

© 2012 by Jibo He. All rights reserved.

LANE KEEPING UNDER COGNITIVE DISTRACTIONS: PERFORMANCE AND
MECHANISMS

BY

JIBO HE

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Psychology
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2012

Urbana, Illinois

Doctoral Committee:

Professor Jason S. McCarley, Chair

Professor Arthur F. Kramer

Professor Daniel Simons

Professor Daniel G. Morrow

Associate Professor Alejandro Lleras

Dr. William Horrey, Liberty Mutual Insurance

ABSTRACT

Cognitive distractions while driving often reduce the variability of lane position. However, data do not make clear whether smaller lane variability should be interpreted as a performance loss, indicating rigidified or unresponsive steering response to external stimuli, or a performance improvement in lane-keeping, indicating better lateral control. Four hypotheses, *rigidified steering*, *visual enhancement*, *lateral prioritization*, and *automatic steering*, debated on the performance implications and mechanisms of smaller lane variability under cognitive distractions. This dissertation project compares these hypotheses, and explores two important questions: first, whether the smaller lane variability under cognitive distraction indicates a performance loss or a performance gain in lane-keeping; second, what is the underlying cognitive mechanisms of lane variability reduction. Three studies have been carried out to assess drivers' responsiveness to heavy lateral winds under varying levels of cognitive load. Data showed that cognitive load reduced the variability of lane position but increased the variability of vehicle speed, engendering more frequent steering activity but less frequent speed manipulation. Cognitive load also increased the coherence, or coupling between steering wheel position and lateral wind strength. More interestingly, distracted drivers produced quicker steering response time to the sudden onset of lateral wind. Results thus suggest that smaller lane variability under cognitive distractions is an indicator of better lane-keeping performance, and distracted drivers achieved better lane-keeping performance by actively prioritizing lateral control. Findings carry practical applications for mitigating driving risks and theoretical implications on the relationship between attention allocation and driving performance.

To Mother and Father

ACKNOWLEDGEMENTS

I deeply appreciate the help from my loved ones. This dissertation would not be completed without the generous supports from them. The first thanks goes to my advisor, Jason S. McCarley, who has been training, helping, and encouraging me during my graduate career. Thanks to my committee members for their help and suggestions for my dissertation, Arthur Kramer, Daniel Simons, Alejandro Lleras, William Horrey, and Daniel Morrow. Their suggestions have greatly improved my dissertation. Thanks are also due to important technical supports from Ronald Carbonari, Chun He, Hank Kaczmarski, John Gaspar, and Yusuke Yamani. I also thank my friends who have offered their supports and encouragements over the many years I have been working towards this goal. Finally, many thanks to my parents who have raised me, supported me unconditionally.

TABLE OF CONTENTS

INTRODUCTION.....	1
Cognitive distraction is critical.....	2
Effects of cognitive distraction on lateral vehicle control.....	3
CHAPTER 1 : THEORIES OF DUAL TASK PERFORMANCE	6
Working memory model.....	6
Central bottleneck model.....	9
Resource theory	10
Threaded cognition theory.....	13
Inattentive blindness view	14
Cross-talk view.....	15
CHAPTER 2: DRIVING PERFORMANCE UNDER COGNITIVE DISTRACTIONS	17
Lateral control	17
Longitudinal control	19
Event detection and hazard response time.....	21
Mental workload.....	22
Eye movement patterns and attentional processing.....	22
CHAPTER 3: EXISTING HYPOTHESES OF LANE VARIABILITY REDUCTION	24
Rigidified steering hypothesis	25
Visual enhancement hypothesis	27
Lateral prioritization hypothesis.....	29
Automatic steering hypothesis	32
Hypothesis summary	32
EXPERIMENT 1: LANE KEEPING PERFORMANCE WITH A CRUISE CONTROL SYSTEM.....	34

Method.....	36
Results	41
Discussion	46
EXPERIMENT 2: LANE KEEPING AND SPEED MAINTENANCE PERFORMANCE ..	48
Method.....	49
Results	54
Discussion	61
EXPERIMENT 3: RESPONSE TIME TO LATERAL WIND AND LEADING VEHICLE	
BRAKE HAZARDS.....	65
Method.....	67
Results	75
Discussion	83
GENERAL DISCUSSION.....	88
Finding Summary	88
Discussion	91
Future Research.....	99
REFERENCES	101

INTRODUCTION

Driver distraction, “*a diversion of attention away from activities critical for safe driving toward a competing activity*” (Regan, Lee, & Young, 2008, page 38), is a major factor causing driving safety problems; data from the 100-Car Naturalistic Driving Study estimated that driver distraction contributed to up to 23 percent of crashes (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006) and that more than 78 percent of crashes and near crashes involved driver inattention (Dingus, et al., 2006).

The U.S. National Highways and Transport Safety Administration has identified four types of driver distraction: visual, auditory, physical (manual dexterity), and cognitive distraction (Ranney, Garrott, & Goodman, 2001). Reimer (2009) offered a similar taxonomy, distinguishing between visual, biomechanical, auditory, and cognitive distraction. It is important to distinguish sources of distraction, because studies have shown that visual, physical and cognitive distraction have different effects on driving performance, especially in eye scanning patterns and lane-keeping performance. Cognitive distractions cause brief off-road glances, usually no greater than 1.6s (Sodhi, Reimer, Llamazares, 2002; Wierwille, 1993), while visual distractions can often cause drivers to glance away from the road as much as several seconds (Reimer, 2009). Liang and Lee (2010) compared the relative impact of visual and cognitive distraction and found that visual distraction caused greater performance decrements than cognitive distraction. Visual and physical distraction, such as dialing a telephone number, are generally believed to decrease lane-keeping performance by causing larger lane variability. For example, more than 10% of drivers in one study made dangerous lateral path deviations while dialing long telephone numbers

(Zwahlen, et al., 1988). In contrast, cognitive distractions often reduce lane variability (Becic et al., 2010; Briem & Hedman, 1995; Horrey & Simons, 2007; Liang & Lee, 2010; however, see Horrey, Lesch, Garabet (2009), Salvucci (2005) and Salvucci & Beltowska (2008) for findings of larger lane variability under cognitive distractions.).

Cognitive distraction is critical

Cognitive distraction is a significant source of driver distractions. A large number of laboratory and real-world studies indicate that cognitive distraction tasks, including language production (Brown et al., 1969; Haigney & Westerman, 2001; Horswill & McKenna, 1999; Kubose, Bock, Dell, Garnsey, Kramer, & Mayhugh, 2006), conversation (McKnight & McKnight, 1993; Strayer & Drews, 2004; Strayer & Johnston, 2001), and memory rehearsal (Salvucci & Beltowska, 2008), can impair on-road or simulated driving performance.

Comparison studies of hand-held and hands-free cell phones have shown that both types of phones produce similar levels of performance decrements, which suggests that it is the comprehension and production of conversation, rather than the manual demands of holding a phone, that cause the driving impairments (Patten, Kircher, Östlund, & Nilsson, 2004; Redelmeier & Tibshirani, 1997; Strayer & Johnston, 2001). Some researchers thus suggest that the impairments caused by cell phone conversation are largely attributable to the diversion of attention from the processing of information important for safe driving (Strayer et al., 2003; Strayer & Johnston, 2001; Strayer, Drews, Crouch, 2006).

Effects of cognitive distraction on lateral vehicle control

Single-vehicle road departure has long been recognized as the most common crash type, causing more fatalities than any other forms of crash. Wang and Knipling reported that single-vehicle road departure crashes accounted for almost 1.3 millions crashes, about 37.4% of all fatal vehicle crashes, based on 1991 General Estimate System and Fatal Accident Recording System data (Wang & Knipling, 1994). Single-vehicle road departure crashes remained the top crash type in recent surveys, accounting for approximately 40% of all crashes, according to Traffic Safety Facts in 2005 (Barickman, Smith, & Jones, 2007). According to the statistics of Iowa in 2006, 60% of all crashes involved a lane departure (Iowa Comprehensive Highway Safety Plan, 2006).

While cognitive distraction is a major contributing factor for driving risks, and lateral crashes are common, the effect of cognitive distraction on lateral lane-keeping performance is still unclear, as the strength and direction of the distraction effect have been inconsistent in the reported studies. Some studies indicate that cognitive distraction tasks increase lane variability (Horrey, Lesch, & Garabet, 2009; Just, Keller, & Cynkar, 2008; Strayer & Johnston, 2001; Salvucci & Beltowska, 2008). For example, a sentence comprehension task was found to increase the root mean squared (RMS) deviation from an ideal lane position and increase the frequency of road-maintenance errors in a study by Just, Keller, and Cynkar (2008), and a memory rehearsal task caused drivers to deviate more from the lane center in a study by Salvucci and Beltowska (2008).

However, many other studies have shown the opposite effect (Becic et al., 2010; Brookhuis, de Vries, & de Waard, 1991; Kubose, et al., 2006; Liang & Lee, 2010). For example, Brookhuis, de Vries, and de Waard (1991) showed that cell phone communication had a seemingly positive effect on lane-keeping, decreasing the frequency of lane deviations.

