The Interaction of Cognitive Load and Attention-Directing Cues in Driving

Yi-Ching Lee, University of Illinois at Urbana-Champaign, Savoy, Illinois,
John D. Lee and **Linda Ng Boyle,** University of Iowa, Iowa City, Iowa

Objective: This study investigated the effect of a nondriving cognitively loading task on the relationship between drivers' endogenous and exogenous control of attention. **Background:** Previous studies have shown that cognitive load leads to a withdrawal of attention from the forward scene and a narrowed field of view, which impairs hazard detection. **Method:** Posner's cue-target paradigm was modified to study how endogenous and exogenous cues interact with cognitive load to influence drivers' attention in a complex dynamic situation. In a driving simulator, pedestrian crossing signs that predicted the spatial location of pedestrians acted as endogenous cues. To impose cognitive load on drivers, we had them perform an auditory task that simulated the demands of emerging in-vehicle technology. Irrelevant exogenous cues were added to half of the experimental drives by including scene clutter. **Results:** The validity of endogenous cues influenced how drivers scanned for pedestrian targets. Cognitive load delayed drivers' responses, and scene clutter reduced drivers' fixation durations to pedestrians. Cognitive load diminished the influence of exogenous cues to attract attention to irrelevant areas, and drivers were more affected by scene clutter when the endogenous cues were invalid. **Conclusion:** Cognitive load suppresses interference from irrelevant exogenous cues and delays endogenous orienting of attention in driving. **Application:** The complexity of everyday tasks, such as driving, is better captured experimentally in paradigms that represent the interactive nature of attention and processing load.

INTRODUCTION

Increasingly, manufacturers and after-market suppliers offer drivers in-vehicle information systems that promise increased productivity, convenience, and mobility. These systems can also undermine driver safety, given the potential for driver distraction. In 2005, the U.S. Department of Transportation's National Highway Traffic Safety Administration estimated that 10% of vehicles driven during daylight hours were by someone conversing on a wireless phone (Glassbrenner, 2005). More generally, drivers engaged in a distracting activity an average of once every 6 min (McEvoy, Stevenson, & Woodward, 2006). A naturalistic driving study demonstrated that driver inattention is the leading contributor to crashes and near-crashes, with inattentive drivers having 3 times the likelihood of a near-crash or crash as attentive drivers (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006).

Simulator experiments can complement naturalistic studies by identifying the mechanisms underlying the increased crash risk associated with driver distraction. For example, Strayer and Johnston (2001) examined the influence of several distracting activities on driving performance in a controlled environment. They observed that active engagement in cell phone conversations interfered with drivers' ability to detect simulated traffic lights, but holding a cell phone or listening to books on tape did not. In a subsequent study, Strayer, Drews, and Johnston (2003) concluded that actively engaging in a secondary, nondriving task led to a withdrawal of attention from the forward scene, yielding a form of inattention blindness. In addition,

Address correspondence to Yi-Ching Lee, Human Factors Division, Institute of Aviation, University of Illinois at Urbana-Champaign, 1 Airport Road, Savoy, IL 61874; chinglee@illinois.edu. *HUMAN FACTORS,* Vol. 51, No. 3, June 2009, pp. 271-280. DOI: 10.1177/0018720809337814.

cognitively loaded drivers had trouble recalling prior encounters with roadway objects even though drivers looked at those objects, suggesting that performing a secondary task disrupts the process of encoding fixated information. Recarte and Nunes (2003) found that performing a cognitively demanding task while driving narrowed drivers' scanning of the road and reduced how frequently they checked the rearview mirror and speedometer. This altered scanning pattern suggests that cognitive load impairs how drivers distribute their attention. However, the specific mechanisms by which nondriving cognitively loading tasks interfere with the control of attention have not been well studied.

The current study was designed to further understand the mechanisms underlying the control of attention and driver distraction. Substantial evidence suggests that two mechanisms influence attentional control: top-down, or endogenous, control and bottom-up, or exogenous, control. Posner's cue-target paradigm (Posner, 1980; Posner, Nissen, & Ogden, 1978) has been used to study the control of visual attention by using different cues to separate the endogenous and exogenous contributions. Endogenous cues consist of symbolic representations, such as an arrow, that direct attention voluntarily and spatially to the cued locations. Exogenous cues consist of physical properties of likely target locations, such as the abrupt onset of cues, that direct attention automatically to the cued locations.

Researchers using Posner's paradigm have shown that cues that indicated the likely location of a subsequent target stimulus enhanced speed and accuracy of target detection and that endogenous cues elicit slow-acting, voluntary orienting of attention, whereas exogenous cues elicit fast-acting, reflexive orienting of attention (Berger, Henik, & Rafal, 2005; Luck & Vecera, 2002; Theeuwes, 1991a, 1994). Invalid cues led to longer reaction times (RTs) and lower accuracy than did valid cues, and neutral cues yielded intermediate performance responses. Jonides (1981) compared the effect of a memory span secondary task on the processing capacity associated with endogenous and exogenous cues. The costs-plus-benefits analysis (RT and error rate differences between invalid and valid trials) indicated that a greater invariance as a function of memory load was observed for the exogenous cue condition than for the endogenous cue condition. As memory load increased, valid endogenous cues became less beneficial and invalid endogenous cues became more costly.

