The Impact of Eye Movements and Cognitive Workload on Lateral Position Variability in Driving

Joel M. Cooper, **Nathan Medeiros-Ward**, and **David L. Strayer**,
University of Utah, Salt Lake City

Objective: The objective of this work was to understand the relationship between eye movements and cognitive workload in maintaining lane position while driving.

Background: Recent findings in driving research have found that, paradoxically, increases in cognitive workload decrease lateral position variability. If people drive where they look and drivers look more centrally with increased cognitive workload, then one could explain the decreases in lateral position variability as a result of changes in lateral eye movements. In contrast, it is also possible that cognitive workload brings about these patterns regardless of changes in eye movements.

Method: We conducted three experiments involving a fixed-base driving simulator to independently manipulate eye movements and cognitive workload.

Results: Results indicated that eye movements played a modest role in lateral position variability, whereas cognitive workload played a much more substantial role.

Conclusions: Increases in cognitive workload decrease lane position variability independently from eye movements. These findings are discussed in terms of hierarchical control theory.

Applications: These findings could potentially be used to identify periods of high cognitive workload during driving.

Keywords: eye movements, cognitive workload, driving behavior, lane maintenance, hierarchical control theory

Address correspondence to Joel M. Cooper, Department of Psychology, University of Utah, 380 S. 1530 E. BEHS 502, Salt Lake City, UT 84112, USA; e-mail: joel.cpr@gmail.com.

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INTRODUCTION

A driver's ability to maintain a central lane position is widely considered to be a simple and automatic task that demands few mental resources and requires little or no conscious effort (Michon, 1985). Although lane keeping performance can be gauged in several ways, it is often assessed with traditional measures of central tendency, such as the mean and standard deviation, coupled with performance criterion measures, such as lane exceedance counts or time in and out of the lane. These measures are appealing because of their intuitive association with lane departure crashes (Smith, Witt, Bakowski, Leblanc, & Lee, 2009). The implicit expectation is that activities commonly regarded as unsafe or dangerous should lead to greater lateral position variability, whereas activities regarded as safe should have little to no disruption on lateral position variability.

However, recent investigations into the effects of secondary nonvisual tasks have yielded some surprising results. Counterintuitively, lane position maintenance while performing secondary, nonvisual cognitive tasks (e.g., talking) is often reported as being "better" than lane position maintenance during single-task, control conditions in that lateral position variability decreases (Atchley & Chan, 2011; Beede & Kass, 2006; Brookhuis, De Vries, & De Waard, 1991; He & McCarley, 2011; Jamson & Merat, 2005; Knappe, Keinath, Bengler, & Meinecke, 2007; Östlund et al., 2004; Reimer, 2009). Currently, it is not clear why a secondary, nonvisual task would decrease rather than increase lane position variability.

One plausible explanation for these counterintuitive results comes from well-established associations between cognitive workload, gaze concentration, and lateral variability. A number of studies have demonstrated that as cognitive workload increases, drivers tend to fixate more on objects immediately in front of their vehicles

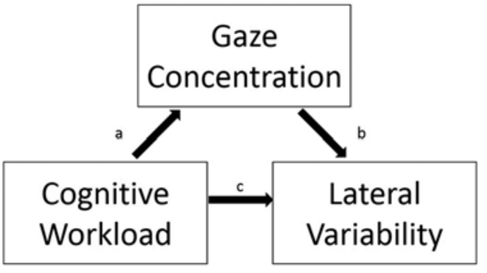

Figure 1. Potential relationships between cognitive workload, gaze concentration, and lateral variability.

and less on dashboard instrumentation and side or rearview mirrors (Recarte & Nunes, 2000; Reimer, 2009; Tsai, Viirre, Strychacz, Chase, & Jung, 2007; Victor, Harbluk, & Engström, 2005). Prior research has also established a tight coupling between where a driver looks and lateral control inputs. The general finding is that drivers tend to steer in the direction of visual gaze and gaze in the direction they intend to steer (Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002; Rogers, Kadar, & Costall, 2005; Wilson, Chattington, & Marple-Horvat, 2008). Taken together, the findings that (a) cognitive workload increases gaze concentration toward the center of the roadway and (b) eye movements are tightly coupled with lateral control inputs suggest a *gaze concentration* hypothesis, whereby decreases in lateral position variability with cognitive workload are mediated by an increase in gaze concentration toward the center of the roadway (Figure 1).

A functional mechanism for the gaze concentration hypothesis could be derived from the two-point visual control model of steering proposed by Land and Horwood (1995). On the basis of their findings, it is suggested that both near (peripheral) and far (focal) visual information is needed to maintain vehicle control and that interruption to either of these sources of visual information has direct effects on the smoothness (far, focal) and the accuracy (near, peripheral) of lane maintenance. Within this context, the fact that one's ability to maintain lateral position is adversely affected by secondary *visual* tasks can be explained by interruptions to focal and peripheral information. And likewise, the fact that one's ability to maintain lateral position is apparently sharpened by secondary *cognitive* tasks might be explained by an increase in visual attention to the elements of the roadway thought to support the smoothness of lane maintenance (e.g., focal visual attention).

