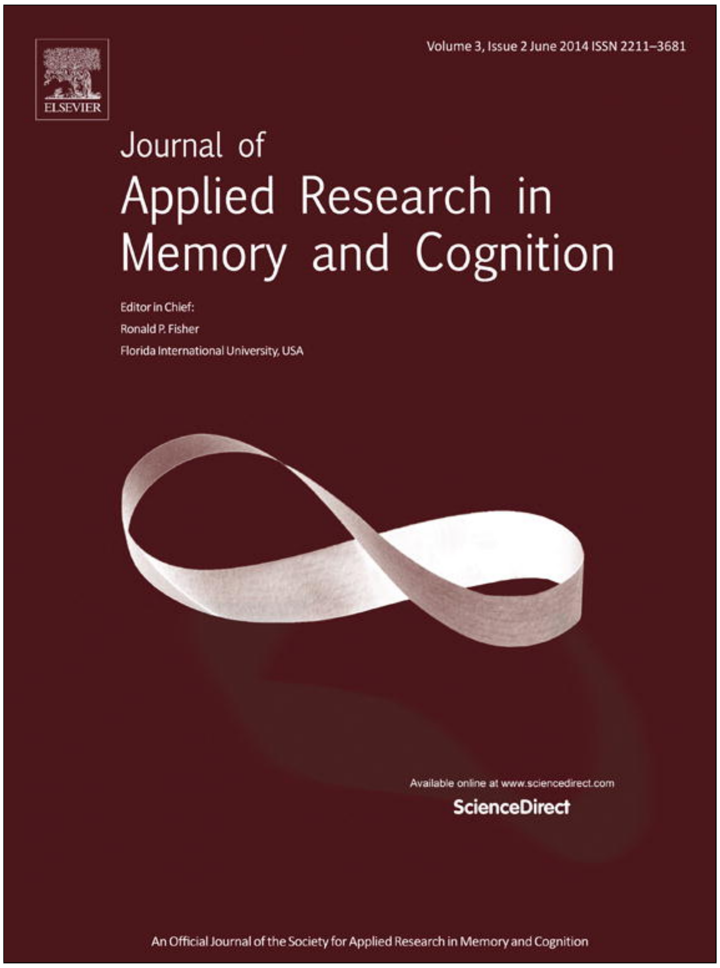
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Cognitive load while driving impairs memory of moving but not stationary elements within the environment☆

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ABSTRACT

The negative impact of cognitive load, such as cell phone conversations, while driving is well established, but understanding the nature of this performance deficit is still being developed. To test the impact of load on awareness of different elements in a driving scene, memory for items within the environment was examined under load and no load conditions. Participants drove through two different scenarios in a driving simulator, were periodically interrupted by a pause in the driving during, and were asked questions regarding moving and stationary objects in the environment. Participants in the load condition drove while concurrently counting backwards by sevens. Results indicate that driving under load conditions led to diminished knowledge of moving, but not stationary, objects in the scene. This result suggests not all types of knowledge are equally impaired. Potential implications for current theories of cell phone use while driving and applied attention theory are discussed.

Driving is a complex task that requires individuals to monitor and update multiple pieces of information (e.g., speed, direction, road signs, other vehicles), often placing heavy demands on attention and memory mechanisms (see Groeger, 2000; Moray, 1990; Senders, Kristofferson, Levison, Dietrich, & Ward, 1967). Successfully keeping track of this information is necessary to get where you are going, avoid accidents, or other undesirable events such as getting a speeding ticket. However, with improvements in technology that are centered on providing information to the driver (e.g., GPS navigational systems) and the multitude of other technology-based distractions (e.g., cell phones), drivers are increasingly operating under conditions that place a greater demand on successfully allocating attentional resources. Research shows these distractions, particularly conversing on a cell phone, can substantially impair driving (Strayer, Drews, & Johnston 2003; Strayer & Johnston, 2001).