Muller and Rabbitt (1989) found that simultaneous task-irrelevant and spatially uninformative flashes interrupted the voluntary, endogenous orienting to a greater degree than they did the reflexive, exogenous orienting. Furthermore, Lavie's load theory of attention (Lavie, 1995; Lavie, Hirst, de Fockert, & Viding, 2004; Lavie & Tsal, 1994; Rees, Frith, & Lavie, 1997) suggests that selective attention of a relevant task and rejection of irrelevant distractors are influenced by the processing load of the relevant task. When the load is high, little or none of the remaining capacity can be distributed to processing irrelevant distractors; as a result, interference from the distractors is reduced. These studies used simple displays that lack the complex, dynamic demands of many tasks, such as driving, and so it is not clear which of these accounts of how cognitive load influences the orientation of attention might apply to driving. For that reason, the current study adapts Posner's paradigm to the driving domain, a complex and dynamic environment that is representative of situations that place high demands on attentional control.

Adapting Posner's paradigm to driving can clarify how cognitively loading secondary tasks influence the exogenous and endogenous control of attention and the degree to which distractors are processed. A top-down visual search task was implemented, and participants searched for target pedestrians while interacting with a simulated in-vehicle system. Consistent with Jonides (1981), we hypothesized that cognitive load from the secondary task would undermine endogenous control of attention, making valid cues less beneficial and invalid cues more costly. We also hypothesized that the influence of irrelevant exogenous-driven stimuli from scene clutter would be particularly strong when the driver was cognitively loaded.

METHOD

Participants

Sixteen native English speakers (5 men and 11 women) ranging in age from 21 to 30 years (M = 26, SD = 2.3) participated in this study.

They had normal or corrected-to-normal vision, drove at least three times per week and 4,828 km (3,000 miles) per year, and possessed a valid driver's license for at least 5 years. They were screened for color perception using Ishihara's tests for color-blindness (Ishihara, 1966). Participants were compensated for their time at a rate of \$15 per hour. A bonus of up to \$9.60 was offered as an incentive to perform well on the secondary task.

Apparatus and Tasks

A fixed-based, medium-fidelity driving simulator was used for the experiment. The simulator uses a 1992 Mercury Sable vehicle cab that has been modified to include a screen with a 50° visual field of view, force feedback steering wheel, and a high fidelity sound system. DriveSafety's Vection™ software generated fully textured graphics at a 60-Hz frame rate with 1,024 × 768 resolution. Data were collected at a rate of 60 Hz.

We collected eye movement data at 60 Hz using a Seeing Machines' FaceLab™ eye tracking system (Version 4.2). This system uses two small video cameras to track head and eye movements and is able to calculate the coordinates for a gaze vector that intersects the simulator screen. The system does not require any head-mounted hardware and is unobtrusive.

The driving task required participants to use cruise control and to drive in the center lane of a foggy, one-way, three-lane highway. The cruise control maintained a constant headway of 28 m to a lead vehicle and was activated by drivers accelerating to 48.3 km/h. Participants were asked to monitor the lead vehicle and to brake as soon as they noticed the lead vehicle braking (the cruise control did not respond to the braking lead vehicle) and to resume their speed and reengage cruise control after each braking event. There was traffic in the adjacent lanes.

Sudden changes of roadside objects that have high-contrast images may capture drivers' attention involuntarily (Theeuwes, 1991b). Thus, the study also included exogenous cues that clutter the driving scene that were different from the locations of target pedestrians. Thus, in half of the drives, billboards that flashed at a rate of four times per second were added to the grassy areas 18 m from either edge of the road.

The secondary task provided a controlled introduction of demands that are similar to those of emerging in-vehicle technology. The task required participants to listen to and respond to auditory messages that were presented by a synthetic English-speaking male adult voice (Reyes & Lee, 2004). Each message presented information on the cost (one dollar sign or two dollar signs), quality (one star or two stars), and wait time (short or long) for three different restaurants. At the end of each message, participants were asked six questions that required transforming the information to categories of restaurants.

Our study included a pedestrian detection task that is similar to the traditional Posner paradigm. The modified cue-target paradigm used pedestrian crossing signs as the endogenous cue and pedestrians located in the parking lane as the target. Drivers were expected to use their knowledge of and experience with road signs to guide their attention endogenously to meaningful objects (Theeuwes, 1991b). Pedestrians were always occluded by trucks in the parking lanes and by fog for all but approximately 2 s. There were 20 pedestrians following each endogenous cue, and each pedestrian could appear behind 1 of 40 pairs of trucks (one on either side of the road). When drivers detected a pedestrian, they responded by pressing a right or left button on the steering wheel corresponding to a pedestrian with a red or green shirt, respectively. The purpose of having participants respond to the shirt color was to ensure that pedestrian locations were independent of response button locations (Spence & Driver, 1994).