Many other studies have also produced null effects of cognitive distraction on lateral maintenance (Alm & Nilsson, 1995; Lamble et al., 1999; Rakauskas, Gugerty, & Ward, 2004). For example, although mobile telephone task was expected to affect drivers' ability to follow the road, Alm & Nilsson (1995) failed to find any effect of mobile telephone task on the mean and variation of lane position. Moreover, naturalistic cell phone conversation did not significantly influence steering variability or mean lateral speed in a driving simulator study, by Rakauskas, Gugerty, and Ward (2004). Horrey and Wickens (2006), in a meta-analytic review, concluded that the effect of distraction on tracking performance decrement was small, and not significantly different from null effect. They explained the small effect size of lane keeping performance by that lane keeping was a relatively automatic skill, supported by ambient vision, and required limited resources.

In light of these inconsistent findings, the current project is devoted to exploring the mechanisms by which cognitive distraction might influence lane-keeping performance. This dissertation is organized in this way. Chapter One reviews existing theories and models of dual-task performance and interference, including the Working Memory Model, the Central Bottleneck Theory, and the Resources theory, Threaded cognition theory, Inattention blindness view, and Cross-talk theory. Chapter Two reviews how cognitive distraction changes driving behaviors and performance in various aspects, e.g., lane-keeping, longitudinal vehicle control, event detection and

hazard response time, mental workload, eye scanning patterns and attentional processing. Chapter Three introduces and compares existing hypotheses on how cognitive distraction changes lane-keeping performance. Chapters Four to six present three experimental studies investigating the behaviors of cognitively distracted drivers and the mechanisms of how cognitive distraction influences lane-keeping performance.

CHAPTER 1 : THEORIES OF DUAL TASK PERFORMANCE

A driver can be conceptualized as an information processing system with limited capacity for both peripheral (visual, manual, auditory etc.) and central (executive control, tactical planning etc.) processing (Kahneman, 1973; Navon & Gopher, 1979). Because of this limited capacity, engaging in multiple tasks concurrently often diverts attention away from the primary driving task, causing driving performance decrements. But despite of the general agreement that secondary tasks can impair primary task performance, existing theories have different explanations about the role of cognitive processing capacity and the locus of task interference. This chapter reviews existing theories about dual task performance to provide a theoretic background for this dissertation. The major differences between these models are the divisibility of information processing capacity (Navon & Miller, 2002) and the locus of interference (Hazeltine, Ruthruff, & Remington, 2006).

Working memory model

Baddeley's working memory model proposes three major components of working memory, including a central executive (responsible for the integration of information) and two slave systems for information storage (Baddeley, 1986; Baddeley, 1996). The two slave systems are a phonological loop for storing linguistic information, and a visuospatial sketch pad for storing visual and spatial information. The model provides a theoretical framework for explaining dual-task performance. Baddeley et al. (1986) investigated the performance of a primary tracking task combined with various

secondary tasks, including an articulatory suppression task, a tone detection task, and a digit span task. Results showed that secondary tasks impaired tracking performance, which was interpreted as overloading of the central executive component of working memory.

Baddeley's model predicts that a secondary task that requires cognitive processing similar to the primary task will cause greater dual-task interference than one which requires different resources (Baddeley, 2003). Driving is largely a visual-spatial-manual task, loading on the central executive and the visuospatial sketch pad of working memory. Cognitive distraction tasks that might be performed while driving are diversified, and include daydreaming, decision making, planning, and listening to music, etc. Many of these tasks load the central executive component, and sometimes on the phonological loop or visuospatial sketch pad. Because both driving and cognitive distraction tasks require the limited central executive resources, concurrently carrying out driving and a cognitive distraction task can cause performance interference in either or both tasks. This argument is confirmed by many empirical studies.

First, it is well-established that cognitive distraction tasks interfere with driving performance. Cognitive distraction can reduce the quality of attentional processing within an area of interest (Strayer et al., 2003) and increase reaction time to traffic hazards (Caird et al., 2008). Cognitive distraction also reduces visual scanning of peripheral information, such as side and rear-view mirror and the speedometer, and caused more glances to road center (e.g., He, Becic, Lee, & McCarley, 2011; Recarte & Nunes, 2000, 2003). Moreover, cognitive distraction tasks that require processing of spatial information, such as a spatial reasoning task, cause more driving decrement than distraction tasks that do not require spatial information processing, for example,

a word generation task (Lamble, Kauranen, Laasko, & Summala, 1999; Recarte & Nunes, 2000).

Second, driving also interferes with cognitive task performance. This is evident in a recent study by Becic et al. (2010), in which participants were asked to drive in a driving simulator while engaging in a story-retelling task with a conversation partner. The accuracy of story-telling and memory for stories both declined when participants were driving. In another study, participants performed a working memory task while driving in easy or difficult conditions (Radeborg, Briem & Hedman, 1999). Results showed that driving impaired memory recall and sentence meaningfulness judgment.

Besides the working memory model, many theories have been proposed to explain dual task performance and interference. Three of the most influential explanations of dual-task interference are capacity sharing, bottleneck (task switching), and cross talk (Pashler, 1994). Examples of capacity sharing models include the unitary resources model (Kahneman, 1973) and multiple resources model (Navon & Gopher, 1979; Wickens, 1984, 2002). The most influential bottleneck model is the central bottleneck model (Pashler, 1994).

The major debates of these models concern the divisibility of information processing capacity (Navon & Miller, 2002) and the locus of interference. The central bottleneck model assumes that processing ability is indivisible, and entails queuing for processing. In contrast, resources theory assumes resources are divisible, and can be shared among parallel tasks (Navon & Miller, 2002).

Central bottleneck model

According to the central bottleneck model, dual-task costs occur because central processing for one task must wait when the central processing channel is occupied by another task (Levy, Pashler, & Boer, 2006; Pashler, 1994; Welford, 1952). The central bottleneck occurs after perceptual processing but before response execution, and is responsible for processes including response selection, decision making and memory retrieval (Pashler, 1994; Pashler & Johnston, 1998). Central processing is serial: when central processing is under way for one task, the other task must wait until the central processing is available, causing postponement of the second task. Other mental processes, such as perceptual analysis and response execution, can be processed in parallel.

The central bottleneck model predicts that reaction time to a secondary task stimulus will increase as the stimulus-onset asynchrony (SOA) decreases, a phenomenon known as the psychological refractory period (PRP) effect. The central bottleneck is a generic limitation, which persists regardless of the pairing of stimuli and response modalities. A PRP effect is observed, for example, with response combinations of manual and eye movement responses (Pashler, Carrier, & Hoffman, 1993), manual and vocal responses (Pashler, 1990), manual and pedal responses (Osman & Moore, 1993).

Several driving studies support the central bottleneck model. Levy et al. (2006) asked participants to perform a choice task and a braking task with varied SOA. Brake response time increased as SOA reduced, showing a standard PRP effect (Pashler, 1994). The effect of SOA on gas-off time was approximately the same as the effect of SOA on brake RT, indicating that SOA had no effect on movement time. Therefore,

the delay in brake performance was in response planning, not motor control (Levy et al., 2006). Stimulus and response modality had either little or no effect on brake RT, supporting the central bottleneck interpretation that dual-task interference primarily arises from central processing (Levy et al., 2006). Another study found that both cell-phone conversation and music listening resulted in longer brake response time. However, drivers showed quicker movement time from the gas pedal to brake pedal, in apparent anticipation of longer response times when distracted (Bellinger, Budde, Machida, Richardson, & Berg, 2009). This finding suggests that dual-task interference occurs before response execution. A couple of other studies also support the idea that it is the response selection process of secondary tasks that interfere with driving performance.

However, some findings cannot be accommodated by the central bottleneck model. For example, subjects can perform a visual-vocal and an auditory-manual task concurrently with minimal interference after moderate practice, suggesting that the central bottleneck does not always limit dual-task performance (Hazeltine et al., 2006).

Resource theory

Capacity-sharing theorists assume one or more common limited mental resources among tasks (Kahneman, 1973; Navon & Gopher, 1979; Navon & Miller, 2002; Wickens, 1980, 2002). If multiple tasks are performed concurrently and demand shared resources, performance for either or all tasks will be impaired (Pashler, 1994). Multiple resources theory (MRT) categorizes attentional resources along four dimensions: processing stage (perception or response), processing code (verbal vs.

spatial), perceptual modalities (visual or auditory), and visual channel (focal or ambient vision) (Norman & Bobrow, 1975; Wickens, 1984, 2002). The model predicts that the strength of interference between dual tasks depends on the overlap of resource requirements. Two tasks without any overlapping resource demands can be processed simultaneously with little interference, whereas two tasks that compete for similar resources and have inconsistent stimulus-response requirements show the greatest dual-task interferences (Kramer, Larish, & Strayer, 1995; Wickens, 2002).

The strict central capacity interference model assumes that processing resources are scarce, elastic, controllable, and divisible (Navon & Gopher, 1979). The model predicts that the performance of an easy primary task will show little, if any, performance decrement, because the resource demands required by the primary and secondary tasks together will not exceed the amount of available capacity. In contrast, the central bottleneck model assumes that processing is indivisible and can work on only one task at a time no matter how easy or difficult that task is. Therefore, the central bottleneck model predicts that two tasks that demand central processing at the same time will cause performance interference regardless of the difficulty of each task.

Driving depends on largely visual, cognitive, and manual resources, and sometimes on auditory perception. Tasks loading on visual or manual channels, such as a cell phone dialing task or a radio tuning task, which overlap with the driving task, are most likely to be detrimental to driving performance. Tasks loading on auditory channels, such as a language shadowing task (merely repeat the sound that is played) and a language production task, are less likely to impair driving performance.