In essence, the tendency for drivers engaged in a secondary, nonvisual task to fixate on objects near the center of the roadway may reduce the influence of lateral position variation incurred by glances to peripheral objects. Previously, researchers have not, however, evaluated lateral position variability while experimentally controlling for eye movements and secondary, cognitive task engagement. Thus, it is not clear whether, and to what extent, changes in gaze concentration mediate the relationship between cognitive workload and lateral variability.

Alternatively, it may be the case that a direct relationship between cognitive workload and lateral variability exists such that increases in cognitive workload lead to reductions in lateral variability irrespective of changes in gaze concentration. According to Michon (1985), maintaining lane position is a driving skill that quickly becomes automated, requiring little or no mental resources to perform. In this regard, maintaining a central lane position may be similar to other highly automated skills that are susceptible to direct interruption from conscious attention.

There are a number of theoretical perspectives that may provide a satisfactory account of the direct relationship between cognitive workload and lateral position variability. One recent attempt to explain the disruptive effects of attention toward highly automated tasks comes from the hierarchical control model by Logan and Crump (2009). Similar to previous hierarchical control theories, they argue that skilled performance is subsumed by two separate control loops: an outer loop and an inner loop. The outer loop is resource demanding and effortful and often plays a major role when one is first learning a task. The inner loop is more automatic and does not require much attention or effort. Logan and Crump have shown that these loops are encapsulated so that the outer loop does not know what the inner loop is doing. In fact, when the outer loop is made to monitor the inner loop, performance declines. This finding has now been shown in typing and musical performance, and it has been used to explain why attention can be disruptive in several other areas of research, such as golfing and playing soccer (Beilock, Carr, MacMahon, & Starkes, 2002; Logan & Crump, 2009).

According to hierarchical control theory, it could be the case that in dual-task conditions (e.g., driving while talking on a hands-free cell phone), participants have less residual attention to allocate toward more automatic components of driving, such as lane position control. As a result, lateral position variability decreases compared with single-task driving when participants are free to spontaneously attend to the inner-loop task of lane position control. If this is the case, then one might expect to see these changes in lateral position variability regardless of eye movements (cf. Figure 1). That is, increases in cognitive workload would directly lead to decreases in lateral variability, irrespective of gaze concentration. In the following three experiments, we systematically manipulated eye movements and cognitive workload to better understand their purported influence on lateral position variability.

Figure 2. High-fidelity driving simulator.

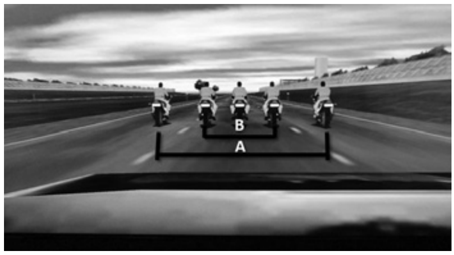

Figure 3. (A) Outer motorcycles are approximately 17° apart. (B) Inner motorcycles are approximately 7° apart. Participants sat approximately 90 cm from the screen.

GENERAL METHOD

Overview

The goal of the current study was to investigate the effects of eye movements and cognitive workload on lateral position variability. This goal was accomplished in a series of three experiments in which we manipulated different aspects of eye movements and cognitive workload. By manipulating both eye fixations and the level of cognitive workload, we could assess the independent contributions of eye movements and cognitive workload on lateral position variability.

Procedure

In each of the three experiments, a PatrolSim fixed-base driving simulator, manufactured by GE I-Sim (www.i-sim.com), was used (Figure 2). The simulator recreated a realistic driving environment. The dashboard instrumentation, steering wheel, and gas and brake pedals were taken from a typical sedan with an automatic transmission. Three 5-min driving scenarios were used. Each scenario consisted of a straight, three-lane, divided highway. In Experiment 1, the scenarios contained three motorcycles that proceeded 22 m ahead of the participant vehicle, side by side in the middle lane, at a constant speed of 65 mph. In Experiments 2 and 3, the scenarios contained five motorcycles that proceeded 22 m ahead of the participant vehicle, side by side in the middle and outer lanes, at a constant speed of 65 mph. Each of the motorcycles had a white license plate illuminated by two adjacent red lights. Only one license place was illuminated at a time, and participants were instructed to always look at the illuminated license plate as they drove (Figure 3).

In each experiment, an ASL5000 head-mounted eye-tracker was used to verify fixation accuracy. Participants were trained with the eye tracker to ensure that eye movements were similar across all experimental conditions. The accuracy of these eye movements was monitored during experimentation, and any deviations from the instructions led to a verbal reminder by the experimenter. However, participants were typically very accurate at following task instructions and, once instructed, rarely needed reminding.

The pattern in which the lights were illuminated was systematically manipulated across the three experiments, and the specific details of each manipulation are explained at the beginning of each experiment. No other traffic was present in any of the experiments, and vehicle speed control was automatically configured at 65 mph so that participants had to only steer the vehicle (e.g., similar to having cruise control activated). In all three experiments, eye movements and cognitive workload were manipulated, and the details of each manipulation are described in each experiment's Method section.