Certain modifications were necessary in adapting Posner's cue-target paradigm to the driving simulator environment. Instead of a fixation point, participants drove through a natural scene and monitored a lead vehicle that braked periodically. Instead of an endogenous cue for each onset of a target, participants had to detect 20 targets after the onset of each endogenous cue. Instead of brief delay between the cue and target onset, approximately 20 s elapsed between the cue and onset of the first target; participants took 5 to 7 s to drive past the next pair of trucks, and participants could make multiple fixations toward the potential target locations before and after they detected the target.

Even though visual attention was less carefully controlled, these modifications exposed participants to a complex, dynamic situation that is more representative of everyday activities than the traditional cue-target paradigm.

Procedure

Participants were informed of the association between pedestrian crossing signs and pedestrians and were told that pedestrians may be observed after the signs. They then learned the definitions of the restaurant categories and the need to transform numerical information to categorical information. Participants' comprehension of the experimental manipulations was assessed by a set of multiple-choice questions. After correctly answering the questions, participants drove a practice drive to get accustomed to the vehicle dynamics, driving environment, and the detection task.

Participants also practiced the secondary task while sitting in the simulator. They were then required to verbally answer each question with the appropriate restaurant name and were encouraged to provide their best answer even if they were not sure. They were rewarded with a $0.20 incentive for each correct answer.

Data collection began after participants fully understood the instructions. Participants were told to scan the driving scene and drive as they normally would. Each drive was 14 km long and took approximately 18 min to complete.

Each drive included two sections with neutral cues, one with a cue to the left, and one with a cue to the right (Figure 1). Each section began with an auditory message that indicated the upcoming presentation of the pedestrian crossing signs. The signs appeared shortly after the auditory message and were visible for approximately 5 s. Participants saw either one pedestrian crossing sign and one merge sign or two pedestrian crossing signs. A pedestrian sign on the right and a merge sign on the left was a predictive cue and analogous to an arrow pointing to the right in the cue-target paradigm (Jonides, 1981; Posner, 1980; Posner et al., 1978). Following the predictive cue, 16 out of 20 targets (80% of the targets in each section) were validly cued targets that appeared on the same side of the road as the sign. The remaining 4 targets (20% of total targets) appeared on the road opposite the sign and so were invalidly cued.

Pedestrian signs on both sides of the road were a neutral cue. Following the neutral cue, there were 10 targets that appeared on the right side of the road, and 10 appeared on the left side of the road. The pedestrian crossing signs in this condition were analogous to a neutral double-headed arrow (Berger et al., 2005; Laubrock, Engbert, & Kliegl, 2005) or a diamond-shaped cue (Jonides, 1980) in the traditional cue-target paradigm.

After the signs, the participants then heard another auditory message, which asked them to report the location of the pedestrian sign(s), on either the right, the left, or both sides of the road. The first pedestrian appeared approximately 20 s after the sign, and subsequent pedestrians were separated by approximately 120 m. Participants were informed that more pedestrians would appear on the cued side as the sign but were not informed of the actual percentage.

Experimental Design

The study used a within-subjects design with the following factors: secondary task (task, no task), scene clutter (high, low), and pedestrian crossing sign (valid, neutral, and invalid). Secondary task and scene clutter varied between drives, and pedestrian crossing sign varied within drives. Participants performed the secondary task in two experimental drives and confronted scene clutter in two experimental drives (one drive in the task condition and one drive in the no-task condition). High scene clutter was defined by the presence of billboards along the side of the road. There were no billboards in the low-clutter condition. The secondary task included a listening period and a responding period that always followed the listening period. Half of the braking events and half of the pedestrian events occurred when participants listened to the auditory message, and the other half occurred while participants responded to the questions. The order of the pedestrian crossing signs was counterbalanced for each drive and across participants and the experimental conditions according to a Graeco-Latin square design.

