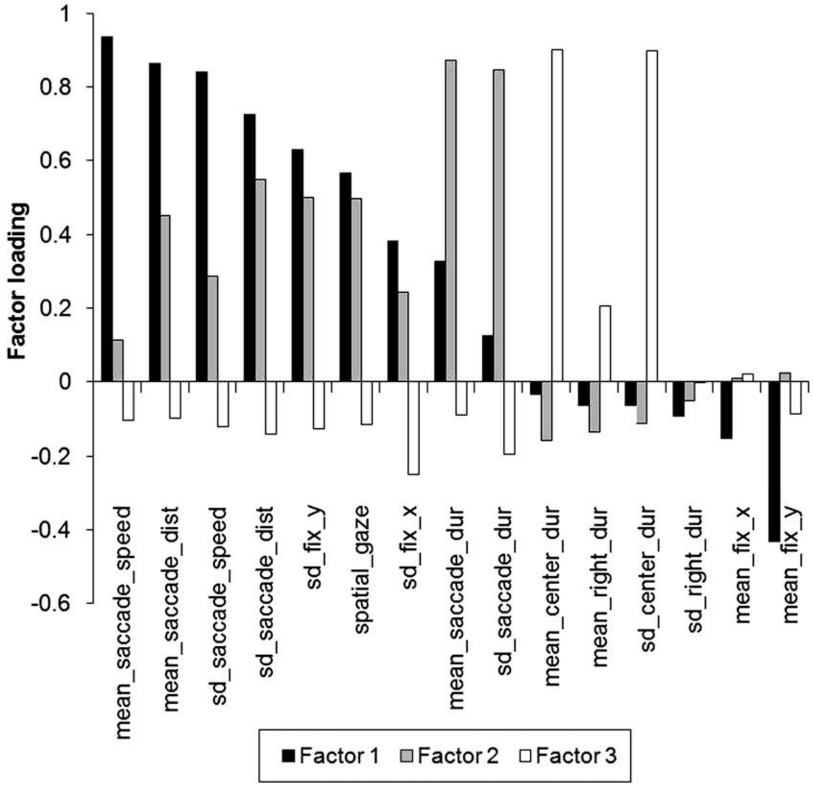

Fig. 3. Rotated factor loadings from a factor analysis that included all eye movement dependent variables.

common dimensions underlying the eye movement measures. Prior communalities were estimated using the squared multiple correlation approach, and the factors were rotated orthogonally using the varimax method. Three factors were found to account for 84% of the variation in the eye movement data.

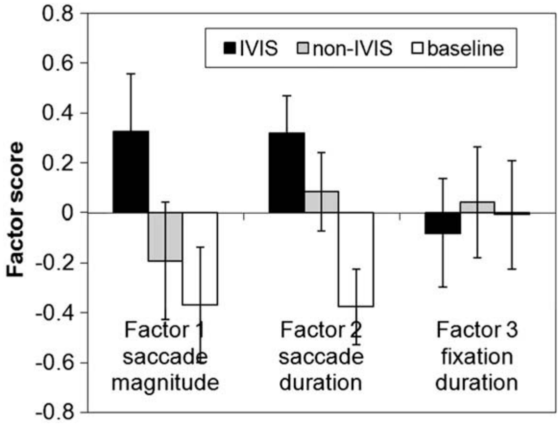

Fig. 4. Factor scores for each IVIS condition.

Factor 1 – saccade magnitude – accounted for 57% of the variation. As shown in Fig. 3, saccade speed and distance variables had the highest loadings (see Fig. 3), followed by variables associated with fixation position variability. This factor was sensitive to IVIS condition (see Fig. 4), $F(2,16) = 73.6$, $p < 0.0001$, and post hoc comparisons revealed that the IVIS task was significantly different from both the non-IVIS, $t(16) = 7.56$, adjusted $p < 0.0001$, and baseline conditions, $t(16) = 11.7$, adjusted $p < 0.0001$. The difference between the non-IVIS and baseline conditions failed to reach statistical significance, $t(16) = 2.46$, adjusted $p = 0.063$. As a result, Factor 1 seems to reflect the concurrent changes in eye movements that are a consequence of cognitive load.