Data Measurement

We calculated three dependent measures related to lateral position variability for each driving segment in each experiment. These measures were the standard deviation of lateral position, root mean squared error, and lane exceedance rate. The standard deviation of lateral position is a measure of lateral offset that evaluates deviations from participants' mean lateral position. As such, it is a measure of lateral variability that is independent of the center of the lane but dependent on participants' variability around their own mean. Thus, the standard deviation of lateral position dissociates mean lateral position from lateral position variability and serves as an important dependent measure that is commonly used in driving research.

By contrast, root mean squared error is defined as a measure of lateral offset that measures deviations from a prescribed route, which was herein defined as the center of the travel lane. Root mean squared error, therefore, may be a more appropriate measure of variability when an ideal and optimal route is known. In driving, however, it could be argued that the best position within the boundaries of a given lane may change, depending on potential threats that evolve and devolve in and around the lane.

Finally, lane exceedance rate is defined as the number of instances per minute that a participant's vehicle touched or crossed an outside lane boundary. Although these values are typically small, they serve as an important applied measure of lateral position variability, and all three measures taken together help to provide a more detailed picture of lateral position variability.

Data Analysis

In each of the three experiments, descriptive statistics for each dependent variable are presented in corresponding tables. In addition, results were analyzed using a 3 (eye movements) × 3 (cognitive workload) repeated-measures ANOVA. For each test, we corrected any violations of sphericity by adjusting the degrees of freedom following the Greenhouse-Geisser procedure. Violations of the homogeneity of variance assumption did not lead to any changes in the overall findings. For clarity and readability, the unadjusted degrees of freedom will be reported, regardless of whether an adjustment was made, thus preserving the ability of the reader to identify the exact number of samples that were used to compute each statistic. In addition, pairwise comparisons were computed between each of the various conditions. Confidence intervals of all comparisons were adjusted with use of the Bonferroni procedure for multiple comparisons.

EXPERIMENT 1

While the overall goal of all three experiments was to investigate the effects of eye movements and cognitive workload on lateral position variability, Experiment 1 was designed to test the effects of predictability in eye movements and cognitive workload on lateral position variability. We accomplished this goal by guiding eye movements using a static and predictable pattern, a dynamic and predictable pattern, or a dynamic and unpredictable pattern while also varying workload. By manipulating both eye fixations and the level of mental workload, we assessed the independent contribution of eye movement patterns and cognitive workload on lateral position variability.

Method

Participants were 27 undergraduates (16 males and 11 females) from the University of Utah who participated in this study for course credit.

Participants ranged in age from 18 to 34 years old with an average age of 23. Participants reported having normal or corrected-to-normal vision and a valid driver's license at the time of the study.

For Experiment 1, there were three motorcycles driving 22 m in front of the participant's vehicle at a constant speed. Each of the three motorcycles had a white license plate illuminated by two adjacent red lights. On average, participants were 90 cm from the center screen, which led to a visual angle of 7° between the outer motorcycles. For each condition, the license plates of the outside left and outside right motorcycle were illuminated for one quarter of the drive, respectively, and the license plate of the middle motorcycle was illuminated for one half of the drive. Only one license plate was illuminated at a time.

Three eye movement patterns were used to guide fixations: static-predictable, dynamic-predictable, and dynamic-unpredictable. In the static-predictable condition, the left license plate was illuminated for the first quarter of the drive, the middle license plate was illuminated for the following two quarters of the drive, and the right license plate was illuminated for the final quarter of the drive. In other words, the pattern was primarily static, but when there were changes, they were predictable. In the dynamic-predictable condition, the fixation pattern progressed left-middle-right-middle-left at a rate of 1 light per 2.5 s. Thus, the pattern was more dynamic but changes were still predictable. In the dynamic-unpredictable condition, the rate of light change was also 2.5 s, and the middle light always illuminated after every left or right light; however, the illumination of the left and right lights was randomized. In this condition, we created a dynamic pattern that was much harder to predict.

Three tasks of varying workload were used. Participants were instructed to just drive (i.e., low workload), to drive while performing a medium-workload digit classification task, or to drive while performing a high-workload backward counting task. These tasks were identical to those used by Pellechia and Shockley (2005) and were modeled after information reduction tasks described by Posner (1964). For the medium-workload condition, participants listened to a recording in which a set of two numbers was presented at a rate of one number per second with a 3-s pause between sets. Participants were instructed to classify a two-digit number as even or odd as well as high or low (low $< 50 \leq$ high). For the high-workload condition, participants listened to a recording that presented them with a starting number, and they were instructed to begin with that number and count backward by threes out loud. A new starting number was presented every 30 s.

For each driving run, participants were instructed to follow the motorcycles. Vehicle speed control was automatically configured so that participants had to only steer the vehicle. After completing three practice sessions that served to orient participants to the driving simulator, participants then completed nine counterbalanced driving runs, consisting of every eye movement pattern with every level of cognitive workload.

Results and Discussion

The data for each dependent measure in each of the experimental conditions are presented in Table 1. The standard deviation of lateral position was affected by eye movement patterns, $F(2, 52) = 5.01$, $p < .05$, partial $\eta^2 = .17$, as well as cognitive workload, $F(2, 52) = 14.87$, $p < .001$, partial $\eta^2 = .36$. In addition, there was an interaction between eye movement patterns and cognitive workload, $F(4, 104) = 5.33$, $p < .001$, partial $\eta^2 = .17$. Pairwise comparisons indicated that the standard deviation of lateral position decreased as cognitive workload increased in every eye movement condition; however, the decreases were significant only in the dynamic-unpredictable condition.