However, this impairment may not be global; that is, when driving with distractions, knowledge of some driving elements may remain intact while others suffer. The current study further examines one possibility by assessing how distracted driving impacts knowledge of both moving and stationary elements in the driving environment using a memory recall task. Measuring knowledge of stationary and moving elements offers insights into how drivers are allocating attention; knowledge of stationary elements indicates attention toward rule following/updating while knowledge of dynamic elements indicates attention toward hazard avoidance.

1. Load and driving

Previous research suggests that conversing on a cell phone while driving (i.e., driving under cognitive load) can significantly impair driving ability above and beyond other distractions such as listening to the radio or conversing with passengers (e.g., Caird, Willness, Steel, & Scialfa, 2008; Drews, Pasupathi, & Strayer, 2008; Horrey & Wickens, 2006; Rakauskas, Gugerty, & Ward, 2004; Redelmeier & Tibshirani, 1997; Strayer & Drews, 2007; Strayer & Johnston, 2001; Strayer et al., 2003). However, as Drews et al. (2008) pointed out, much of the prior work on the impact of cell phone use while driving has focused on assessing the level of impairment, and has glossed over the cognitive mechanisms underlying the impairment. Recent research, however, has begun to examine these mechanisms.

☆ Portions of these data were previously published in the 2009 Proceedings of the Human Factors and Ergonomics Society 53rd Annual Meeting (Blalock, Sawyer, Kiken, & Clegg, 2009).

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Strayer and Drews (2007) (see also Strayer et al., 2003) argue that cell-phone use while driving can lead to inattentional blindness (the failure to notice prominent objects in the environment; Wickens & McCarley, 2008). More specifically, they argue that the cell phone conversation diverts attention from driving, causing drivers to sometimes miss critical events in the driving environment (e.g., a car in a driver's blindspot; Strayer & Drews, 2007; Strayer et al., 2003; Strayer & Johnston, 2001). Strayer et al. (2003) showed that participants who drove while talking on a hands-free cell phone were also unable to recognize billboards present in the drive in a surprise recognition test – even though a separate eye tracking experiment showed participants fixated on the signs. This evidence provides support for an inattentional blindness hypothesis: even when drivers look at elements in the driving environment, they may not process them.

This inattention also holds true for high priority (e.g., child playing near a road) elements in the driving environment, suggesting that drivers are not strategically diverting attention away from low priority elements (e.g., billboards) to high priority elements when driving under cognitive load conditions (Strayer & Drews, 2007; though see Gugerty, 1997, 1998; for a different view). In fact, Strayer and Drews (2007) report no association between recognition memory of driving elements, and the priority of those elements in terms of safety relevance, suggesting an overall reduction of attention for all driving elements when drivers are under a cognitive load. The interference between a primarily visual task (driving) and a primarily verbal task (cell phone conversation) also suggests the impairment may be due to limited general resource or a central attentional bottleneck (Strayer & Drews, 2007; see also Morey & Cowan, 2005).

Similarly, in examining change blindness in driving McCarley et al. (2004) measured change detection performance and eye movements while participants viewed snapshots of real-world driving scenes. Change detection was impaired when participants held an ongoing, naturalistic cell phone conversation even though they were not actively driving. Importantly the cell phone use condition also resulted in less efficient visual search; in other words, more saccades were required to detect changes, and participants exhibited a slower fixation time. McCarley et al. thus argued that changes in visual scanning as a result of load suggested reduced visual encoding of objects in driving scenes, which could be related to inattentional blindness. There is therefore some evidence to suggest that load during driving could result in both change blindness and inattention blindness (although we caution that both do not have to jointly apply).