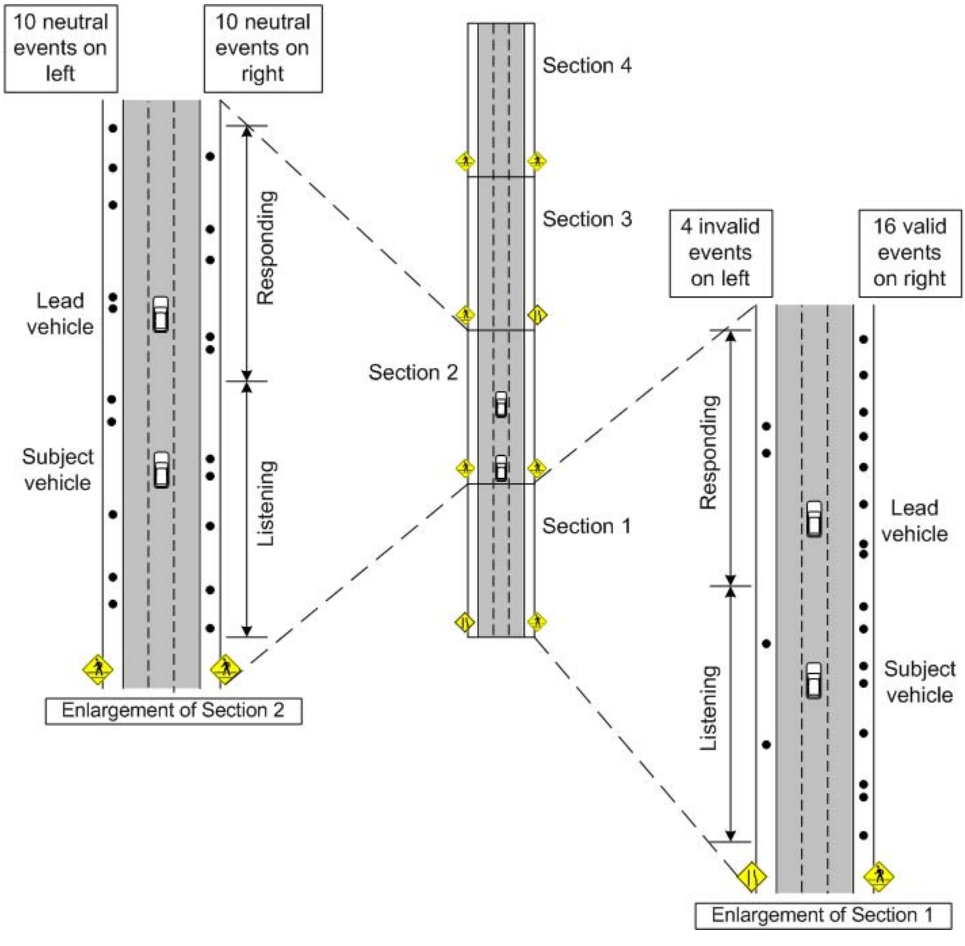

Figure 1. Design and configurations of the four sections within one drive. Black dots indicate target pedestrians.

Dependent Variables

Button responses and eye fixations were recorded to assess the degree to which attention was influenced by secondary task, scene clutter, and pedestrian crossing signs. Consistent with the analysis used for the traditional cue-target paradigm, the dependent variables, accuracy (percentage of correct responses), and RT to button presses were averaged across each drive from responses made within 3 s after participants drove by each pedestrian location. Responses made more than 3 s after passing the pedestrian location were excluded because such a long delay suggests that the response did not relate to the appearance of the pedestrian.

Eye fixations were categorized according to the five equal-area boxes shown in Figure 2. Based on the fixations made during the 3-s response windows after participants drove by each potential pedestrian location, percentages of fixations to each area of interest were calculated to assess how the concurrent performance of an auditory task, the billboards with flashing points, and the pedestrian crossing signs influenced scanning behavior.

RESULTS

The effects of secondary task, scene clutter, and pedestrian signs on target detection performance and eye movements were analyzed as a 2 (secondary task: task, no task) × 2 (scene clutter: high, low) × 3 (pedestrian signs: valid, neutral, invalid) within-subjects ANOVA. The SAS MIXED procedure with a compound symmetry

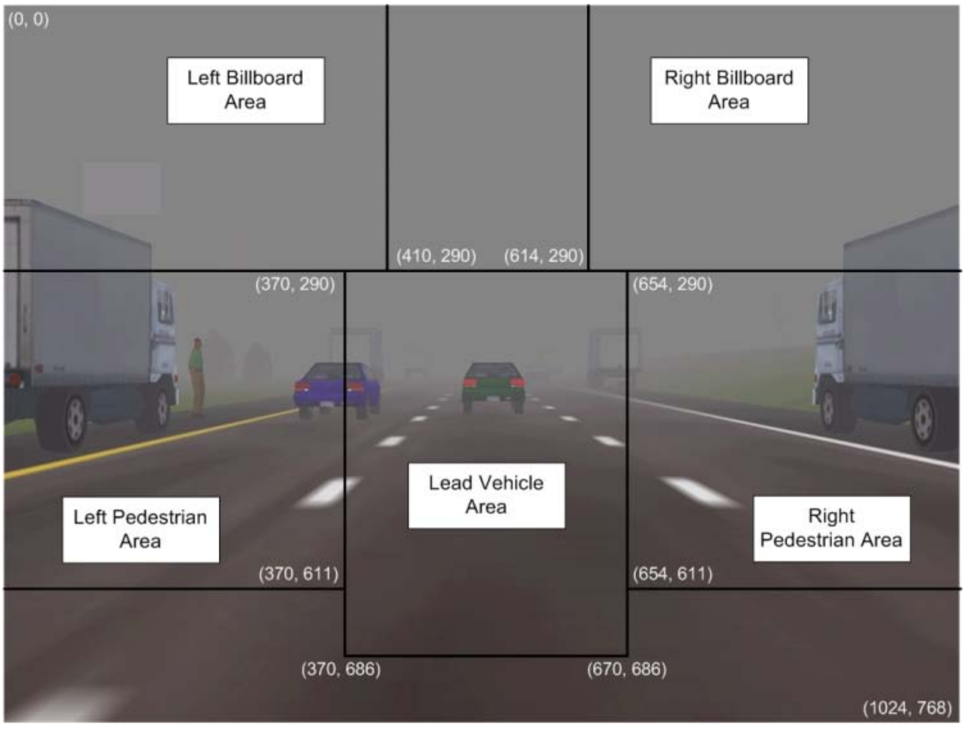

Figure 2. The scene that confronted the drivers, with a pedestrian on the left, the lead vehicle in the center, traffic in adjacent lanes, and occluding trucks on either side: an overlay of the five areas of interest.

covariance structure was used. Cohen's *d* was calculated to show the magnitude of the effects.