Factor 2 – saccade duration – accounted for approximately 15% of the variation. The saccade duration measures had the highest positive loadings (see Fig. 3). Factor 2 was sensitive to IVIS condition, $F(2,16) = 46.5$, $p < 0.0001$. Post hoc comparisons showed all three IVIS conditions to be significantly different from one another (see Fig. 4). Specifically, the baseline condition was shown to be quite different from both the IVIS, $t(16) = 9.59$, adjusted $p < 0.0001$, and non-IVIS, $t(16) = 5.31$, adjusted $p = 0.0002$, conditions, whereas the difference between the IVIS and non-IVIS conditions was smaller, $t(16) = 2.79$, adjusted $p < 0.033$. These results suggest that Factor 2 is sensitive to the effects of cognitive distraction that persist after the IVIS interactions have ended. This contrasts with Factor 1, which lacks sensitivity to carryover effects during the non-IVIS condition.

Finally, Factor 3 – central fixation duration – accounted for 12% of the variation. Fixation duration and fixation duration variability in the center of the driving scene had very high loadings for this factor. This factor was not sensitive to IVIS condition, $F(2,16) = 1.36$, $p = 0.285$, and these results suggest that a subset of eye movement measures is unaffected by cognitive load.

IVIS task duration did not have a significant effect on any of the factors. Overall, these three factors appear to reflect the immediate (Factor 1) and persistent (Factor 2) effects of cognitive distraction on eye movements, as well as the constant visual demand inherent in driving (Factor 3).

4. Discussion

Contrary to our hypothesis, driver response to the LV braking events was surprisingly uniform across IVIS conditions. Previous research had demonstrated consistently slower reactions to a braking lead vehicle when drivers performed cognitively demanding tasks (Horrey & Wickens, 2006; Lamble, Kauranen, Laakso, & Summala, 1999; Lee, Caven, Haake, & Brown, 2001). One likely explanation is that the drivers in this study were always cognitively loaded because when they were not performing the IVIS task they were concentrating on the bicyclist detection task. The demands of bicyclist detection seem similar to the effects of scene complexity that led to longer reaction times to braking lead vehicles in a previous study (Lee et al., 2001). A second explanation is that the lane change that preceded each LV braking event acted as a cue to drivers. However, the lane changes that were not followed by LV braking were examined, and we found that drivers rarely released the accelerator pedal in response to the lane change.

The strong effect of IVIS condition on bicyclist detection performance demonstrates the diminished sensitivity to events in the periphery. In particular, reaction times were about 230 ms longer, and this effect on the reaction times increased after the first minute of the interaction and then remained relatively constant during the second, third, and fourth minutes of the interaction. On average, driver sensitivity to the bicyclist fell by 15% during IVIS interactions relative to the baseline condition. Interestingly, a similar decrease in sensitivity occurred during the non-IVIS periods between IVIS interactions. The effect of the IVIS interaction on event detection performance is consistent with previous studies (Horrey & Wickens, 2006). However, the persistent effect of the IVIS interactions after they have ended is a novel finding that is consistent with the goal activation model (Altmann & Trafton, 2002) and suggests that old goals, such as those associated with IVIS interaction, can interfere with new goals, such as those associated with scanning the driving environment.

One explanation for the influence of the IVIS task on bicyclist detection is that drivers may have considered the detection task as optional and readily shed it as the load increased. Further research should explore whether the performance decline observed in this study reflects an artifact of the simulator environment or whether it reflects the tendency for drivers to shed safety-critical detection tasks on the road. Eye movements and event detection performance in other studies suggest that safety-critical event detection does tend to decline as cognitive load increases in a similar manner to what was observed in this study (Greenberg et al., 2003; Recarte & Nunes, 2003).

Both the ANOVA and factor analyses of the eye movements show that many different variables were affected by the IVIS task but none were sensitive to the duration of the IVIS task. Changes in eye movements with IVIS task onset were immediate rather than cumulative, and some of these changes persisted even after drivers completed the IVIS interactions. Further, some of the variables "recovered" from the effects of the IVIS task very quickly while others "recovered" more slowly.

Evidence from this experiment regarding the mechanisms underlying the diminished event detection performance is mixed. Previous studies have suggested that cognitive load undermines event detection through increased gaze concentration. In this study, a common measure of gaze concentration (the product of the standard deviation of vertical and horizontal fixation positions) increased with cognitive load rather than decreased as it did in other studies (Recarte & Nunes, 2003). However, the detection task employed in this study was different from other paradigms; the targets were located on only one side rather than centered on the driver's line of sight and immersed in the driving scene rather than located inside or on the vehicle. Nevertheless, the findings of this study suggest that a single, simple measure may not accurately link eye movements to driver distraction. Consistent with a tendency for cognitive load to increase gaze concentration, drivers had far greater kurtosis in the fixation distribution when they were performing the IVIS task. These findings correspond with Recarte and Nunes' suggestion that gaze concentration reflects a strategic allocation of visual attention that undermines event detection.