According to the resources model, dual-task interference can arise from any stages of mental process, including not only response selection, but also perceptual

disruption and manual dexterity. The resource model suggests that driving interference can be caused by visual, physical, and cognitive distraction. Studies in driving have provided support for this argument of resource model. Recarte and Nunes (2003) found that mental tasks during driving increased perception time but did not change decision time for detection of a flashed signal. They concluded that visual detection impairment was due to late detection and poor identification rather than a response selection delay, further supporting the argument of multiple resources model and arguing against the central bottleneck model. Physical distraction can cause significant driving performance decrement too. For example, physical distraction increased lane variability and lane excursions (Caird et al., 2008). Reed and Green (1999) also found that dialing a phone number manually impaired the maintenance of lane position.

Resource models also predict that interference is specific to the stimulus and response modality and code of cognitive processing. This is supported by many empirical findings. For example, one study found that a mental task requiring spatial-imagery operation produced more pronounced and different changes in visual scanning behaviors than a verbal task, including longer fixation duration and remarkable reduction of visual inspection window (Recarte & Nunes, 2000). Liang and Lee (2010) compared the relative impact of visual distraction and cognitive distraction, and found that visual distraction caused more driving performance decrements than cognitive distraction. Further supports for the resource model come from the finding that dual-task interference was content-specific, depending on the input/output modality pairing (Hazeltine, et al., 2006). Subjects practiced doing two tasks concurrently. In one condition, a visual–manual task was coupled with an auditory–vocal task; in the other condition, the input–output pairing was reversed,

combining a visual–vocal task with an auditory–manual task. Throughout practices, dual-task interference for the pairing of visual–vocal/auditory–manual tasks was more than twice as large as the opposite modality pairing.

There are some studies that cannot be accounted by the resource model too. For example, the resource model predicts that practice in either or both of cell phone conversation and driving can free up processing resources, resulting in better dual-task performance (Norman & Bobrow, 1975). However, several studies have suggested that practice does not alleviate dual-task interference (Brookhuis et al., 1991; Cooper & Strayer, 2008). Brookhuis et al. (1991) asked subjects to practice driving while doing a concurrent Paced Auditory Serial Addition Task (PASAT) for 15 days. They did not find any evidence that practice reduced dual-task interference. Real-world experience of cell phone use, as measured by the frequency of cell phone use, also does not seem to have any beneficial effect on alleviating or reducing driving performance decrement during cell phone conversations (McKnight & McKnight, 1993; Strayer, Drews, & Johnston, 2003).

Threaded cognition theory

The threaded cognition theory, built on the ACT-R cognitive architecture, posits a resource-bounded cognitive processor. Peripheral sensory processing, such as perception and motor movement, can operate in parallel to subserve multiple tasks, while central procedural resource can only operate serially, resulting a central cognitive bottleneck (Salvucci & Tatgen, 2008).

The threaded cognition theory is similar to the central bottleneck model in that both models emphasize a central cognitive bottleneck. The major difference is,

threaded cognition theory proposes that multitask interferences are because two tasks both heavily and continuously utilize a common resource of declarative memory, not because an executive process can attend to only one task at a time, an argument claimed by the central bottleneck model (Pashler, 1994; Salvucci & Tatgen, 2008).

Inattentional blindness view

The inattentional blindness view (Most et al., 2005; Strayer et al., 2001, 2003, 2007) suggests that dual-task interference results from superficial encoding and cognitive processing of visual information. The “looked but failed to see” error, a common cause of traffic accident in which the drivers gaze in the correct direction of road hazard but fail to perceive it, can be regarded as a form of inattentional blindness (Langham, Hole, Edwards, & O’Neill, 2002). Even if drivers have fixated on an area of interest, it does not guarantee that objects in that area have been processed enough for recognition (Mack & Rock, 1998; Most et al., 2001; Simons & Chabris, 1999). This attentional lapse can be engendered by purely cognitive load.

Recarte & Nunes (2003) found that distraction produced target omissions and errors in a visual discrimination task, consistent with the inattentional blindness view. In a series of driving studies, Strayer et al. (2001, 2003, 2007) found that cell phone conversation resulted in poor recognition memory of stimuli presented within driving scenarios, even if drivers had fixated on the stimuli directly. Conversation also reduced the amplitude of the P300 wave of the ERP component generated in response to onset of a lead vehicle’s brake lights (Strayer et al., 2007). Because cell phone

conversation does not share overlapping resources with driving, Strayer et al. (2001, 2003, 2007) argued against the resource models of dual-task interference and favored the inattention blindness view.

Cross-talk view

The cross-talk view suggests that dual tasks interfere with each other when each task produces outputs and side effects harmful to the processing of the other task (Hazeltine et al., 2006; Navon & Miller, 1987; Pashler, 1994). It is more difficult to perform two tasks concurrently when the tasks involve similar information input. In the cross-talk view, dual-task interference does not result from resources competition, but reflects unwanted interactions between processing for two tasks. Therefore, interference can occur even when resources are available (Hazeltine et al., 2006).

An example of cross-talk interference is the difficulty to draw a circle with one hand and a square with the other hand simultaneously (e.g., Spijkers, Heuer, Steglich, & Kleinsorge, 2000). Hazeltine, et al. (2006) found that input/output modality pairings determined persistent dual-task costs after practices. Throughout practices, dual-task costs were generally more than twice as large with visual-vocal/ auditory-manual tasks as with visual-manual/auditory-vocal pairing. Hazeltine, et al. (2006) attributed the different interference of input/output pairing to the cross-talk between processing of two tasks.

The cross-talk interference is also demonstrated in several driving studies. For example, Spence and colleagues found that cognitive spatial tasks interfered with driving performance, if the secondary cognitive task and driving task emphasized different spatial locations (Spence & Ho, 2008; Spence & Read, 2003). In another

Lane Change Task study, Hurts (2011) demonstrated that a secondary spatial reasoning task was more distracting than an acoustic version of an otherwise identical secondary task. Hurts (2011) interpreted this finding in the view of cross-talk, that is, dual task interference depends on the compatibility of spatial cues simultaneously used by primary driving task and secondary cognitive task.

CHAPTER 2: DRIVING PERFORMANCE UNDER COGNITIVE DISTRACTIONS

When distracted, drivers exhibit performance decrements in many aspects. Driving safety researchers have measured performance using an array of metrics, including lateral control, longitudinal control, event detection and hazard response times, mental workload, eye movement patterns and attentional processing. This section describes some of the changes in behavioral, performance, and subjective measures seen under cognitive distractions.

Lateral control

Lateral control refers to drivers' ability to maintain a steady and safe lane position. Lateral control performance is usually measured by the average lane position, the standard deviation of lane position, and the number of lane excursions. Lateral control is thought of as being controlled by ambient vision, which requires little attentional resources and therefore is robust against the interference from driver distraction (Horrey & Wickens, 2006). In two meta-analyses of the effect of cell phone usage on driver performance, Horrey & Wickens (2006) and Caird et. al. (2008) found only a modest effect of distraction on lateral control, suggesting that cell phone conversation has minimal effect on lane keeping. However, it is important to note that the effect is quite variable, and inconsistent.

A possible reason for these mixed findings is that the effects of distraction on lane keeping performance depend on the modality and demand of the secondary tasks. Visual, manual and cognitive distraction apparently have different effects on

lane keeping performance (Engström et al., 2005; Liang & Lee, 2010). Secondary visual or manual tasks, particularly tasks requiring a large amount of visual attention, adversely affect drivers' ability for lane keeping, incurring more variable lane position (Jancke, Musial, Vogt, & Kalveram, 1994; Wikman, Nieminen, & Summala, 1998). For example, drivers produced larger lane variability and more lane excursions while dialing or talking over a hand-held phone (Green, Hoekstra, & Williams, 1993; Reed & Green, 1999). Drivers also produced poorer lane keeping performance, as indexed by the standard deviation of lane position and the number of lane excursions, when they were manually entering information to a route guidance system or reading visual navigational instructions (Dingus, McGehee, Hulse, Manakkal, Mollenbauer, & Fleischman, 1995).

In contrast, cognitive distraction often leads to more precise lateral control, reducing lane variability (e.g. Becic et al., 2010; Briem & Hedman, 1995; Brookhuis et al. 1991; Horrey & Simons, 2007; Kubose , et. al., 2006; Liang & Lee, 2010; Reimer, 2009). For example, Kubose et al. (2006) found that a language production task reduced the variability of lane position as compared to driving-only condition. In another driving simulator study, Reimer (2009) found that as the difficulty of a secondary N-back counting task increased, lane variability decreased. Ranney and colleagues had subjects drive an instrumental vehicle in a closed test track while performing a combination of tasks, including car-following, peripheral target detection and secondary in-vehicle tasks (Ranney, Harbluk, & Noy, 2005). Steering reversal rates were higher for trials involving secondary tasks, compared to the no-secondary task condition, and extended periods of steering inactivity were less frequent. Higher steering reversal rates and less frequent steering inactivity under

distraction conditions suggested that drivers were more active in maintaining a steady lane position.

However, several other studies found that cognitive distraction tasks can increase lane variability (Horrey, Lesch, & Garabet, 2009; Just, et al., 2008; Salvucci, 2005; Salvucci & Beltowska, 2008; Strayer & Johnston, 2001). For example, Horrey, Lesch, Garabet (2009) found that both a Paced Auditory Serial Addition Task and a guessing task increased the standard deviation of lane position. Salvucci and Beltowska (2008) found that a memory rehearsal task significantly increased the rooted mean square error of lane position.