Accuracy in Detecting Pedestrians

The validity of pedestrian signs affected how accurately participants responded to pedestrians, $F(2, 30) = 28.47$, $p < .0001$. The accuracy was higher for responding to validly cued pedestrians ($M = .94$) than for invalidly cued pedestrians ($M = .84$), $t(30) = 5.80$, $p < .0001$, $d = 2.20$, and for neutrally cued pedestrians ($M = .86$), $t(30) = 7.08$, $p < .0001$, $d = 0.94$. The accuracy was not different between detecting invalidly cued and neutrally cued pedestrians, $t(30) = 1.28$, $p = .609$, $d = 0.20$. The accuracy in detecting pedestrians did not decrease while participants performed a secondary task, $F(1, 15) = 0.75$, $p = .386$, $d = 0.12$, or in the presence of scene clutter, $F(1, 15) = 0.31$, $p = .578$, $d = 0.08$. There were no significant two-way or three-way interactions.

Reaction Time to Detecting Pedestrians

Performing a secondary task while driving increased participants' RT to detect pedestrians from 1.35 s to 1.48 s, $F(1, 15) = 36.92$, $p < .0001$, $d = 0.59$. The validity of pedestrian signs also affected reaction time, $F(2, 30) = 4.60$, $p = .011$, with the mean RTs for responding to validly cued pedestrians (1.39 s), $t(30) = –2.48$, $p = .042$, $d = 0.27$, and neutrally cued pedestrians (1.39 s), $t(30) = –2.75$, $p = .019$, $d = 0.32$, being shorter than those for responding to invalidly cued pedestrians (1.46 s). The RT for detecting pedestrian was not significantly different between the validly cued and neutrally cued conditions, $t(30) = 0.27$, $p = 1.000$, $d = 0.03$. The presence of scene clutter did not increase RT, $F(1, 15) = 1.94$, $p = .165$, $d = 0.13$. There were no significant two-way or three-way interactions. Accuracy and RT were not correlated across participants, $r(192) = –.08$, $p = .267$, or within participants (*p* value ranged from .11 to .80), and therefore there was no evidence of a speed–accuracy trade-off in any of the experimental conditions.

RTs, averaged across four experimental drives, were examined to determine if the Simon effect (Proctor & Vu, 2006) was observed:

There was a difference among the four possible stimulus–response combinations, $F(3, 45) = 6.61$, $p = .0009$, and this significant effect was attributable to slightly faster responses ($M = 1.26$ s) for the combination of pedestrians wearing red shirts appearing on the left side of the road and participants pressing the right steering wheel button (mean RTs for the three other combinations were 1.45 s, 1.40 s, and 1.45 s). A similar pattern was found in the high-clutter, no-task drive, $F(3, 45) = 3.01$, $p = .04$ (1.22 s vs. 1.47 s, 1.39 s, 1.35 s) but not in the other three drives (ps > .05). These findings suggest that there was no systematic advantage of compatible mapping between location of pedestrians and color of shirts for button-pressing responses.

Percentage of Fixations in the Lead Vehicle Area

Performing a secondary task while driving increased the percentage of fixations in the lead vehicle area from 46% to 50%, $F(1, 15) = 5.07$, $p = .029$, $d = 0.38$. Scene clutter did not significantly decrease the percentage of fixations in the lead vehicle area, $F(1, 15) = 2.60$, $p = .113$, $d = 0.27$. There was no significant interaction between secondary task and scene clutter.

Percentage of Fixations in the Pedestrian Areas

The validity of pedestrian signs affected the percentage of fixations to the pedestrian areas, $F(2, 30) = 10.17$, $p < .0001$. The mean percentage of fixations was lower in locations that were invalidly cued ($M = 17\%$) than those that were validly cued ($M = 22\%$), $t(30) = –4.46$, $p < .0001$, $d = 0.56$) and neutrally cued ($M = 20\%$), $t(30) = –2.82$, $p = .015$, $d = 0.44$. The percentage of fixations was not different for validly cued and neutrally cued locations, $t(30) = 1.63$, $p = .313$, $d = 0.22$. Performing a secondary task significantly decreased the percentage of fixations in pedestrian areas from 21% to 18%, $F(1, 15) = 6.27$, $p = .013$, $d = 0.27$. Scene clutter did not affect the percentage of fixations in pedestrians areas, $F(1, 15) = 1.32$, $p = .252$, $d = 0.12$, and none of the interactions was significant.