Converging evidence is found in examining the literature on driver situation awareness. Situation awareness refers to operators' ability to perceive, understand, and predict events in the environment (Durso & Gronlund, 1999; Endsley, 1988, 1995a, 1995b, 2000). The dynamic nature of driving makes it a good domain for applying the construct of situation awareness. Relevant to the discussion of how load impacts drivers, Kass, Cole, and Stanny (2007) examined how cognitive load impacts situation awareness by comparing experienced and novice drivers who drove under non-distracted (driving normally) or distracted (simulated hands-free cell phone conversation) conditions. Regardless of experience level, drivers conversing on the phone suffered significant situation awareness deficits (measured as subjective recall such as "how many cars backed out in front of you?"), providing evidence that cognitive load plays a role in the attention-related components of driving.

Taken together, the above research suggests the driving impairments found while talking on a cell phone can be attributed to reduced attention resources (e.g., Strayer et al., 2003), inefficient visual search patterns (McCarley et al., 2004), and poor situation awareness (Kass et al., 2007). However, in all of this research, the impairment was examined at a global level; that is research has not yet compared whether drivers allocate attention differently to different types of elements in the driving scene. The current experiment examines this question.

2. Current experiment

The key issue for the current study was to examine knowledge of elements that differed in a key characteristic (moving or stationary locations) in the driving environment, and how this knowledge may be altered under conditions of cognitive load. Although driving naturally induces changes in the egocentric location of elements (i.e., relative to the driver's viewpoint, such as buildings or signs moving past the driver), some elements also change in allocentric location (i.e., relative to a fixed point in space, such as other moving cars). There is evidence that memories for egocentric and allocentric information are derived independently but in parallel (for a review, see Burgess, 2006). Once motion begins, almost all elements within the driving scene would require constant updating relative to an egocentric frame of reference. This updating process could promote reliance on an allocentric spatial representation to lower the cognitive costs of updating, which would require working memory resources (Hegarty, Montello, Richardson, Ishikawa, & Lovelace, 2006; Miyake, Friedman, Rettinger, Shah & Hegarty, 2001; Shah & Miyake, 1996).

However, variations in the allocentric location also exist for objects within the driving environment. We define *moving elements* as those changing in allocentric location, and *stationary elements* as those with fixed allocentric locations. Crucially these two distinctions in allocentric location characteristics are highly related to different primary tasks in driving. Driver navigation and rule following/updating depend primarily on information from within the environment that is fixed in allocentric coordinates (for example, road signs and lane indicators). In contrast, hazard avoidance depends on monitoring and predicting elements in the environment with changing allocentric coordinates (such a nearby vehicles; e.g., Gugerty, 1997, 1998, 2004).

Establishing which types of knowledge are affected by cognitive load during driving provides additional explanatory power in understanding the role of distraction. Contrasting predictions, though not necessarily mutually exclusive, can be made for how these different types of information might be impacted. On the one hand, static elements within a driving scene tend to be by their very nature in the periphery when drivers are looking forward, since stationary items within the roadway itself would tend to impede traffic. Thus, reduced attentional capacity may differentially impact these items given that cognitive load is known to reduce scanning of the periphery (e.g., Recarte & Nunes, 2003), and should lead to worse memory for the static items within a driving scene. On the other hand, changes in allocentric location might make maintaining effective representation of those items harder, especially given reduced activity in the parietal lobe areas responsible for spatial processing occurs when a secondary verbal task is added to driving (Just, Keller, & Cynkar, 2008). This reduction in spatial processing would suggest that a differential impact might occur for the higher bandwidth spatial elements (such as other road users' locations) compared to lower bandwidth items. This would lead to lower memory for dynamic items within a driving scene. The current study sought to investigate how driver distraction impacts memory for different, yet critical, types of information (moving versus stationary elements) present in a typical driving environment.

3. Method

3.1. Participants and design

Thirty-three Colorado State University undergraduate students (mean age = 19; 20 males, 13 females) with valid driving licenses participated for partial course credit in an introductory psychology course. Participants were randomly assigned to either the load ($n = 16$) or no load conditions ($n = 17$); five participants did not complete the experiment due to motion sickness or technical difficulties, leaving a total of 28 participants (16 in no load, 12 in load).