The changes of lane variability may be a result of different steering behaviors under distractions. Cognitive distraction was found to increase steering wheel manipulation (Ranney, et al., 2005; Seppelt, & Wickens, 2003). For example, in an on-road driving study, an auditory continuous memory task significantly increased the steering wheel reversal rate (with one degree gap threshold), compared to drive-only conditions (Engström et al., 2005).

Longitudinal control

Longitudinal control is usually measured using the mean and standard deviation of speed, headway distance, and headway time.

Distracted drivers were often found to drive more slowly with more variable speed (Alm & Nilsson, 1994; Brown et al., 1969; Green, Hoekstra, & Williams, 1993; Kubose et al., 2006; Rakauskas, Gugerty, & Ward, 2004; Reed & Green, 1999). For example, Alm and Nilsson (1994) found that the use of telephone reduced the speed when the driving task was easy. Several on-road and simulator studies also

found that drivers using a cell phone showed greater variation in speed and less throttle control (Green, 2004; Zylstra, Tsimhoni, Green, & Mayer, 2004).

Drivers may also adopt a longer headway distance when distracted (Greenberg, Tijerina, Curry, Artz, Cathey, Grant, Kochlar, Kozak, & Blommer, 2003; Östlund et al., 2004). For example, drivers engaging in a cognitively demanding cell phone conversation often maintain longer headway distance in a car-following situation as compared to when driving without a distraction task (Ranney et al. 2005; Strayer et al. 2003; Strayer & Drews 2004). However, this effect is not ubiquitous.

Drivers engaging cognitive distraction tasks also produced more variable braking behaviors. For example, Harbluk et al. (2007) reported that drivers driving in the city traffic while doing a difficult digit addition task produced more hard brakes than drivers without distractions. In another study, Strayer and colleagues (2006) compared the effects of cell phone conversation and alcohol on driving performance. Compared to control condition, drivers engaging in a cell phone conversation initiated braking response about 9% slower to the leading vehicle braking events, and took about 19% longer time to recover their speed before braking. These studies suggested that drivers were less involved in manipulating speed when engaging in a cognitive distraction task.

The increase of headway distance (Ranney, Harbluk, Noy, 2005) and reduction of speed (Dingus, et al. 1997; Pohlman & Traenkle, 1994; Rizzo, Stierman, Skaar, Dawson, Anderson, & Vecera, 2004) are interpreted as a compensatory behavior of distracted drivers to adapt to the increase of driving risks. However, this compensatory behavior were not consistently observed (Horrey & Simons, 2007; Lambell et al., 1999). For example, Horrey & Simons (2007) did not find any increase in safety margins during overtaking maneuvers. Lambell et al. (1999)

reported that the time-to-collision was shorter under a concurrent cognitive task and a phone dialing task, compared to when drivers were not distracted.

Event detection and hazard response time

Two meta-analyses showed that the major effect of cell phone conversations on driver performance is to increase response times to hazards and other critical events (Caird et al., 2008; Horrey & Wickens, 2006). Slower braking responses under high cognitive load conditions have been reported in many empirical studies (Alm & Nilsson, 1995; Lamble, et al., 1999; Lee, McGehee, Brown, & Reyes, 2002; Levy, Pashler, & Boer, 2006; Strayer, Drews, & Johnston, 2003). Secondary tasks, for example, rehearsing a nine-item list, phone dialing, music listening, and conversations (Bellinger, Budde, Machida, Richardson, & Berg, 2009; Lamble, et al., 1999; Salvucci, & Beltowska, 2008), all resulted in longer response times to hazards. According to Brookhuis, de Vries, and de Waard (1991), cell phone conversations while driving delayed adaptation to the speed changes of a leading vehicle by 600 msec and increased response time to the brake signal of the leading vehicle by 130 msec. The delay in brake response could have resulted from the late detection of stimuli and events. In another study, drivers talking with the passengers or over a cell phone had longer response times to pedestrian incursion events, relative to when drivers were not talking at all (Laberge, Scialfa, White, Caird, 2004).

Mental workload

Mental workload of drivers can be measured using psychophysiological measures such as heart rate variability (HRV, Brookhuis & De Waard, 1993, 2001), skin conductance (Reimer, Mehler, Coughlin, Godfrey, Tan, 2009), blink rate, and fixation duration, or using subjective rating scales (such as NASA-TLX), or by comparing secondary task performance.

Distracted drivers often exhibit or self-report higher mental workload. For example, drivers using a cell phone reported higher workload in the Rating Scale of Mental Effort (RSME), regardless of the complexity of the cell phone conversations (Rakauskas, et. al., 2004). Similarly, drivers reported higher mental workload in the NASA-TLX scale when they were using a cell phone (Alm & Nilsson, 1995). Brookhuis, de Vries, & de Waard (1991) found that mental workload measured by the average and variability of heart rate increased as the task demands increased. Drivers rated higher subjective workload and had higher heart rates when they were talking while driving (Fairclough et al., 1991; Reimer, Mehler, Coughlin, Godfrey, Tan, 2009). Skin conductance also increased dramatically when drivers performed a secondary task (Reimer, et. al., 2009).

Eye movement patterns and attentional processing

Visual scanning window size reflects the allocation of attention while driving. Appropriate allocation of attention is important for visual perception and safe driving (Recarte & Nunes, 2000).

Cognitive distractions have been consistently found to constrain the breadth of visual scanning (Chisholm et al., 2006; Recarte & Nunes, 2000, 2003; Victor, et al. 2005). For example, Reimer (2009) had drivers do an N-back task while driving in an instrumental vehicle. The horizontal gaze dispersion during the most difficult N-back task was significantly smaller than during the easier versions of the N-back task. Interestingly, the vertical eye position increased in high cognitive load conditions, which suggested that drivers adapted to the increase of cognitive load by increasing their sight distances (Reimer, 2009). Moreover, reduced eye movement dispersion is sometimes accompanied by poor steering and driving performance (Wilson, Chattington, & Marple-Horvat, 2008). Wilson and colleagues had subjects drive under anxiety . Drivers under emotional pressure made smaller distribution of eye movements, and reduced the correlation of eye movements with steering.

Cognitive distraction also reduces the sampling of peripheral information, such as the side and rear-view mirrors and the speedometer, and caused more glances to road center (He, et al., 2011; Recarte & Nunes, 2000, 2003). Recarte and Nunes (2000) studied the effect of verbal and spatial-imagery tasks on the eye scanning patterns of drivers. They reported that the spatial-imagery task reduced the inspection frequency of mirrors and speedometers, and increased the average fixation duration. Harbluk et al. (2007) asked drivers to perform a digit addition task while driving in city traffic. Drivers in their study reduced the visual inspection of the instruments and mirrors, and some drivers even abandoned visual inspection to these areas entirely.

CHAPTER 3: EXISTING HYPOTHESES OF LANE VARIABILITY REDUCTION

Cognitive distractions often reduce the lane variability (e.g. Becic et al., 2010; Briem & Hedman, 1995; Brookhuis et al. 1991; Horrey & Simons, 2007; Kubose , et. al., 2006; Liang & Lee, 2010; Reimer, 2009; however, see Just, Keller, & Cynkar (2008) and Strayer & Johnston (2001) for the findings of higher lane variability under cognitive distraction). The reduction of lane variability under cognitive distraction is interesting and counter-intuitive. Does this smaller variability indicate a performance loss or a performance gain in lane keeping? In one hand, it is natural to speculate that the smaller lane variability indicates a performance loss. As reviewed in Chapter 2, cognitive distractions cause performance decrements in many aspects of driving, for example, longer hazard response time, narrower visual scanning, more variable headway time and speed etc. Intuitively, cognitive distractions should cause impairment in lane keeping too. On the hand, the smaller lane variability is generally interpreted as a a performance gain, as it means lower risks of an unintended lane departure or collision with incoming vehicles.

Several hypotheses have emerged to explain this counter-intuitive finding of smaller lane variability under cognitive distraction, including the rigidified steering hypothesis, the attentional enhancement hypothesis, the lateral prioritization hypothesis, and the automatic steering hypothesis. This chapter explains and compares these hypotheses.

Rigidified steering hypothesis

The rigidified steering hypothesis interprets the smaller lane variability under cognitive distractions as a performance loss in lane keeping (Mehler, Reimer, Coughlin, Dusek, 2009; Reimer, 2009; Son, Reimer, Mehler, Pohlmeier, Godfrey, Orszulak, Long, Kim, Lee, & Coughlin, 2010). This hypothesis holds that when drivers engage in a cognitive distraction task, attention is shifted away from vehicle control, which induces intermittent or unresponsive steering behaviors (Cliff, 1973; Liang & Lee, 2010). Therefore, a decrease in lane variability represents an intermittent, compensatory behavior pattern to allow attention to shift to the cognitive distraction task (Reimer, 2009). To my best knowledge, no reports have yet offered a direct behavioral measure of rigidified steering. But behavioral study did found that distractions caused an intermittent throttle adjustment. In the baseline conditions, drivers produced continuing correction of throttle position. In contrast, drivers using a navigational system controlled their speed by intermittently adjusting the throttle, producing a flat lining of the throttle position. Distracted drivers alternated between periods of throttle inactivity and periods of throttle adjustment (Green, 2004; Zylstra, Tsimhoni, Green, & Mayer, 2004). Analogously, it is possible that distractions can cause intermittent and rigidified steering control too.