Evidence of consolidation failure was also seen. When drivers were interacting with the IVIS, they were less likely to respond to the bicyclist even if they looked at the right side of the driving scene when the bicyclist was present. Response to the bicyclist given that the driver looked to the right improved during both non-IVIS and baseline conditions. In addition, response after a look to the right was unaffected by IVIS task duration, suggesting that consolidation failure depends on direct competition for processing resources rather than goal interference.

Overall, these results suggest that two separate mechanisms may underlie the effects of cognitive distraction. One involves a general interference that undermines the consolidation of fixated information and is associated with resource competition (Wickens, 1984, 2002) or a response bottleneck (Pashler, 1998). Drivers sometimes look but do not see events when cognitively loaded. This mechanism seemed to be active primarily during the IVIS interaction. A second mechanism involves goal interference in which competing goals result in strategic shifts of attention (Altmann & Trafton, 2002). The carryover seen in the eye movements and the decreased sensitivity to the bicyclist during the non-IVIS periods may reflect the cost of switching to a new goal. Goal interference and the associated strategic shifts of attention also seem to correspond to strategic management of attention associated with the gaze concentration results of Recarte and Nunes (2003).

The finding that bicyclist detection performance was affected by IVIS interaction while driver response to a braking lead vehicle was not indicates that brake reaction time is not a definitive measure of driver distraction. These results are consistent with the multi-dimensional description of driver distraction that others have identified (Young & Angell, 2003). While response to a braking lead vehicle may indeed give insight into driver state, it alone is not a sufficient indicator of the full extent to which cognitive load can interfere with driving.

Although this study provides some interesting insights into how cognitive load might influence driver performance, these insights must be considered in light of the study's limitations. This study suffered from the obvious restrictions associated with extrapolating results from simulator driving to driving on the road. In particular, this study simplified and distorted the driving task. The requirement to detect the bicyclist placed an explicit requirement on drivers that is only implicit in normal driving. This explicit requirement may have distorted the scanning behavior and may be one reason why the gaze concentration effects seen in this study do not match those seen in other studies.

Another limit of this study concerns the IVIS task. The cognitive demands the IVIS task posed in this study are certainly not representative of the full range of demands in-vehicle devices can pose, and the effects of these various demands are not known. This study suggests that task duration may be a useful dimension to consider in describing the demands of these systems. An important difference between the IVIS task in this study and those tasks that drivers might actually perform is that this task held little intrinsic interest for the drivers. Tasks of great interest or those with great financial or emotional consequences might pose a much greater distraction than those used in this study. For example, had drivers been day traders who had large investments in the stocks that they were monitoring, the effects on event detection might have been greater.

5. Conclusions

These results have implications for IVIS design, evaluation, and development of real-time estimates of driver distraction. Regarding IVIS design, these results show that, at least for some tasks, longer interactions can lead to greater degrees of distraction. In addition, some tasks, such as the relatively engaging one used in this experiment, can have a persistent effect on drivers and undermine their performance even after they have completed the IVIS interaction. System design should consider the effects of task duration and the persistence of these effects after drivers have completed an interaction.

Regarding evaluation, this study demonstrates that cognitive distraction can undermine driving safety in several ways and focusing on a single element of driving performance may underestimate its effect. This result is particularly important given the finding that at least some of these effects persist beyond the end of the interaction. As measured by response to a braking lead vehicle, the results suggest the IVIS interactions have little effect on the driver; however, bicyclist detection performance portrays a very different situation. System evaluation should consider multiple measures of distraction and consider the effects of a potentially distracting interaction beyond the duration of the interaction.

Real-time assessment of driver state represents a promising way to mitigate driver distraction (Donmez, Boyle, & Lee, 2006). If eye movements and other variables can be used to identify driver distraction, this information can be used to adapt the IVIS and driver support systems, such as collision warnings. This study shows that simple measures such as gaze concentration may not precisely reflect driver distraction. Both goal activation and resource competition influence distraction and these are reflected in different sets of eye movement variables. Further research is needed to confirm these results and assess the degree to which different IVIS interactions contribute to distraction associated with both resource competition and activation of competing goals.

Acknowledgments

This work was completed as part of the SAfety VEhicle(s) using adaptive Interface Technology (SAVE-IT) program. The authors would like to thank the reviewers and the graduate students of the Cognitive Systems Laboratory for their valuable comments.

References

Altmann, E. M., & Trafton, J. G. (2002). Memory for goals: An activation-based model. *Cognitive Science: A Multidisciplinary Journal, 26*(1), 39–83.