The experiment was a 2 (load, no load) × 2 (question; moving or stationary object) mixed design with load between subjects, and type of question manipulated within. Load was induced using a count out loud task. Counting and repeating numbers aloud has been used extensively in the basic working memory literature to induce a load on the central executive component of working memory (for example, see Baddeley, 2000; Morey & Cowan, 2005). Thus, in the load condition, participants were asked to count aloud backwards by sevens from a random number presented on screen every 30 s; no counting was required in the no load condition and no number was presented.

During pauses in driving, questions were posed to participants about two types of information: moving and stationary elements in the environment (refer to Appendix A to see all questions asked from each question category). In the moving element condition, questions regarded aspects of the driving environment that could move in allocentric location within the driving environment, such as location of surrounding cars (e.g., "Is there a car behind you?") or movements of other cars (e.g., "What vehicles have passed you since your last turn?"). In the stationary condition, questions referred to aspects of the environment with fixed allocentric coordinates (such as the most recent posted speed limit), and landmarks passed during the drive (e.g., "What was the first building you passed on the right?").

To ensure that the elements queried in the driving task were relevant to the driving task, a separate group of 16 participants rated still images of driving scenes from the simulator environment that featured 23 objects designated as 'stationary' and 'moving' in the main experiment. Items were rated in terms of how important those elements were to attend to while driving (1 – very important; to 5 – not important). The average overall rating was 2.00 ($SD = .58$), indicating that the critical items in the main experiment were considered important even within a still image of the road scene. A paired samples t-test also showed that moving items ($M = 1.76$, $SD = .53$) were rated as being significantly more important than stationary items ($M = 2.24$, $SD = .54$; $t(15) = 2.19$, $p < .05$). These pilot results demonstrated that the elements were subjectively important to the driving task, and that drivers rated objects that move allocentrically as more important than static objects – even when this task was presented via still image 'snapshots'.

3.2. Apparatus

A fixed platform driving simulator (DS-600c) was used in this experiment, providing a 180° simulated field of view from the front half of a Ford Focus. The simulator also included side and rear view mirrors, force-feedback steering, and an immersive audio environment.

Two environments simulating approximately 20 min of driving in sunny conditions with dry pavement and intermittent oncoming traffic were generated. At intersections, directions indicating which way to turn appeared in green letters in the frontal field of view, overlaying but not obstructing the driving environment. No randomly generated traffic or random events of any nature were utilized.

3.3. Procedure

Participants completed two driving sessions. The first session (acclimation) lasted approximately 15 min and occurred on the day immediately prior to the experimental drive. The acclimation session familiarized participants with the driving simulator, and was also used to screen participants for motion sickness which was self-reported by the participant. To this end, participants drove two short routes; the first was a straight drive, and the second also included both left and right turns.

During the second, experimental session, participants drove two separate counterbalanced routes. Participants were instructed to follow onscreen directions at intersections indicating whether a turn was necessary and/or which direction to turn. The instructions and the route for each map were identical across conditions. In the load condition a three-digit number (with a visual angle of 1.3° × 3.3° within the 180° scene) was also presented for 5 s in green font, and overlaid on the center of the driving scene approximately every 30 s. Instructions were given to count aloud backward by sevens until a new three-digit number was presented, and then to start the process again with the new number. An experimenter was present during the drive to enforce the counting as well as to ensure that participants complied with instructions. Participants were simply reminded to continue counting backward by sevens if they stopped counting. While accuracy on the counting task was not recorded, all participants did comply with the instructions by repeating three digit numbers aloud consistently during the drive. Thus, while some participants may have not done the math correctly, they were still under a verbal load.

In both load conditions, a total of three pauses were interjected within each route. Participants were advised of the pauses and questions before beginning the drive and told to answer the questions to the best of their ability. The final pause in each route occurred at the end of the drive.