The rigidified steering hypothesis might be explained by several of the theories discussed above. According to the resource models, performance is positively correlated with the amount of allocated resources when performance is not constrained by available information (data-driven). When drivers engage in a cognitive distraction task, attentional resources are shifted from driving to secondary

tasks, leaving fewer resources available for the primary driving task (Reimer, 2009). Accompanying the shifts of attention, drivers might exhibit rigidified steering, longer response time to hazards and poorer situational awareness, all of which indicate poor safety margins.

According to the central bottleneck model, the central executive operates serially, processing one task at a time (Pashler, 1994). If the central executive is already engaged in a distracting task, all other cognitive processes, including steering control and speed manipulation, are forced to wait till the release of the central executive. Therefore, a cognitive distraction task can produce psychological refractory periods for steering control, which leads to more periods of steering inactivity, a rigidified steering style.

The rigidified steering hypothesis explains lane keeping performance as a result of a compensatory steering pattern following attention shift to secondary tasks. Therefore, it expects reduced cognitive processing of the driving scenes, and fewer steering corrections. The reduction of cognitive processing is confirmed in several studies. For example, the parietal lobe activation, which is associated with spatial processing, decreased by 37% when drivers concurrently did an auditory language comprehension task (Just, et al., 2008). The amplitude of the P300 wave, which reflects stimulus encoding, was reduced by 50% when drivers were talking on a cell phone compared to the drive-only conditions (Strayer & Drews, 2007).

However, contrary to the expectation of reduced steering corrections, several studies have suggested that cognitive distraction increases steering manipulation. For example, an auditory continuous memory task increased the steering reversal rate (Engström et al., 2005). In an on-road driving study, Ranney et al. (2005) found that distracted drivers had higher steering reversal rate and less steering inactivity,

compared to drive-only condition. These data suggest that the shift of attention to a distracting task does not necessarily cause rigidified or intermittent steering behaviours.

Visual enhancement hypothesis

The visual enhancement hypothesis regards the reduction of lane variability under cognitive distractions as a performance gain resulting from enhanced perception of visual information which are important for steering control. Lateral driving performance has been found to be closely related to eye scanning patterns. Wann and Swapp (2000) suggested that drivers look where they steer and steer in the direction where they look. Because of the strong linkage of attention and eye movements, changes of eye movements can have an important impact on lateral performance. For example, Engström and colleagues found that the reduction of lane variability under cognitive distractions was accompanied by increased steering activity and a narrower visual inspection window (Engström, et al. , 2005; Östlund, et al. , 2004). They argued that a gaze concentration toward the road center improved perceptual processing necessary for lateral control, which allows enhanced tracking responses , therefore, producing smaller lane variability. Attentional narrowing resulted from cognitive distractions (Harbluk, Noy, Trbovich, & Eizenman, 2007; Liang & Lee, 2010; Recarte & Nunes, 2000, 2003; Victor, et al., 2005), should thus reduce drivers' detectability of events in the visual periphery, but enhance perceptual analysis of objects in the central visual field, thereby improving steering response (Engström et al., 2005; Östlund et al., 2004). Because the retinal sensitivity reduces in the peripheral vision, fixation away from the future path region will deteriorate path

control, for example, increasing the standard deviation of lane keeping (Victor et al., 2005). Studies show that fixations towards the road center increase under cognitive distractions. Therefore, lane keeping performance may be improved when cognitive distractions narrow the visual inspection window.

The visual enhancement hypothesis is analogous to the well-known zoom-lens model of attention (Eriksen & St. James, 1986; LaBerge, 1983). The “spotlight” of attention can adjust its focus, or processing efficiency for stimuli within the focus, according to the requirement of tasks. As the area of the attentional focus decreases, the processing efficiency for the stimuli within the focus increases (Eriksen & St. James, 1986). The zoom-lens of attention suggests an inverse relationship between the size of focus and the visual processing efficiency. Because the attentional resources are limited and fixed, the smaller the focus is, the higher the visual processing ability will be in the region of the scene, as the fixed attentional resources will be distributed over a smaller area. Additionally, studies show that the distribution of focused attention in three-dimensional space is an ellipsoidal shape, with higher attentional processing ability in the forward view and at the near distance (Anderson, 1990; Anderson & Kramer, 1993). Therefore, when cognitive distractions narrow the visual scanning, the processing of information in the forward view will be enhanced, which allows better steering control to keep a straighter lane position.

Although the visual enhancement hypothesis is intuitively reasonable, it contradicts the inattention blindness theory and several empirical findings. According to inattention blindness theory, cognitive distractions often result in superficial encoding of visual information. Strayer and colleagues (2001, 2003, 2007) reported that drivers engaging in a cell phone conversation had poorer recognition memory of stimuli presented in the driving scenes, compared to driving-only

conditions. Notably, distracted drivers showed impaired memory for the dashboards even if they had fixated on them directly while driving. Distraction tasks also reduced the activation of the parietal lobe (Just, et al., 2008; Strayer & Drews, 2007), suggesting less cognitive processing of visual and spatial information, which is critical for safe driving. Moreover, in contrast to the argument of perceptual improvement, a sentence judgement task was found to impair the gap perception (Brown, Tickner, Simmonds, 1969). In a peripheral detection task of LED onsets, Ranney reported that a voice-activated secondary in-vehicle task reduced the percentage of detected targets, and increased the target-detection response time, compared to drive-only condition (Ranney et al., 2005). These studies suggest that even if gazes concentrated more narrowly under cognitive distractions, the visual processing of the fixated information was reduced, rather than improved according to the expectation of the visual enhancement hypothesis.

Additionally, if cognitive distractions did enhance visual perception and it was the visual perception enhancement that contributes to straighter lane position, in the same logic, better perceptual processing will also improve longitudinal performance, for example, reducing hazard response time to the sudden brake of a leading vehicle. However, as reviewed above, cognitive distractions delay hazard response time consistently in the literature.

Lateral prioritization hypothesis

A third explanation of the smaller lane variability under cognitive distractions is the lateral prioritization hypothesis. This hypothesis posits that the smaller lane variability under distractions indicates better lane keeping performance resulting from

strategic prioritization of steering control . Drivers may prioritize lateral lane keeping performance by any or a combination of three ways. One way is to shift resources from longitudinal vehicle control and other aspects of driving to lane keeping. The second way is to moderate the secondary task performance to prioritize lane keeping. The third way is to increase the overall vigilance level. Driving may be viewed as a satisficing process, in which performance on individual task elements is not ideal but reaches only the level necessary to produce an overall safe and relatively high performing system (Boer, 2000). The lateral prioritization hypothesis argues that during normal driving, drivers do not need to invest all available resources in lane keeping, as long as they stay in a subjectively chosen ‘safety zone’. When distracted by secondary tasks, however, drivers become increasingly concerned with their lateral performance and therefore try to protect lane keeping by investing more resources in steering control (Beede & Kass, 2006; Engström, et al., 2005). The lateral prioritization hypothesis is often explained using the resource model in existing literature (Beede & Kass, 2006; Engström, et al., 2005). The underlying assumption is that the central executive resources are divisible and sharable. Drivers can try to achieve their satisfactory lateral performance by shifting resources between lateral and longitudinal aspects of driving, and secondary tasks. For example, if drivers shift resources from longitudinal speed manipulation to lateral control, lane keeping performance will increase, and longitudinal performance will decrease. Please note that this resources-sharing strategy will not necessarily lead to inactivity in speed manipulation (This only happens if no resources are left for longitudinal speed manipulation and speed manipulation is data-limited.).

The lateral prioritization hypothesis can also be explained using the central bottleneck model. Drivers can prioritize lateral performance by time-sharing the

limited serial central processor among lateral, longitudinal and other aspects of driving, and secondary tasks. If the needs of steering or speed adjustment happen at the same time or adjacently, in which no perfect time-sharing is possible, drivers have to choose to finish one task first. If drivers choose to prioritize lateral performance, speed manipulation has to be delayed until the central processor disengages from steering control. Therefore, according to the central bottleneck theory, lateral prioritization will lead to more inactivity in speed manipulation.

Liang & Lee (2010) hypothesized that two factors contributing to reduced lane variability. One factor is that drivers adopt a cautious strategy when perceiving higher risks under cognitive distractions. Therefore, distracted drivers prioritize lateral lane keeping to maintain a better safety margin. The other factor is that gaze concentration improves tracking response thanks to enhanced visual processing in the forward view. In their study, Liang & Lee (2010) found that gaze concentration explained only 5 percent variance of the lane position variation. Therefore, they attributed the observed reduction of lane variability primarily to lateral prioritization.

The lateral prioritization hypothesis is also supported by several other studies (Beede & Kass, 2006; Seppelt & Wickens, 2003; Victor et al., 2005). For examples, Beede and Kass (2006) had drivers drive while responding to a signal detection task or a simulated cell phone conversation task. Drivers not engaged in either secondary tasks had the most frequent lane changes, compared to distraction conditions. When drivers concurrently responding to a signal detection task or a conversation task, they simplified their driving behaviours by reducing lane changes and speed adjustments. Based on these findings, Beede and Kass suggested that distracted drivers protected lane keeping performance by shedding peripheral tasks to maintain a straighter lane position. Victor et al. (2005) found that drivers engaged in an auditory task looked

more concentrated at the road center, reducing glances to the road scene periphery (e.g. traffic signs) and inside the vehicle (e.g. the speedometer). They proposed that drivers prioritized the visual guidance of path-control task, over event detection and planning task.