Eye movement patterns were also associated with changes in root mean squared error, $F(2, 52) = 3.34$, $p < .05$, partial $\eta^2 = .11$. Pairwise comparisons indicated that the difference in root mean squared error between the static-predictable ($M = .246$, $SE = .014$) and the dynamic-unpredictable ($M = .220$, $SE = .013$) conditions was significantly different, but there were no differences compared with the dynamic-predictable condition. Cognitive workload was also associated with changes in root mean squared error, $F(2, 52) = 10.49$, $p < .001$, partial

TABLE 1: Experiment 1 Descriptive Statistics

	Workload		
Eye Movement Pattern	Low	Medium	High
Standard deviation of lateral position			
Static-predictable	.189 (.048)	.178 (.060)	.178 (.056)
Dynamic-predictable	.179 (.050)	.175 (.048)	.136 (.038)
Dynamic-unpredictable	.191 (.043)	.161 (.054)	.146 (.038)
Root mean squared error			
Static-predictable	.255 (.078)	.243 (.098)	.241 (.077)
Dynamic-predictable	.255 (.095)	.242 (.083)	.204 (.097)
Dynamic-unpredictable	.250 (.080)	.219 (.083)	.192 (.074)
Lane exceedance rate			
Static-predictable	.496 (.594)	.572 (.800)	.277 (.401)
Dynamic-predictable	.470 (.724)	.404 (.637)	.258 (.483)
Dynamic-unpredictable	.530 (.734)	.418 (.653)	.242 (.465)

Note. Means shown with standard deviations in parentheses.

η^2 = .29, although pairwise comparisons indicated that all three levels differed from one another, with the high-workload condition (*M* = .212, *SE* = .014) exhibiting the lowest root mean squared error, followed by the medium-workload condition (*M* = .235, *SE* = .015) and the low-workload condition (*M* = .254, *SE* = .013). There was no interaction between eye movement patterns and cognitive workload in terms of root mean squared error.

Finally, for the lane exceedance rate, there was no effect of eye movement patterns; however, there was an effect of cognitive workload, $F(2, 52) = 6.47$, $p < .01$, partial $\eta^2 = .20$. Pairwise comparisons indicated that the lane exceedance rate for the high-workload condition (*M* = .259, *SE* = .071) was significantly lower than for the medium-workload condition (*M* = .465, *SE* = .110) and the low-workload condition (*M* = .499, *SE* = .098), but the medium- and low-workload conditions were not different from each other. There was no interaction between eye movement patterns and cognitive workload in terms of lane exceedance rate.

The overall goal of this research was to investigate the effects of eye movements and cognitive workload on lateral position variability. In Experiment 1, we tested three eye movement patterns and three levels of cognitive workload. On the basis of previous findings, we expected to see a reduction in lateral position variability associated with secondary-task performance, and our results confirmed this expectation. We also expected to see increased lateral position variability with the dynamic eye movement patterns; however, we found that the active movement of eyes caused drivers to maintain a more central lane position. In addition, the dynamic eye movement patterns interacted with cognitive workload such that the combination of dynamic eye movements and cognitive workload resulted in the least amount of lateral position variability.

If differences in visual scanning had accounted for differences in lateral position variability, then no effect of cognitive workload should have been observed in the current study. However, systematic differences in lateral position variability associated with secondary-task load were observed. This finding suggests that differing patterns of eye movements cannot fully account for changes in lateral position variability and that cognitive workload must be considered.

Previous research has indicated that drivers steer in the direction of gaze and gaze in the direction they steer. This finding suggests that the lateral position variability measures in the dynamic eye movement conditions should have been significantly higher than in the static-predictable condition; however, the opposite pattern was found, with the dynamic eye movements leading to the lowest lateral position variability. Thus, within the restricted range of fixations presented in this research, eye movement patterns did not appear to be coupled with lateral position variability in the way we hypothesized, whereas increases in cognitive workload were associated with decreases in lateral position variability regardless of eye movements.

There are at least two explanations for why eye movements did not influence lateral position variability in Experiment 1 in the manner in which we hypothesized. First, it is possible that the limited range of fixation movement was insufficient to elicit an effect. Second, it is possible that some time lag may be necessary for vehicle position to fully follow the direction of gaze and that the frequency of fixation change in the dynamic conditions was sufficiently high that vehicle position never had time to follow gaze. Experiment 2 was designed so that we could examine the former hypothesis, and Experiment 3 was designed so that we could examine the latter hypothesis.

EXPERIMENT 2

The goal of Experiment 2 was to further investigate the effects of eye movement eccentricity (i.e., the distance the eyes shifted laterally) and cognitive workload on lateral position variability. As with Experiment 1, if central eye movements are responsible for a decrease in lateral position variability, then one might predict that increasing the eccentricity of guided eye movements would lead to increased lateral position variability irrespective of cognitive workload. In other words, having participants look farther from the center of the road should lead to increases in lateral position variability. In contrast, if increased cognitive workload is more responsible for decreases in lateral position variability, then one might predict that increasing cognitive workload would lead to decreased lateral position variability irrespective of eye movement eccentricity.