The probability of detecting a pedestrian given that participants fixated the pedestrian areas within the 3-s response window was not different within drives (means were .97, .97, and .96 for valid, neutral, and invalid locations, respectively), $F < 1$, or between drives ($M = .96$ in task condition, $M = .97$ in no-task condition, $M = .97$ in low-clutter condition, and $M = .95$ in high-clutter condition), Fs < 1. This finding suggests that detection performance was similar for all conditions if the participant fixated the area of pedestrians.

Duration of Fixations in the Pedestrian Areas

Scene clutter decreased the duration of fixation in the pedestrian areas from 0.21 s to 0.18 s, $F(1, 15) = 11.89$, $p = .0007$, $d = 0.40$. Performing a secondary task also decreased duration of fixations in the pedestrian areas from 0.20 s to 0.18 s, $F(1, 15) = 4.09$, $p = .044$, $d = 0.23$. The validity of pedestrian signs did not affect the duration of fixation, $F(2, 30) = 1.84$, $p = .162$. There was a significant interaction between scene clutter and pedestrian signs, $F(2, 30) = 5.88$, $p = .003$, suggesting that clutter decreased fixation durations for invalidly cued pedestrians but not for validly cued or neutrally cued pedestrians (Figure 3). The interaction between secondary task and scene clutter was also significant, $F(1, 15) = 11.30$, $p = .001$, suggesting that scene clutter decreased fixation durations in the no-secondary-task condition but not when there was a secondary task (Figure 4). No other interaction effects were significant.

Percentage of Fixations in the Billboard Areas

Scene clutter increased the percentage of fixations in the billboard areas from 5% to 7%, $F(1, 15) = 12.33$, $p = .001$, $d = 0.42$. Performing a secondary task did not affect the percentage of fixations in the billboard areas, $F(1, 15) = 0.21$, $p = .647$, $d = 0.06$, nor did the pedestrian signs, $F(2, 30) = 2.76$, $p = .066$. There were no significant interactions.

Secondary Task Performance

Scene clutter did not affect the percentage of correct responses to the auditory messages, $F(1, 15) = 0.45$, $p = .502$, $d = 0.11$, nor did the configurations of pedestrian crossing signs (i.e., two neutral cues or one valid cue), $F(1, 15) = 0.89$, $p = .348$, $d = 0.16$. The interaction was not significant.

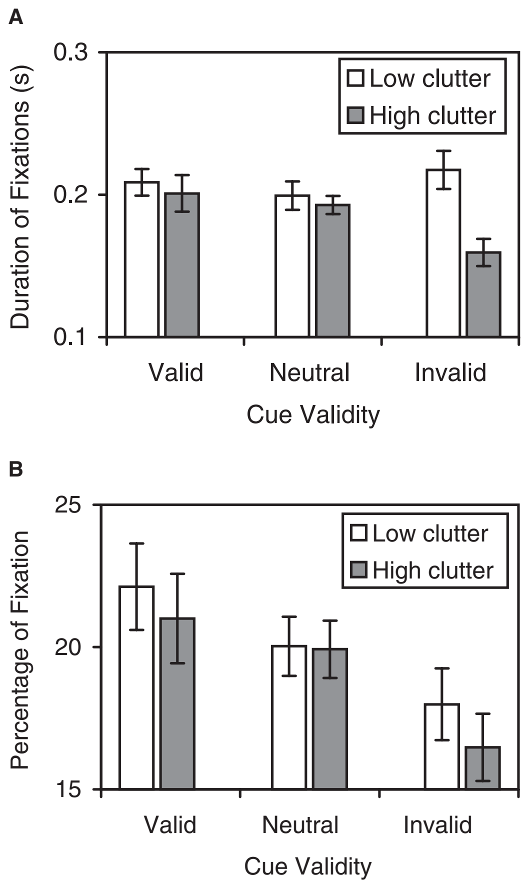

Figure 3. Mean (± SE) fixation duration and percentage of fixation in pedestrian areas as a function of scene clutter and validity of pedestrian signs.

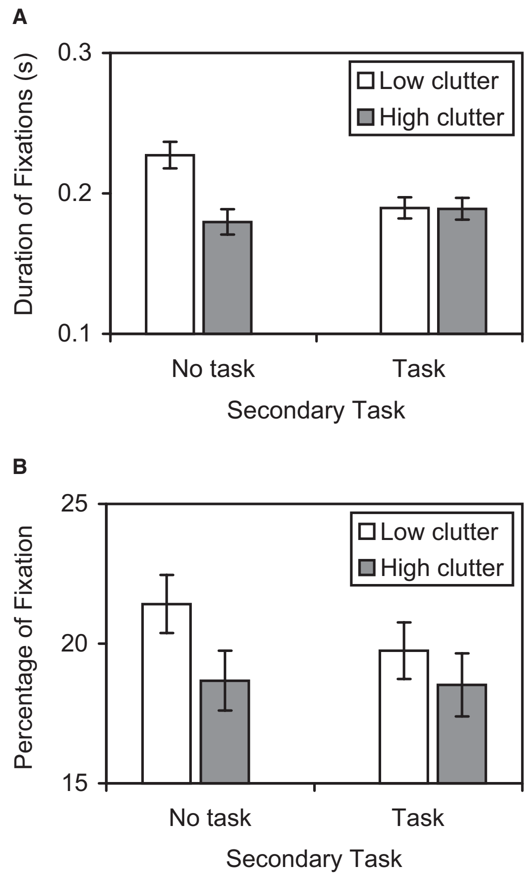

Figure 4. Mean (± SE) fixation duration and percentage of fixation in pedestrian areas as a function of scene clutter and secondary task.