Automatic steering hypothesis

The automatic steering hypothesis regards the smaller lane variability under cognitive distractions as a performance gain in lane-keeping (Kubose, et al., 2006). The automatic steering hypothesis suggests that more attention devoted to automatic behaviors is harmful for performance (Beilock & Carr, 2001; Beilock, Carr, MacMahon, & Starkes, 2002). Lane-keeping is an automatic behavior for experienced drivers. When a cognitive distraction task takes attention away from the automatic steering manipulation, the interference from conscious control is reduced, therefore producing better lane-keeping performance (Kubose, et al., 2006).

Hypothesis summary

To summarize, the four hypotheses differ in how cognitive distraction influences the allocation of attention and the performance implication of smaller lane variability (See Table 1). The rigidified steering hypothesis and the automatic steering hypothesis suggest that cognitive distraction reduces attention devoted to lane keeping. In contrast, the lateral prioritization hypothesis and the visual enhancement hypothesis suggest that cognitive distraction increases attention to lane-keeping. The rigidified steering hypothesis regards the smaller lane variability as a performance

loss, while all three other hypotheses, the automatic steering hypothesis, the lateral prioritization hypothesis, and the visual enhancement hypothesis, regard the smaller lane variability as a performance gain in lane-keeping.

Table 1. Comparisons of the predictions of the four hypotheses about the effect of cognitive distractions on lane-keeping performance.

	Lateral performance loss	Lateral performance gain
Decrease attention to lane keeping	Rigidified steering	Automatic steering
Increase attention to lane keeping		Lateral prioritization & Visual enhancement

Research has yet to explain why lane variability often decreases when drivers are distracted cognitively, and whether this effect indicates a performance gain or a performance loss in lane keeping, and what's the underlying mechanisms for lane-keeping performance change. This dissertation project explores these important questions using three experiments.

EXPERIMENT 1: LANE KEEPING PERFORMANCE WITH A CRUISE CONTROL SYSTEM

As reviewed in Chapter 3, researchers have yet to agree on the performance implications of smaller lane variability under cognitive distraction. To answer the question of whether the smaller lane variability under cognitive distractions indicates a performance gain or a performance loss in lane keeping, we have to measure lane keeping performance in alternative ways.

Experiment 1 was inspired by the spectral coherence analysis used in studies of car-following performance (for example, Brookhuis et al., 1994; Dastrup, Lees, Dawson, Lee, & Rizzo, 2009). Spectral coherence analysis takes the velocities of the leading vehicle and subject vehicle as input variables, and generates a coherence value measuring the strength of the coupling between the velocities of leading and subject vehicles. Higher coherence values indicate that subject drivers follow the velocity changes of the leading vehicle more closely, implying better car-following performance.

Experiment 1 used the spectral coherence analysis to measure lane-keeping performance. In analogy to the velocity variations of the leading vehicle in the car-following paradigm, Experiment 1 implemented lateral wind gusts which changes strengths and directions continuously as determined by the sum of three sinusoid waves. The spectral coherence analysis accepted the lateral wind strengths and steering wheel position as input variables, and generated a coherence value, measuring drivers' ability to adjust steering wheel position in response to lateral wind. Higher coherence values in this task indicate better responses to the change of the

lateral wind, therefore, better lane-keeping performance. If the smaller lane variability under cognitive distractions reflects a performance gain in lane-keeping, it should be accompanied by higher coherence values between steering wheel position and lateral wind strength; in contrast, if it reflects a performance loss, it should be accompanied by smaller coherence values.

The rigidified steering hypothesis assumes attention shifts away from lateral control during cognitive distraction, and it therefore predicts poorer lane-keeping performance, that is, lower coherence between steering wheel position and lateral wind strength. The visual enhancement hypothesis proposes that cognitive distractions improve perceptual processing in the central forward view, leading to better steering control. Therefore, the visual enhancement hypothesis expects higher coherence under cognitive distraction. The lateral prioritization hypothesis argues that drivers shift more resources to lane-keeping to compensate for the higher driving risks under cognitive distraction. With more resources, the lateral prioritization hypothesis would expect better lane-keeping, including higher coherence. The automatic steering hypothesis assumes that steering performance will be improved when distraction tasks take attention away from the automatic steering control. Therefore, this hypothesis also predicts higher coherence under distraction.

Method

Subjects

Eighteen subjects (12 female and 6 male, mean age = 23.8 years, SD = 4.6 years) were recruited from the local university community. All subjects had held a valid driver's license for at least three years (M = 7.64 years, SD = 4.42 years); the mean self-reported number of miles driven annually was 7139 miles (SD = 7486 miles). All subjects had normal or corrected-to-normal visual acuity, and none of them reported any experience of motion sickness. Subjects were paid eight dollars per hour for their participation.

Apparatus and Stimuli

Data were collected in a fully immersive fixed-base driving simulator, consisting of a 1998 Saturn SL positioned in a wrap-around environment with 135° forward and rear visual fields. Eight Epson Powerlite 703C projectors (1024 × 768 pixels of resolution) projected the driving scenes onto eight separate screens. Road and traffic information was visible through the interior and exterior rear view mirrors.

The simulator control dynamics were modeled after a typical four-door Saturn sedan. Drive Safety's Vection Simulation Software™ Version 1.6.1 (DriveSafety, 2004) displayed the virtual driving scenarios. The driving environments and traffic scenarios were created using HyperDrive Authoring Suite™ Version 1.6.1. The wind turbulence, button and brake press events, and other environmental features were coordinated through Tcl scripts. Measures of real-time driving performance, including time stamp, velocity, steering wheel position, etc., were sampled at 60 Hz and auto-recorded during the execution of a simulated drive for later analysis.

Driving Scenario

The simulated driving environment consisted of a straight highway, which is 16000 meters long with three lanes of traffic in each direction. Each lane was 3.6 meters wide. The two directions of the highway were divided by bushes and trees in the middle. There was no traffic except the subject's vehicle.

Heavy lateral wind began after the subjects had driven exactly 350 meters from the starting point of each trial. Wind velocity followed a pattern created by the sum of three sine waves, a manipulation inspired by Andersen and Ni (2005), who manipulated the leading vehicle velocity using a combination of three sine waves in a car following paradigm. The summation of three sinusoids was used to make the change of lateral wind difficult to predict. The amplitudes of the three sinusoids were 1000, 2000, and 1500 Newtons respectively, and their temporal frequencies were 0.117, 0.083, and 0.033 Hz. The phases of the first two sinusoids were assigned a random value from 0 to 1. The phase of the third sinusoid was set to the value that made the initial strength of wind zero. The random phase shift values made the lateral wind pattern differ from subject to subject. The directions of wind gusts varied between leftward and rightward, as determined by the sign of the summed sinusoids.

Loading Task

An auditory loading task was used to manipulate drivers' level of cognitive distraction. Stimuli were audio recordings of the spoken digits one to nine, created using the Text-to-Speech web service by AT&T Labs Natural Voices[®]. The duration of digits ranged from 0.58 second to 0.91 second, with a mean of 0.68 second. Recordings were grouped to create one-hundred sets of four digits. The digits in each

set were randomly sampled from one to nine without replacement, and were in random order under the constraint that they were not monotonically increasing. Digits within each set were played at a time interval of 17ms. The auditory presentation time was 2.77 seconds on average, with a range of 2.48 seconds to 3.10 seconds. The time interval between sets was randomly sampled from a uniform distribution with a range of five to ten seconds.

In the drive-only condition, the subjects only need to drive, without any auditory stimuli played. In the low-load dual-task condition, subjects performed a shadowing task that required them to repeat the four digits they had just heard in the same order they had been spoken. In the high load dual-task condition, subjects were required to report the four digits back in ascending order. The high load dual-task condition thus imposed working memory demands (re-ordering the digits) that the low-load condition did not.

Procedure

Upon arriving at the lab, subjects completed an informed consent form, a screening questionnaire inquiring about their driving experience and propensity for simulator sickness, and a demographic questionnaire. Subjects with at least four years of driving experience, normal or corrected-to-normal visual acuity, and no history of simulator sickness were allowed to participate in this experiment.

The subjects' primary task was to drive while maintaining an appropriate lane position. To let subjects focus their attention on lateral vehicle control, a cruise control system was implemented to assist velocity maintenance. At the beginning of each drive, the subject accelerated the vehicle's speed to 45MPH. The cruise control

system then took over the speed control and kept a constant speed of 45MPH without driver's intervention. Drivers could not change the speed of vehicle thereafter.

After receiving a brief description of the experimental task, subjects completed a practice drive to get familiar with the simulator and the driving environment. They were free to ask questions during the practice drive. The practice drive included all three task conditions, in the order of drive-only, drive-shadowing, and drive-ordering, each lasting about three minutes. The experimental blocks began after subjects reported that they fully understood the tasks and were comfortable driving in the simulator. All subjects completed three drives, one in each of the task conditions. The order of the three drives was counterbalanced across subjects. Each drive lasted approximately ten minutes, and subjects were given a chance to rest between blocks.