Method

Participants were 27 students (13 males and 14 females) from the University of Utah, who participated in this study for course credit. Participants ranged in age from 18 to 48 years old with an average age of 24. Participants reported having normal or corrected-to-normal vision and a valid driver's license at the time of the study.

Similar to Experiment 1, a high-fidelity, fixed-base driving simulator was used in this study. In addition, three 5-min driving scenarios were used. Each scenario consisted of a straight, three-lane, divided highway and contained motorcycles that proceeded 22 m ahead of the participant's vehicle, side by side in the middle and outer lanes, at a constant speed. These scenarios were identical to those in Experiment 1 with the exception that there were two additional motorcycles on the far left and far right of the outer lanes, for a total of five motorcycles. On average, the visual angle for the outer motorcycles was 17° and 7° for the inner motorcycles (see Figure 3).

Each of the five motorcycles had a white license plate illuminated by two adjacent red brake lights. In the outer-light condition, the brake lights on the motorcycles in the outer lanes illuminated in a constantly alternating pattern, which would lead to large lateral shifts in eye movements. In the inner-light condition, the brake lights on the motorcycles in the inner lane (but not the centermost motorcycle) illuminated in an alternating pattern, leading to small lateral shifts in eye movements. Finally, in the middle-light condition, the brake lights of just the centermost motorcycle illuminated in the same frequency as the alternating patterns for the other conditions, which would lead to no lateral shift in eye movements. Only one license place was illuminated at a time, and participants were instructed to always look at the illuminated license plate as they drove. Furthermore, an eye tracker was used to ensure that participants complied with fixation instructions.

Workload was varied across three conditions in the same manner as Experiment 1. In the low-workload condition, participants were instructed to just drive. In the medium-workload condition, participants drove while performing the digit classification task. In the high-workload condition, participants were instructed to drive while performing the backward counting task. As with

TABLE 2: Experiment 2 Descriptive Statistics

	Workload		
Eye Movement Eccentricity	Low	Medium	High
Standard deviation of lateral position			
Middle light	0.206 (0.080)	0.176 (0.059)	0.161 (0.052)
Inner lights	0.207 (0.071)	0.179 (0.077)	0.163 (0.079)
Outer lights	0.195 (0.054)	0.189 (0.065)	0.164 (0.044)
Root mean squared error			
Middle light	0.297 (0.117)	0.262 (0.151)	0.262 (0.113)
Inner lights	0.275 (0.120)	0.284 (0.113)	0.254 (0.096)
Outer lights	0.248 (0.089)	0.263 (0.122)	0.236 (0.107)
Lane exceedance rate			
Middle light	0.992 (1.273)	0.534 (0.871)	0.614 (1.200)
Inner lights	0.727 (0.974)	0.734 (0.981)	0.442 (0.535)
Outer lights	0.631 (0.684)	0.757 (1.129)	0.602 (0.979)

Note. Means shown with standard deviations in parentheses.

the previous experiment, verbal responses were coded by an experimenter.

For each driving run, vehicle speed control was automatically configured so that participants had to only steer the vehicle while following the motorcycles. After completing three practice sessions that served to orient participants to the driving simulator, participants then completed nine counterbalanced driving runs, consisting of every eye movement eccentricity condition (outer, inner, and middle) with every level of cognitive workload (high, medium, and low).

Results and Discussion

The data for each dependent measure for each of the experimental conditions are presented in Table 2. Results indicated that the standard deviation of lateral position was not affected by eye movement eccentricity. There was, however, a main effect of cognitive workload, $F(2, 52) = 21.00$, $p < .001$, partial $\eta^2 = .45$. Pairwise comparisons indicated that all levels of cognitive workload differed significantly from each other, with the high-workload condition ($M = .163$, $SE = .010$) exhibiting the lowest standard deviation of lateral position, followed by the medium-workload condition ($M = .181$, $SE = .012$) and the low-workload condition ($M = .203$, $SE = .012$). There was no interaction between eye movement eccentricity and cognitive workload, nor was there an effect of eye movement eccentricity or cognitive workload in terms of root mean squared error or lane exceedance rate.

The goal of Experiment 2 was to further investigate the effects of eye movements and cognitive workload on lateral position variability by manipulating eye movement eccentricity as well as cognitive workload. On the basis of Experiment 1, it was predicted that as cognitive workload increased, lateral position variability would decrease. This prediction was confirmed by the changes in the standard deviation of lateral position. As for the effects of eye movements, research has found that drivers tend to steer in the direction they look, and other research has found that drivers have more central eye movements with increased workload; therefore, it was predicted that as eccentricity of eye movements increased, lateral position variability would also increase. This prediction was not supported in any of the measures of lateral position variability.

If central eye movements are responsible for decreases in lateral position variability, then one might predict that forcing participants to laterally shift their eyes when there are varying cognitive workloads would lead to increased lateral position variability. In Experiment 2, we manipulated the eccentricity of eye movements within the forward roadway, yet this manipulation did not yield any effects on lateral position variability. By contrast, if increased cognitive workload is more responsible for a decrease in lateral position variability, then one might predict that increasing cognitive workload would lead to decreased lateral position variability, and this result is exactly what was found.