DISCUSSION

This experiment assessed how an auditory-verbal task and irrelevant exogenous-driven stimuli (scene clutter represented as flashing billboards) affected the use of endogenous cues (pedestrian crossing signs) to detect pedestrians. We hypothesized that cognitive load and irrelevant exogenous cues would undermine endogenous control of attention, and the results show that cognitive load delayed drivers' responses and irrelevant exogenous cues decreased the duration of pedestrian fixations. The accuracy of pedestrian detection was higher for validly cued pedestrians than for invalidly cued and neutrally cued pedestrians. In contrast with our hypothesis, cognitively loaded drivers were less, not more, susceptible to irrelevant exogenous cues.

Results show that drivers had more fixations, higher accuracy, and shorter RTs when responding to validly cued pedestrians than to invalidly cued pedestrians. This finding suggests that the manipulations of pedestrian crossing signs as the endogenous cues were effective in altering drivers' search behavior in a manner consistent with the Posner paradigm. When drivers did fixate on invalidly cued locations, the duration of fixations did not differ from those of validly cued locations. Contrary to findings of Strayer et al. (2003), there was no evidence that information consolidation was affected by pedestrian crossing signs, secondary task, or scene clutter. In this study, drivers consistently detected targets that they fixated across all conditions. In addition, there was no evidence of the typical Simon effect, provided that participants responded to the shirt color of target pedestrians instead of the pedestrian locations. This suggests that the use of buttons for the target detection responses in our context was appropriate.

Results show delayed responses to pedestrians when drivers were engaged in the secondary task, and this is consistent with others' findings (Alm & Nilsson, 1994, 1995; Horrey & Wickens, 2006; Lee, Caven, Haake, & Brown, 2001). Performing the secondary task also reduced fixations to pedestrian areas, regardless of the validity of pedestrian signs. We did not find evidence of reduced benefits of valid cues and increased costs of invalid cues in the presence of the secondary task as reported in Jonides (1981). However, the current finding parallels results of Lee, Lee, and Boyle (2007), which involved the use of a dynamic change blindness paradigm to show that cognitive load uniformly diminished participants' sensitivity in detecting vehicle changes, independent of their safety relevance.

A higher percentage of fixations was observed in the area of the billboards (the irrelevant exogenous cues), indicating that scene clutter attracted attention. Although drivers did not fixate on potential target locations significantly less with the scene clutter present, scene clutter did decrease duration of fixations in pedestrian areas when the pedestrians were invalidly cued. Such short glances to pedestrians in the presence of irrelevant exogenous cues suggest that the influence of exogenous cues is stronger when the endogenous control is less beneficial (Muller & Rabbitt, 1989).

Cognitively loaded drivers appeared to be less susceptible to irrelevant exogenous cues, which is consistent with Lavie's load theory of attention (Lavie, 1995; Lavie et al., 2004; Lavie & Tsal, 1994; Rees et al., 1997). In our study, when drivers engaged in a secondary task while also performing the visual search task, the elevated task load diminished the interference effect of irrelevant scene clutter. Lavie's account seems to explain the continuous orienting of attention in dynamic driving situations such that selective attention is dependent on the moment-to-moment loads from operating the vehicle, interacting with in-vehicle devices or passengers, and roadway environments. The nature of our auditory messages was cognitively and perhaps perceptually demanding (listening to eight combinations of characteristics for each restaurant and linking numerical information to categorical information). A follow-up study is being conducted to further examine the relationship between type of information load from an in-vehicle secondary task and drivers' resistance to irrelevant distractors.

In summary, our study extended the lead vehicle following task with Posner's cue-target paradigm to precisely examine how exogenous and endogenous cues influence drivers' attention. The results indicate that irrelevant exogenous-driven stimuli and the level of cognitive load combined to influence the endogenous and exogenous orienting of attention in driving. Although irrelevant visual stimuli on the road and auditory messages are both distracting in nature, they have differential effects on drivers—interacting with in-vehicle devices can delay drivers' responses to roadway events, and the presence of visually attractive objects and cognitive load both shorten drivers' fixations to driving-related objects. When irrelevant visual stimuli and auditory messages are present, elevated cognitive load can suppress the distraction from objects outside the vehicle that are irrelevant to current driving.

In conclusion, the modified Posner's paradigm provides the foundation for connecting theoretical construct to an applied, practical task, and Lavie's account takes into consideration the interactive, less predictable nature of sustained operations in which control of attention is influenced by processing load and presence of to-be-ignored distractors.