During the pause, the experimenter orally queried participants about the current driving situation (see Fig. 1). During these pauses, the simulation environment was obscured with solid blue for 2 min. The experimenter asked three questions per pause (for a total of nine questions per route) about the current driving environment with the question types (moving versus stationary) in a fixed random order, and an equal number of questions for each type. The participants typically responded with one to two word answers, and the experimenter recorded those answers while the participant remained in the simulator. For example, the experimenter would ask, "What was the most recent sign you passed?" and the participant responding may answer "Deer crossing" (see Appendix A for a list of all questions asked).

4. Results

All analyses were significant at an alpha level of .05 unless otherwise noted. Questions from the recall questionnaire were divided into moving and stationary questions, scored for accuracy, and then averaged across both maps.

Mean recall accuracy was analyzed in a 2 (load condition: load vs. no load) × 2 (question type: moving vs. stationary) mixed analysis of variance (ANOVA). A significant main effect of load was found [$F(1, 26) = 9.42$, $MSE = .02$, $\eta^2 = .27$], with the no load condition [$M = .67$, $SD = .10$] being significantly more accurate than the load condition [$M = .55$, $SD = .10$]. The main effect of question type also reached significance [$F(1, 26) = 14.22$, $MSE = .01$, $\eta^2 = .35$], with the stationary questions [$M = .67$, $SD = .13$] being significantly more accurate than the moving questions [$M = .57$, $SD = .16$]. These main effects should be interpreted in light of a significant Load x Question Type interaction [$F(1, 26) = 9.05$, $MSE = .01$, $\eta^2 = .26$]; see Fig. 2.

To further examine the Load × Question Type interaction, independent samples t-tests were conducted between load and no load conditions for each of the two question type conditions. There was a significant difference between load and no load conditions

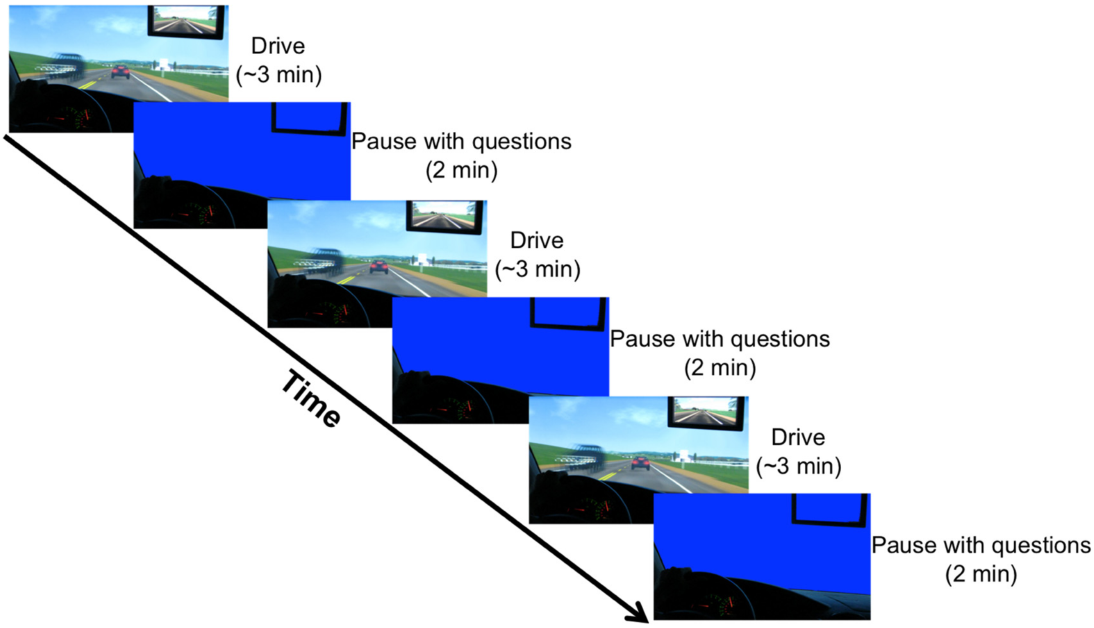

Fig. 1. Procedure used for each drive. During the drive portions, participants either counted backwards by 7 s or drove normally. During the pauses, three questions were asked about the current driving situation.