Crundall, D. E., & Underwood, G. (1998). Effects of experience and processing demands on visual information acquisition in drivers. *Ergonomics, 41*(4), 448–458.

Donmez, B., Boyle, L. N., & Lee, J. D. (2006). The impact of driver distraction mitigation strategies on driving performance. *Human Factors, 48*(4), 785–804.

Greenberg, J., Tijerina, L., Curry, R., Artz, B., Cathey, L., Grant, P., et al. (2003). Evaluation of driver distraction using an event detection paradigm. In *Paper presented at the transportation research board 82nd annual meeting*.

Hancock, P. A., Lesch, M., & Simmons, L. (2003). The distraction effects of phone use during a crucial driving maneuver. *Accident Analysis and Prevention, 35*(4), 501–514.

Horrey, W. J., & Wickens, C. D. (2006). Examining the impact of cell phone conversations on driving using meta-analytic techniques. *Human Factors, 48*(1), 196–205.

Lamble, D., Kauranen, T., Laakso, M., & Summala, H. (1999). Cognitive load and detection thresholds in car following situations: Safety implications for using mobile (cellular) telephones while driving. *Accident Analysis and Prevention, 31*(6), 617–623.

Lee, J. D., Caven, B., Haake, S., & Brown, T. L. (2001). Speech-based interaction with in-vehicle computers: The effect of speech-based e-mail on drivers' attention to the roadway. *Human Factors, 43*, 631–640.

Lee, J. D., & Strayer, D. L. (2004). Preface to a special section on driver distraction. *Human Factors, 46*, 583–586.

Liang, Y., Reyes, M. L., & Lee, J. D. (2007). Real-time detection of driver cognitive distraction using support vector machines. *IEEE Transactions on Intelligent Transportation Systems, 8*(2), 340–350.

Matthews, G., Sparkes, T. J., & Bygrave, H. M. (1996). Attentional overload, stress, and simulated driving performance. *Human Performance, 9*(1), 77–101.

McCartt, A. T., Hellinga, L. A., & Bratiman, K. A. (2006). Cell phones and driving: Review of research. *Traffic Injury Prevention, 7*, 89–106.

Monk, C. A., Boehm-Davis, D. A., & Trafton, J. G. (2004). Recovering from interruptions: Implications for driver distraction research. *Human Factors, 46*(4), 650–663.

Pashler, H. E. (1998). *The psychology of attention*. Cambridge, MA: The MIT Press.

Patten, C. J. D., Kircher, A., Ostlund, J., & Nilsson, L. (2004). Using mobile telephones: Cognitive workload and attention resource allocation. *Accident Analysis and Prevention, 36*(3), 341–350.

Ranney, T. A., Harbluk, J. L., & Noy, Y. I. (2005). Effects of voice technology on test track driving performance: Implications for driver distraction. *Human Factors, 47*(2), 439–454.

Recarte, M. A., & Nunes, L. M. (2000). Effects of verbal and spatial-imagery tasks on eye fixations while driving. *Journal of Experimental Psychology: Applied, 6*(1), 31–43.

Recarte, M. A., & Nunes, L. M. (2003). Mental workload while driving: Effects on visual search, discrimination, and decision making. *Journal of Experimental Psychology: Applied, 9*(2), 119–137.

Redelmeier, D. A., & Tibshirani, R. J. (1997). Association between cellular-telephone calls and motor vehicle collisions. *New England Journal of Medicine, 336*(7), 453–458.

Regan, M. A., Lee, J. D., & Young, K. L. (2008). *Driver distraction: Theory, effects and mitigation*. CRC Press.

Seo, D. C., & Torabi, M. R. (2004). The impact of in-vehicle cell-phone use on accidents or near-accidents among college students. *Journal of American College Health, 53*(3), 101–107.

Stanislaw, H., & Todorov, N. (1999). Calculation of signal detection theory measures. *Behavior Research Methods, Instruments, & Computers, 31*, 137–149.

Strayer, D. L., Drews, F. A., & Johnston, W. A. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology: Applied, 9*(1), 23–32.

Victor, T. W., Harbluk, J. L., & Engstrom, J. A. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F, 8*, 167–190.

Wickens, C. D. (1984). Processing resources and attention. In R. Parasuraman & R. Davies (Eds.), *Varieties of attention* (pp. 63–102). New York: Academic Press.

Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science, 3*(2), 159–177.

Young, R. A., & Angell, L. S. (2003). The dimensions of driver performance during secondary manual tasks. In *Paper presented at the second international driving symposium on human factors in driver assessment, training, and vehicle design*.