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REFERENCES

Alm, H., & Nilsson, L. (1994). Changes in driver behavior as a function of handsfree mobile phones: A simulator study. *Accident Analysis & Prevention*, *26*, 441–451.

Alm, H., & Nilsson, L. (1995). The effects of a mobile telephone task on driver behavior in a car following situation. *Accident Analysis & Prevention*, *27*, 707–715.

Berger, A., Henik, A., & Rafal, R. (2005). Competition between endogenous and exogenous orienting of visual attention. *Journal of Experimental Psychology–General*, *134*, 207–221.

Glassbrenner, D. (2005). *Driver cell phone use in 2005: Overall results*. Retrieved April 20, 2006, from http://www-nrd.nhtsa.dot.gov/Pubs/809967.PDF

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

Ishihara, S. (1966). *Ishihara's tests for colour-blindness*. Tokyo, Isshinkai Foundation.

Jonides, J. (1980). Towards a model of the mind's eye's movement. *Canadian Journal of Psychology–Revue Canadienne De Psychologie*, *34*, 103–112.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and performance IX* (pp. 187–203). Hillsdale, NJ: Lawrence Erlbaum.

Klauer, S. G., Dingus, T. A., Neale, V. L., Sudweeks, J. D., & Ramsey, D. J. (2006). The impact of driver inattention on near-crash/crash risk: An analysis using the 100-Car Naturalistic Driving Study data [Electronic version]. Retrieved January 7, 2007, from http://www-nrd.nhtsa.dot.gov/departments/nrd-13/810594/images/810594.pdf

Laubrock, J., Engbert, R., & Kliegl, R. (2005). Microsaccade dynamics during covert attention. *Vision Research*, *45*, 721–730.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology–Human Perception and Performance*, *21*, 451–468.

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology–General*, *133*, 339–354.

Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics*, *56*, 183–197.

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, Y.-C., Lee, J. D., & Boyle, L. N. (2007). Visual attention in driving: The effect of cognitive load and visual disruption. *Human Factors*, *49*, 721–733.

Luck, S. J., & Vecera, S. P. (2002). Attention. In H. Pashler & S. V. E. Yantis (Eds.), *Stevens' handbook of experimental psychology : Vol. 1. Sensation and perception* (3rd ed., pp. 235–286). New York: Wiley.

McEvoy, S. P., Stevenson, M. R., & Woodward, M. (2006). The impact of driver distraction on road safety: Results from a representative survey in two Australian states. *Injury Prevention*, *12*, 242–247.

Muller, H. J., & Rabbitt, P. M. A. (1989). Reflexive and voluntary orienting of visual attention: Time course of activation and resistance to interruption. *Journal of Experimental Psychology–Human Perception and Performance*, *15*, 315–330.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*, 3–25.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. Pick & E. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137–158). Hillsdale, NJ: Lawrence Erlbaum.

Proctor, R. W., & Vu, K.-P. L. (2006). *Stimulus-response compatibility principles*. Boca Raton, FL: CRC.

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*, 119–137.

Rees, G., Frith, C. D., & Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science*, *278*(5343), 1616–1619.

Reyes, M. L., & Lee, J. D. (2004). The influence of IVIS distractions on tactical and control levels of driving performance. In *Proceedings of Human Factors and Ergonomics Society 48th Annual Meeting* (pp. 2369–2373). Santa Monica, CA: Human Factors and Ergonomics Society.

Spence, C. J., & Driver, J. (1994). Covert spatial orienting in audition: Exogenous and endogenous mechanisms. *Journal of Experimental Psychology–Human Perception and Performance*, *20*, 555–574.

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*, 23–32.

Strayer, D. L., & Johnston, W. A. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological Science*, *12*, 462–466.

Theeuwes, J. (1991a). Exogenous and endogenous control of attention: The effect of visual onsets and offsets. *Perception and Psychophysics*, *49*, 83–90.

Theeuwes, J. (1991b). Visual selection: Exogenous and endogenous control. In A. G. Gale, I. D. Brown, C. M. Haslegrave, H. W. Kruysse, & S. P. Taylor (Eds.), *Vision in vehicles: III* (pp. 53–61). Amsterdam, Netherlands: Elsevier Science.

Theeuwes, J. (1994). Endogenous and exogenous control of visual selection. *Perception*, *23*, 429–440.

Yi-Ching Lee is an assistant professor of human factors within the Institute of Aviation at the University of Illinois at Urbana-Champaign, where she holds appointments in the Beckman Institute for Advanced Science and Technology and the Department of Industrial and Enterprise Systems Engineering. She received her PhD in industrial engineering in 2006 from the University of Iowa.

John D. Lee is a professor of industrial engineering and director of the Cognitive Systems Laboratory at the University of Iowa. He received his PhD in mechanical engineering in 1992 from the University of Illinois at Urbana-Champaign.

Linda Ng Boyle is an associate professor at the University of Iowa with joint appointments in the Department of Mechanical and Industrial Engineering and Public Policy Center. She received her PhD in civil and environmental engineering in 1998 from the University of Washington.

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