Although the results of Experiment 1 and 2 present a strong case against the notion that eye movements alone can account for changes in lateral position variability, it is possible that there is a delay in the coupling between eye movements and lateral position variability; therefore, an effect of eye movements might be found only at varying frequencies of shifts in eye movements. Because in Experiment 2 we manipulated only the eccentricity, but not the frequency, of the shift in eye movements, it is not clear how varying frequencies might influence lateral position variability. Experiment 3 was designed to address the effect of frequency of shifts in eye movements on lateral position variability.

EXPERIMENT 3

The goal of Experiment 3 was to further investigate any possible effects of eye movements and cognitive workload on lateral position variability by manipulating both eye movement frequency as well as cognitive workload. While Experiments 1 and 2 demonstrated very limited support for an effect of eye movements on lateral position variability, it is possible that a more pronounced effect occurs after greater intervals of time. Thus, in Experiment 3, we varied the frequency of the shifts in eye movements along with cognitive workload to better understand whether there is an effect of eye movements on lateral position variability and, if so, how strong that effect is compared with that of cognitive workload.

Method

Participants were 27 students (8 males and 19 females) from the University of Utah, who participated in this study for course credit. Participants ranged in age from 18 to 44 years old with an average age of 24. Participants reported having normal or corrected-to-normal vision and a valid driver's license at the time of the study.

Similar to Experiments 1 and 2, a high-fidelity, fixed-base driving simulator was used in this study. In addition, three 5-min driving scenarios were used. Each scenario consisted of a straight, three-lane, divided highway and contained five motorcycles that proceeded 22 m ahead of the participant's vehicle, side by side in the middle and outer lanes, at a constant speed.

Eccentricity was held constant in that only the motorcycles on the outer left and outer right had their white license plates illuminated by two adjacent red brake lights. In the high-frequency condition, the brake lights on the motorcycles in the outer lanes alternately illuminated every 2.5 s. In the medium-frequency condition, the brake lights on the motorcycles in the outer lanes alternately illuminated every 5 s. Finally, in the low-frequency condition, the brake lights on the motorcycles in the outer lanes alternately illuminated every 7.5 s. Only one license plate was illuminated at a time, and participants were instructed to always look at the illuminated license plate as they drove.

Workload was varied across three conditions in the same manner as Experiment 1 and Experiment 2. In the low-workload condition, participants were instructed to just drive. In the medium-workload condition, participants drove while performing the digit classification task. In the high-workload condition, participants were instructed to drive while performing the backward counting task. As with the previous experiment, verbal responses were coded by an experimenter.

For each driving run, vehicle speed control was automatically configured so that participants had to only steer the vehicle while following the motorcycles. After completing three practice sessions that served to orient participants to the driving simulator, participants then completed nine counterbalanced driving runs, consisting of every eye movement frequency condition (high, medium, and low) with every level of cognitive workload (high, medium, and low).

TABLE 3: Experiment 3 Descriptive Statistics

	Workload		
Eye Movement Frequency	Low	Medium	High
Standard deviation of lateral position			
Low frequency	0.212 (0.079)	.176 (.076)	.170 (.074)
Medium frequency	0.214 (0.072)	.185 (.067)	.174 (.064)
High frequency	0.224 (0.083)	.192 (.072)	.190 (.066)
Root mean squared error			
Low frequency	0.252 (0.088)	.229 (.085)	.225 (.078)
Medium frequency	0.258 (0.099)	.228 (.080)	.231 (.087)
High frequency	0.273 (0.108)	.226 (.077)	.233 (.084)
Lane exceedance rate			
Low frequency	0.768 (1.042)	.368 (.623)	.293 (.552)
Medium frequency	0.734 (0.993)	.400 (.629)	.290 (.511)
High frequency	0.912 (1.132)	.409 (.570)	.380 (.553)

Note. Means shown with standard deviations in parentheses.

Results and Discussion

The data for each dependent measure for each of the experimental conditions are presented in Table 3. Results indicated that the standard deviation of lateral position was affected by eye movement frequency, $F(2, 52) = 5.28$, $p < .01$, partial $\eta^2 = .17$. Pairwise comparisons indicated the low-frequency condition (M = .186, SE = .013) led to the greatest decrease in standard deviation of lateral position, followed by the medium-frequency condition (M = .191, SE = .012) and the high-frequency condition (M = .202, SE = .013), although the difference between the low and medium conditions did not reach significance. Cognitive workload also led to a significant change in the standard deviation of lateral position, $F(2, 52) = 18.51$, $p < .001$, partial $\eta^2 = .42$, with the medium-workload (M = .184, SE = .013) and high-workload (M = .178, SE = .012) conditions being significantly lower than the low-workload (M = .217, SE = .014) condition, although they did not differ from each other. There was no interaction between eye movement frequency and cognitive workload.

Eye movement frequency did not affect root mean squared error, but cognitive workload did, $F(2, 52) = 8.84$, $p < .001$, partial $\eta^2 = .25$. Similar to the standard deviation of lateral position, pairwise comparisons indicated that the medium-workload (M = .227, SE = .014) and high-workload (M = .230, SE = .015) conditions yielded lower root mean squared error compared with the low-workload (M = .261, SE = .017) condition, and the difference between the medium and high conditions was not significant. There was no interaction between eye movement frequency and cognitive workload.