for questions regarding movement elements [$t(26) = 4.55$, $d = 1.81$], showing accuracy for moving elements was worse in the load condition. However stationary elements did not differ in accuracy between groups [$t(26) = .46$, $p > .05$, $d = .13$]. To ensure that these effects are not due simply to greater difficulty of the moving element questions, a paired-samples *t*-test was conducted in the no load condition between question types. The comparison was not significant [$t(15) = -.64$, $p > .05$, $d = -.33$], suggesting moving object questions were not inherently more difficult than the stationary questions.

5. General discussion

The present results demonstrate degraded memory for allocentrically moving elements, but not allocentrically stationary elements while driving under cognitive load. Under no cognitive load, these types of knowledge were equally remembered. These data support prior research demonstrating impairments in driving awareness under load conditions (e.g., Kass et al., 2007; Strayer et al., 2003). The data are also consistent with the hypothesis that cognitive load could lead to a form of inattentional blindness while driving, since drivers likely viewed some of the moving elements but later did not remember them. The current study also goes beyond a simple effect of a cognitive load during driving; that is, a verbal count-out-loud task selectively impaired recall of allocentrically moving, but not allocentrically stationary elements in the driving environment.

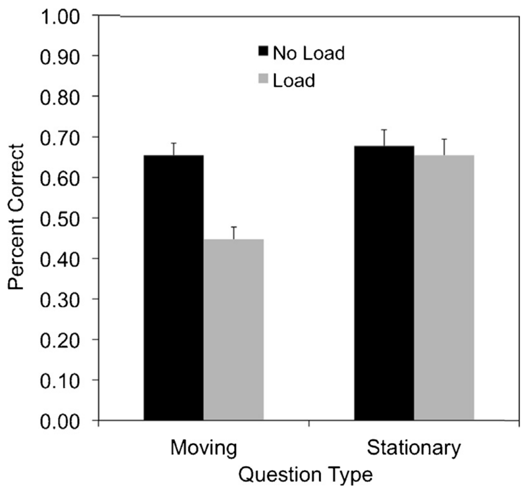

Fig. 2. Percent correct on the recall questionnaire as a function of question type and load condition. Error bars represent standard error of the mean.

There are several possible explanations for why this distinction exists, as moving and stationary elements vary on several key dimensions. For example, moving elements require more bandwidth (rate of updating) since they must be sampled more frequently in order to maintain the current status (Wickens & McCarley, 2008). Stationary elements, on the other hand, require fewer fixations in order to get the current status (e.g., speed limits). Moving objects may also be more salient than stationary objects given that they tend to occur within the forward view region whereas stationary objects tend to be in the periphery. Expectancy may also play a role, with moving elements being more likely to behave in an unpredictable way, thereby requiring more attention to track (Steelman, McCarley, & Wickens, 2011). Future work should examine these possibilities. Overall, the current results are consistent with the notion that the moving elements require more attention to maintain and are thus more affected by a cognitive load than the stationary elements.

5.1. Theoretical implications

Strayer and Drews (2007) suggest that one possible theoretical explanation for the impairment in driving while conversing on a cell phone could be due to a central attentional bottleneck (or limited general attentional resources; e.g., Wickens, 2002) in which performing two complex tasks can lead to performance decrements in one or both of the tasks, despite the tasks being in different modalities. These data are compatible with this view; when participants were given a demanding attentional load their knowledge of moving objects in the environment was reduced. However, these data offer an important caveat to the idea, implying that not all information suffers equivalent impairment.