Dependent Variables

Lane-keeping performance was calibrated using the mean and standard deviation of lane position, steering reversal rate, and spectral coherence analysis of steering wheel position and lateral wind strength.

Lane position was measured as deviation in meters from the center of the subject's lane. Positive values indicate positions to the right of lane center, and negative values indicate positions to the left. The lane variability was measured using both the standard deviation of lane position (SDLP) and the root mean square error (RMSE) (Regan, Lee, Young, 2008; Marcotte, et al., 2003).

The *steering reversal rate* measured drivers' efforts in adjusting the steering wheel's direction to maintain lane position. A steering reversal was defined as a change in steering direction with a velocity of more than 3.0 deg/s (Theeuwes, Alferdinck, & Perel, 2002; Groot, Winter, Garcia, Mulder, & Wieringa, 2011).

Spectral coherence analysis examined the relationship between steering wheel position and lateral wind velocity. To maintain steady lane position, drivers need to steer in the direction opposite that of the lateral wind. Therefore, the steering wheel position was reversed for analysis. Both steering wheel position and lateral wind strength were standardized before being submitted to the spectral coherence analysis. A Tukey-Hanning window was used to smooth the data (Janacek, 2008). Spectral coherence analysis generates three measurements: coherence, delay, and gain. *Coherence* measured the extent to which the steering wheel position covaried with the strength and direction of the lateral wind. Coherence values can range from zero to one, with higher values indicating a better match of steering wheel and lateral wind. *Delay* measured how quickly drivers adjusted the steering wheel in response to lateral wind changes. *Gain* measured the amplification factors of steering wheel adjustment relative to lateral wind strength change. A gain value larger than one indicates overshoot of steering wheel adjustment, while a gain value smaller than one indicates undershoot.

Results

For statistical analysis, dependent measures were submitted to one-way within-subject analyses of variance with three levels of task condition: single-task driving (drive-only), dual-task driving while shadowing spoken digits (drive-shadowing), and driving while mentally re-ordering spoken digits (drive-ordering). Subjects' lateral vehicle control performance was measured by the standard deviation of lane position, the steering reversal rate, and the spectral measures of the relationship between steering wheel position and lateral wind velocity, as described below.

Lane-Keeping

The average lane position was 0.12m for drive-ordering conditions, 0.13m for drive-shadowing conditions and 0.10m for drive-only condition. The main effect of cognitive load on the average lane position was not significant, $F(2, 34) = 1.19, p = .32$.

The analyses of SDLP and RMSE yielded similar results. Therefore, only the results of the SDLP analysis are reported here. Figure 1 presents mean SDLP as a function of task condition. Subjects showed less lane variability when driving under high cognitive load, $F(2, 34) = 4.21, p = .02$. Pair-wise comparisons using Tukey's LSD procedure demonstrated that lane variability in the drive-only conditions ($M = .51$) was marginally larger than in the drive-shadowing conditions ($M = .45, t(17) = 1.95, p = .07$) and reliably larger than in the drive-ordering conditions ($M = .44, t(17) = 2.34, p = .03$).

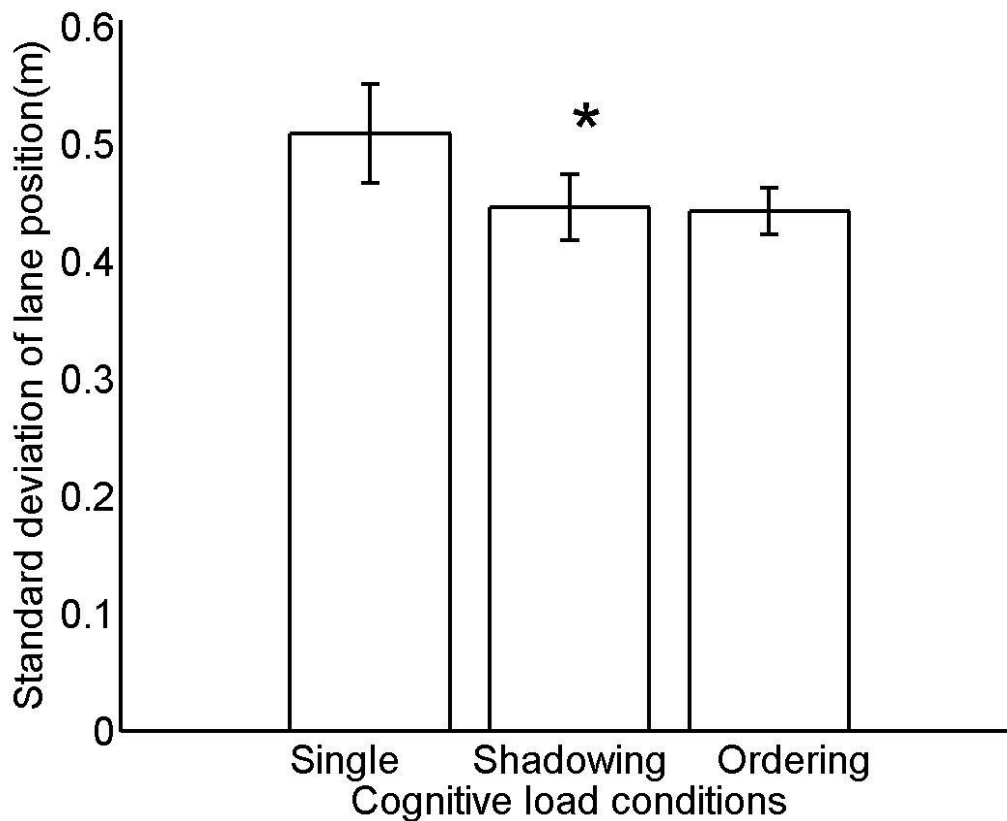


Figure 1. The average standard deviation of lane position under different cognitive load conditions. Error bars in all figures indicate within-subject standard errors (Loftus & Masson, 1994).

Steering Reversal Rate

An analysis of steering reversal rate assessed drivers' efforts in adjusting the steering wheel in order to maintain lane position. Figure 2 depicts the average steering reversal rates. Statistical analysis showed a main effect of cognitive load, $F(2, 34) = 4.51, p = .02$, with pair-wise comparisons indicating that the steering reversal rate was higher in the drive-ordering conditions ($M = 0.90$ Hz) than in the drive-only conditions ($M = 0.66$ Hz), $t(17) = 2.73, p = .01$. The steering reversal rate was numerically higher in the drive-shadowing conditions ($M = 0.86$ Hz) than drive-only conditions, but this difference was not significant, $t(17) = 1.80, p = .09$.

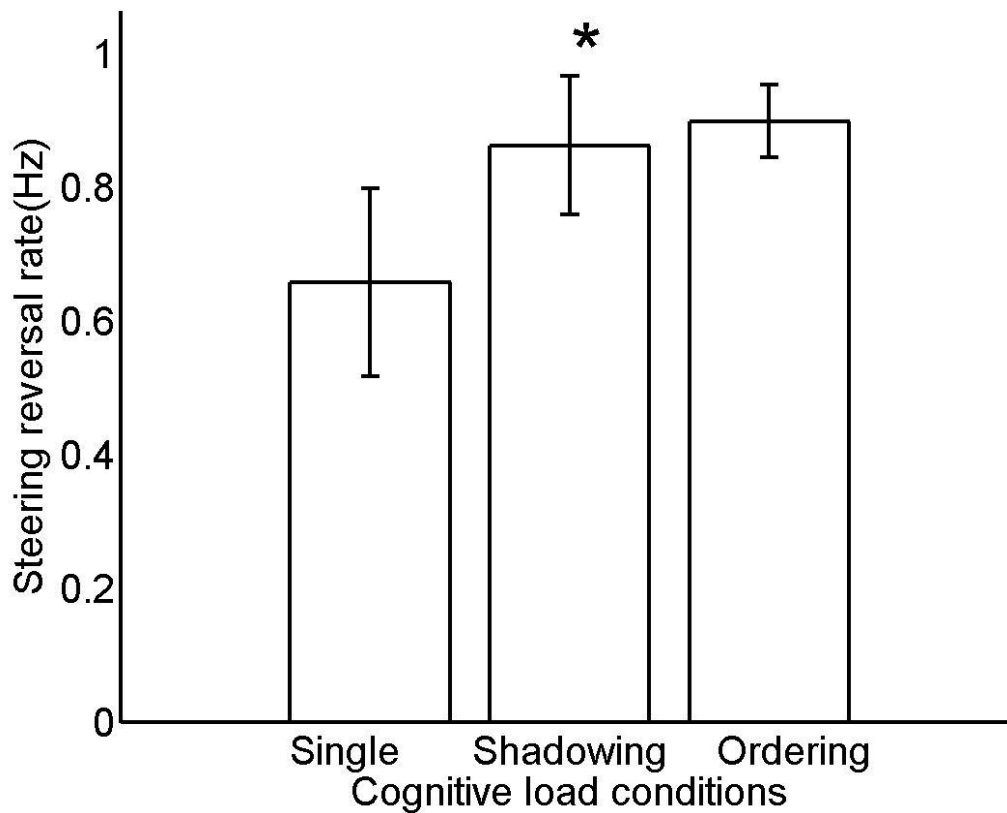


Figure 2. The average steering reversal rate under different cognitive load conditions.

Spectral Coherence Analysis

Coherence, delay and gain values obtained from special coherence analysis were submitted to separate two-way ANOVAs with cognitive load and frequencies of the three sinusoids which comprised the lateral wind as within-subject factors.