There was no effect of eye movement frequency in terms of lane exceedance rate, but there was a main effect of cognitive workload, $F(2, 52) = 13.98$, $p < .001$, partial $\eta^2 = .36$. Pairwise comparisons indicated the medium-workload (M = .392, SE = .105) and high-workload (M = .321, SE = .093) conditions led to lower lane exceedance rates compared with the low-workload (M = .804, SE = .177) condition. The difference between the medium- and high-workload conditions was not significant, and there was no interaction between eye movement frequency and cognitive workload.

The goal of Experiment 3 was to further investigate the effects of eye movements and cognitive workload on lateral position variability by manipulating eye movement frequency as well as cognitive workload. On the basis of previous research on cognitive workload, it was predicted that as cognitive workload increased, lateral position variability would decrease. This prediction was confirmed by all of the measures of lateral position variability. As for the effects of eye movements, it was predicted that as the frequency in lateral eye movement shifts decreased, so would lateral position variability. This finding would be consistent with previous reports that cognitively loading tasks lead to both a decrease in the frequency of scanning behaviors and a reduction in lateral position variability. This prediction was supported by the observation that decreases in lateral eye movement frequency led to a slight reduction in only one of the measures of lateral position variability.

If eye movements are responsible for decreases in lateral position variability, then one might predict that forcing participants to change the frequency of lateral eye shifts would lead to changes in lateral position variability. In Experiment 3, we manipulated the frequency of lateral eye movement shifts, yet this manipulation yielded only minimal effects on lateral position variability. By contrast, if increased cognitive workload is more responsible for decreases in lateral position variability, then one might predict that increasing cognitive workload would lead to decreased lateral position variability regardless of eye movements, and this result is what was found in all dependent measures of Experiment 3.

GENERAL DISCUSSION

In this research, we aimed to investigate the effects of eye movements and cognitive workload on lateral position variability. With regard to eye movements, in Experiment 1, we manipulated eye movement patterns and found a main effect of eye movements but in the opposite direction of what was predicted. In Experiment 2, we manipulated eye movement eccentricity within the forward roadway and found that varying the eccentricity of lateral shifts in eye movements did not lead to changes in any of the dependent measures. In Experiment 3, we manipulated eye movement frequency and found that decreased frequency of lateral eye movement shifts led to moderate decreases in just one of the measures of lateral position variability. Taken together, these three experiments suggest that eye movements play a limited role, at best, in terms of influencing lateral position variability. When there was an effect of eye movements, either it was in the opposite direction of our prediction or it was much smaller than the corresponding effect of cognitive workload (Table 4).

On the other hand, in all three experiments, we found robust effects of cognitive workload on lateral position variability regardless of eye movements. In Experiment 1, we found that increases in cognitive workload led to reductions in the standard deviation of lateral position, reductions in root mean squared error, and fewer lane exceedances. In Experiment 2, we found that as cognitive workload increased, the standard deviation of lateral position decreased. In Experiment 3, we found that increases in cognitive workload led to reductions in the standard deviation of lateral position, reductions in root mean squared error, and fewer lane exceedances.

In this important study, we investigated the effects of eye movements and cognitive workload, and in all three experiments, increases in cognitive workload led to decreases in lateral position variability, but in only a few instances did eye movements lead to changes in lateral position variability. In the few cases in which eye movement patterns did lead to changes in lateral variability, the effect was inconsistent (e.g., increased eye movements led to a reduction in lateral variability in Study 1 but an increase in Study 3). Given the strong and consistent effect of cognitive workload regardless of eye movements across all three studies, these findings provide strong support for the hypothesis that increases in cognitive workload led to direct reductions in lateral variability, irrespective of any associated changes in gaze concentration.

An important constraint of this research was that maximum eccentricity of all fixations was 8.5° of visual angle to the right and left of the road center. This maximum ensured that peripheral vision could still be used to maintain lane position (see Summala, Nieminen, & Punto, 1996). Within the range of eccentricities evaluated in this research, we found relatively little effect of eye movements on lateral vehicle control; however,

TABLE 4: Statistically Significant Results Across Experiments 1, 2, and 3

Measure	Eye Movements			Cognitive Workload		
	F	p	η^2	*F*	p	η^2
Experiment 1: Movement/predictability						
Standard deviation of lateral position	5.01	<.05	.17	14.87	<.001	.36
Root mean squared error	3.34	<.05	.11	10.49	<.001	.29
Lane exceedance rate				6.47	<.01	.2
Experiment 2: Eccentricity						
Standard deviation of lateral position				21.00	<.001	.45
Root mean squared error						
Lane exceedance rate						
Experiment 3: Frequency						
Standard deviation of lateral position	5.28	<.01	.17	18.51	<.001	.42
Root mean squared error				8.84	<.001	.25
Lane exceedance rate				13.98	<.001	.36

on the basis of prior research, we expect that at some point, increasingly eccentric glances would have led to increases in drivers' lateral position variability (Engström, Johansson, & Östlund, 2005; Greenberg et al., 2003; Horrey, Wickens, & Consalus, 2006; Merat & Jamson, 2008; Östlund et al., 2004; Zwahlen, Adams, & de Bald, 1988). That is, the results of this research do not readily apply to secondary visually demanding tasks, such as dialing a phone or tuning the radio, but rather, they apply to secondary cognitively demanding tasks that do not include a visual component. Examples include conversing on a cell phone or interacting with a speech-based in-vehicle information system.