One aspect of the current data that is not congruent with prior work by Strayer and colleagues is the lack of impairment for stationary elements (e.g., road signs). Strayer et al. (2003) showed lower recognition memory performance for billboards shown while driving under load, and this has been replicated in other work (Strayer & Drews, 2007). This discrepancy could be due to a methodological difference between Strayer et al. and the current study, specifically the method in which knowledge or memory was measured. Strayer et al. used an incidental-learning paradigm in which participants were given a surprise recognition test. The current study, on the other hand, used a recall task and participants were aware that their memory was going to be tested. Differences in memory accuracy between recall and recognition is a common finding in memory research (see Roediger, 2008 for a review), and therefore differences in instructions may have led participants in this study to pay more attention to stationary elements. However the interaction between element type and load condition indicate the difference is still reliable.

These data also have potential implications for current theories of situation awareness, and particularly offer some discriminant validity between measuring basic memory phenomena versus measuring situation awareness. While memory is certainly a key aspect of maintaining situation awareness, theories of situation awareness typically focus on the evolving representation of dynamic elements within a situation (e.g., Endsley, 1995a, 2000). The current experiment emphasizes the link between dynamic knowledge and situation awareness by showing evidence for selective impairment of the moving elements within a dynamic driving environment coupled with preserved memory for stationary objects under cognitive load. Thus, within a dynamic environment situation awareness may be linked with specific types of dynamic elements in that environment. We note that the moving versus stationary distinction identifies only two types of knowledge. It remains a question for future research whether unique decrements in performance are present for these items, or whether other types of situation awareness relevant information are similarly impacted.

5.2. Practical application

Driving while distracted significantly impairs driving performance and increases the risk for accidents (Redelmeier & Tibshirani, 1997; Strayer et al., 2003; Strayer & Johnston, 2001). Our research adds to the now large body of research demonstrating that impairment but our data also provide additional insights as to how distractions while driving impact cognition. Specifically, one important practical implication of these findings relates to drivers' own awareness of decrements occurring from cell phone use. The current experiment suggests that drivers could be misled when attempting to monitor their awareness of the driving scene. Unchanging portions of their environment might seem to offer an external, reliable standard for drivers to index their internal sense of awareness against at any time (see O'Regan, 1992), and hence infer whether their cell phone usage is impairing their driving. For example, drivers might know their vehicle should have recently passed an exit to a highway, and use the availability of that knowledge as a basis for concluding they are effectively monitoring their driving environment even while conversing on a cell phone.

In contrast, moving elements, also critical for situation awareness and clearly linked to hazard avoidance, are by their very nature temporary states of the environment. Their fleeting existence means that drivers have fewer opportunities to attend to them; thus when under a demanding cognitive load drivers simply miss more information as related to rates of updating and monitoring (see Moray, 1986). However, drivers may still prioritize attention to certain elements and ignore others (e.g., Gugerty, 1997). Therefore, unlike the case of realizing that a to-be-taken highway exit must have passed by (stationary information), drivers who are unaware that a vehicle which was behind them is now in their blind spot (movement information) could have no basis to recognize that such an error even occurred – in essence, change blindness. Further research in this area can help to distinguish between different types of information that may also be differentially affected by load in addition to validating the current results in follow up experiments.

Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A.

All recall questionnaire questions (with answers in parentheses) for each question type

Moving questions	Stationary questions
What vehicles are you currently passing and how many are there? (2 school busses)	What was the most recent road sign you passed? (Deer crossing)
Which direction did the dump truck turn? (Left)	On which side of the road was the gas station? (Left)
How many motorcycles have you passed so far? (Two)	What is the current posted speed limit? (35)
Were there any cars behind you when you were following the tractor? (No)	On which side of the road did you see emergency vehicles? (Left)
Is there a car behind you? (Yes)	What directions could you have turned at the last intersection? (Right or left)
Did a truck pass you from the other direction? (No, a car did)	After turning at the intersection, what was the first building you passed on the right? (Fire station)
Did a vehicle pull out behind you in the residential neighborhood? (Yes)	What was the last turn you made? (Right)
What vehicles(s) have passed you since your last turn? (Truck and ambulance)	What color is the car in front of you? (White)

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