At first blush, the finding that an *increase* in cognitive workload leads to a systematic *decrease* in lateral position variability may seem counterintuitive. However, these findings can be accounted for by a number of potential theories. For example, Logan and Crump (2009) suggest that skilled performance is accomplished by developing hierarchical control systems, with higher levels dealing with larger goals (e.g., navigation) and larger chunks of information than lower levels. For experienced drivers, this finding suggests that lane maintenance may become an encapsulated inner-loop process that requires minimal attention for successful performance. For example, this finding can explain why drivers do not often drive off the road when their mind wanders. When driving in low-cognitive-workload conditions, drivers may spontaneously attend to their lane position, disrupting performance in a manner similar to what is observed when expert golfers are instructed to pay attention to their swings (Beilock et al., 2002). As cognitive workload increases, the likelihood that drivers have residual attention to allocate to lane maintenance decreases, and this aspect of driving performance becomes more stereotypic.

Note, however, that cognitive workload often impairs other aspects of driving performance, such as detecting and reacting to unexpected events (Strayer & Drews, 2007). Unexpected or unpredictable events by definition cannot be handled with encapsulated or automatic inner-loop processing and therefore rely on limited-capacity attention. Thus, increasing cognitive workload increases reaction time and miss rates for unexpected events and also improves lane maintenance. Taken together, these findings suggest an important property of hierarchical cognitive models: Increasing attentional demands based on secondary-task cognitive workload can make performance based on encapsulated inner-loop processing *better* while at the same time making performance based on higher-level outer-loop processing *worse*.

To differentiate between the many potential explanations for the findings presented in this research, a number of additional studies should be undertaken. First, it would be useful to provide a more rigorous test of the hierarchical control model proposed by Logan and Crump (2009). Specifically, their model predicts that as the predictability of lane maintenance decreases, maintaining lane position should transition from an inner-loop to an outer-loop process. This prediction could be demonstrated experimentally by forcing drivers to increase their attention toward lane maintenance in the same way that paying attention to a free throw in basketball has been shown to disrupt performance (Hossner & Ehrlenspiel, 2010).

In additional to hierarchical control theory, there are a number of other potential perspectives that could account for the results obtained in these studies. In a recent series of investigations, He and McCarley (2011) evaluated lateral vehicle control in a variety of wind conditions and concluded that reductions in lateral variability with cognitive load were likely the result of strategic control prioritization. This conclusion was primarily based on the finding that drivers responded more accurately to wind gusts with cognitive workload but at the same time exhibited degradations in longitudinal control. However, if drivers do strategically protect and prioritize lateral control when there is secondary cognitive demand, then it would be expected that very difficult secondary tasks might eventually lead to a sudden breakdown of lateral control performance. Because this result was not seen in the current set of studies, a more general account, which does not rely on strategic prioritization or compensation, may be more favorable. However, researchers could specifically test the assumptions of strategic control prioritization through additional manipulations of mental workload.

A limitation to these experiments concerns the complexity of the driving environment. We made two major simplifications to driving. First, to preserve the angle of visual presentation across conditions and between participants, speeds were experimentally controlled and did not need to be adjusted by participants. This manipulation was similar to driving with cruise control. Second, to maximize the sensitivity of our measures, the driving environment was kept as simple as possible. Although the general findings of this research have been observed in considerably more complex and demanding environments, the novel findings should be generalized with caution, and authors of future studies should examine the effects of eye movements and cognitive workload in more complex driving scenarios. Recent research involving instrumented vehicles on public roads has shown similar decreases in lateral position variability as cognitive workload increases (e.g., Brookhuis et al., 1991; Engström et al., 2005); however, authors of these studies have not controlled for eye movements. Thus, another future direction would be to use manipulations similar to those in these three experiments to tease apart the purported influence of eye movements along with cognitive workload.

This research helps to clarify the way in which cognitive distraction affects lateral vehicle control. The autonomous detection of distraction has been, and continues to be, an important goal for improving roadway safety. Understanding how eye movements are related to lateral position variability, and how they do and do not interact with cognitive workload, provides an important contribution toward the development of autonomous distraction detection algorithms.

KEY POINTS

- Increases in cognitive workload reduce lateral position variability and peripheral eye movements.
- The effects of cognitive workload on lateral position variability are independent of eye movements.
- Lateral position variability may prove to be a useful predictor of the driver's cognitive workload irrespective of eye movements. The findings support hierarchical theories of cognitive control.

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Joel M. Cooper is the owner of Precision Driving Research and a research assistant professor in the Department of Psychology at the University of Utah. He received his PhD from the University of Utah in 2010.

Nathan Medeiros-Ward is a graduate student in the Department of Psychology at the University of Utah. He received his MS from the University of Utah in 2010.

David L. Strayer is a professor in the Department of Psychology at the University of Utah. He received his PhD from the University of Illinois at Urbana-Champaign in 1989.

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