Figure 3 depicts the average coherence values for all three sinusoidal wind components, as a function of experimental condition. Not surprisingly, coherence was lower on average for the higher frequency components of the wind than for low-frequency components, $F(2, 34) = 1121.43, p < .001$. Of more interest, coherence increased reliably as cognitive load increased across task conditions, $F(2, 34) = 4.78, p = .02$. The main effects were qualified by a significant interaction, $F(4, 68) = 3.05,$

$p = .02$. Simple effect tests further explored the influence of load condition separately for each level of wind component frequencies. For the 0.033Hz component, the simple effect of task condition was not significant, $F(2, 34) = 2.26, p = .12$. However, simple effects for the 0.083Hz and 0.117Hz components were both significant, $F(2, 34) = 3.82, p = .03$ and $F(2, 34) = 3.89, p = .03$, respectively. For the 0.083Hz component, coherence was higher in the driving-ordering conditions ($M = 0.76$) than in the drive-only conditions ($M = 0.71$), $t(17) = 2.27, p = .036$, but did not differ significantly between the drive-only conditions and the drive-shadowing conditions ($M = 0.76$), $t(17) = 1.69, p = .11$. For the 0.117Hz component, similarly, the drive-ordering conditions ($M = 0.08$) produced higher coherence than the drive-only conditions ($M = 0.05$), $t(17) = 2.38, p = .03$, while the coherence was statistically similar across the drive-shadowing ($M = 0.05$) and drive-only ($M = 0.05$) conditions, $t(17) = .57, p = .57$.

Analysis of delay and gain both showed reliable main effects of wind frequency component, $ps < .001$, but no reliable main effect of cognitive load and no interaction, all $ps > .15$.

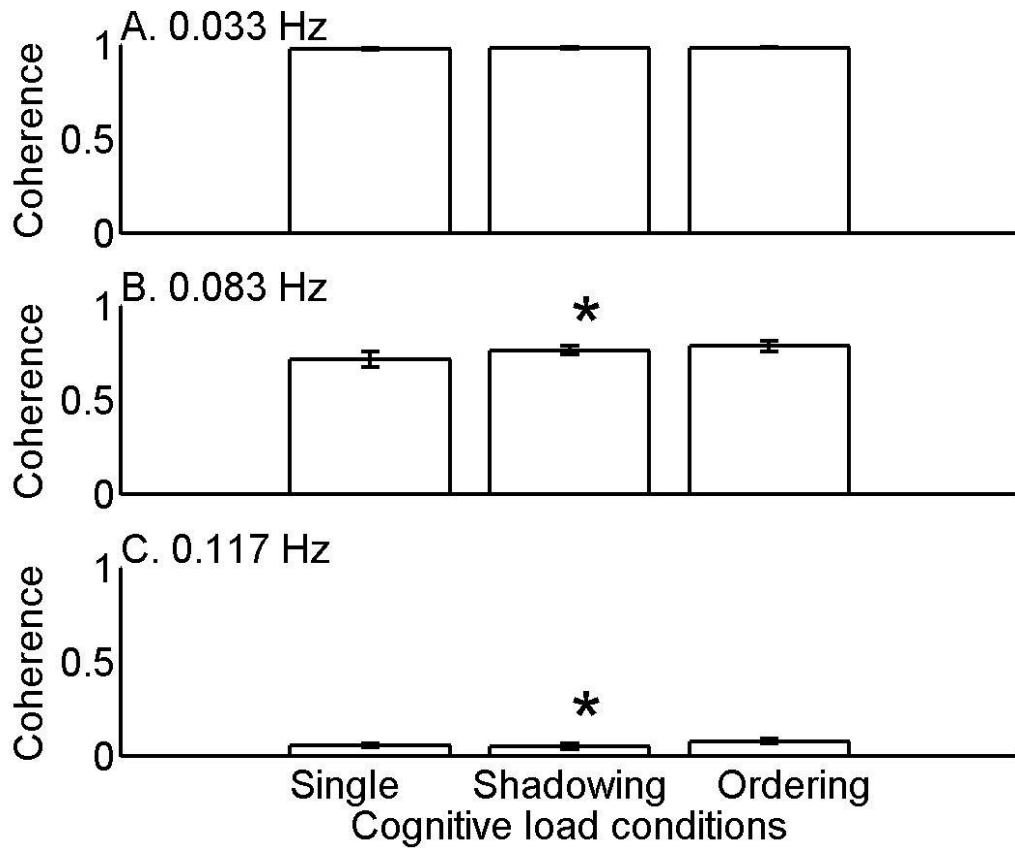


Figure 3. The average coherence values of steering wheel position and lateral wind strength under different cognitive load condition. (A. Coherence for 0.033 Hz component; B. Coherence for 0.083 Hz component; C. Coherence for 0.117 Hz component)

Discussion

Consistent with the findings of earlier research (Brookhuis, et al., 1991; Engström, et. al., 2005; Jamson & Merat, 2005; Östlund, et al., 2004; Rakauskas, et al., 2004; Reimer, 2009), Experiment 1 showed that high cognitive load reduced the variability of lateral lane positions, an effect that was apparently produced by drivers' more active steering behavior (cf., Östlund, et al., 2004). More tellingly, changes in steering behavior manifest themselves as an increase in coherence values between wind velocity and steering wheel position. This effect argues against the possibility that the reduced variability of lane position was the result of a rigidified steering behavior, an hypothesis which predicts a decrease in coherence between wind strength and steering wheel position.

Why should cognitive load have improved drivers' lateral vehicle control? As reviewed in Chapter 3, researchers have offered various hypotheses. One possibility is that drivers under high cognitive load prioritize lateral vehicle control over peripheral driving tasks in an effort to protect their lane-keeping performance (Beede & Kass, 2006; Östlund, et al., 2004). This suggestion is consistent with earlier studies indicating that task prioritization can indeed modulate lane-keeping performance (Horrey, Wickens, & Consalus, 2006). Alternatively, improvements in lateral control under cognitive load might be a felicitous result of the gaze concentration that occurs under cognitive distractions (e.g., He, et al., 2011; Recarte & Nunes, 2000, 2003). By causing visual attention to focus more narrowly in this way, cognitive distractions may incidentally allow drivers the ability to better monitor their lane-keeping performance and more quickly respond to deviations from the preferred lane position (Engström et. al., 2005; Östlund et. al., 2004). Alternatively, as suggested by the

automatic steering hypothesis, drivers might achieve better lane-keeping performance by reducing attention to lateral control, which allows less interference of the automatic steering manipulations from conscious control (Kubose et al., 2006). Further research will be necessary to disentangle these possibilities, and explore the mechanisms how drivers achieve better lane-keeping performance under cognitive distractions.

Experiment 1 is limited in its use of a cruise control system to assist drivers' speed maintenance. With a cruise control system, drivers do not need to spend as much efforts in speed maintenance as they should do normally. With such assistance, drivers can put more efforts in lane-keeping, which probably make the prioritization of lane-keeping possible. Future studies need to validate the findings in Experiment 1 in more driving scenarios, for example, by incorporating a speed maintenance task or a car-following task.

Experiment 1 is also limited in that by itself it provided insufficient information to distinguish between the three hypotheses that predict better lane-keeping performance under cognitive distraction. For example, the visual enhancement hypothesis explains smaller lane variability as a by-product of a gaze concentration effect. Visual scanning data would therefore offer useful information to test the visual enhancement hypothesis. The lateral prioritization hypothesis predicts better lane-keeping performance will be accompanied by costs to longitudinal speed maintenance. Experiment 1, however, did not measure speed maintenance performance. Further studies should consider tracking visual scanning patterns while driving using an eye-tracking system to test the visual enhancement hypothesis. Further studies may also consider incorporating a longitudinal task to test the lateral prioritization hypothesis.

EXPERIMENT 2: LANE KEEPING AND SPEED MAINTENANCE PERFORMANCE

Experiment 1 compared the lane keeping performance with and without cognitive distraction. Results showed that cognitive distraction reduced lane variability, increased the coherence of steering wheel position and lateral wind strength, and increased the steering reversal rate. Based on these findings, we speculated that the reduction of lane variability when drivers are cognitively distracted is not an indicator of performance loss, but a performance improvement (He & McCarley, 2011). A decisive conclusion requires further evidence, though. In our previous study, drivers were assisted with a cruise control system, which helped them maintain a constant speed of 45 MPH, allowing drivers to focus on lane keeping and secondary tasks. The over-emphasis of lane keeping might have biased our findings. Therefore, it is important to validate previous findings without a cruise control system. Moreover, we speculated that cognitively distracted drivers might improve their lane keeping performance either by enhancing attentional perception in the foveal view or by strategically prioritization of lateral lane keeping. However, previous experiment did not provide much empirical evidence for the visual enhancement hypothesis and lateral prioritization hypothesis.

Experiment 2 aimed to replicate and extend the findings in Experiment 1, further exploring the mechanisms by which drivers improved their lane-keeping performance. Eye movement data were collected to test visual enhancement hypothesis. A speed maintenance task was introduced to test the possibility of strategically prioritization of lateral performance over longitudinal performance.

Method

Subjects

Eighteen subjects (10 female and 8 male) were recruited through online advertisement and campus posters. The ages of the subjects ranged from 20 to 44 years, with a mean of 27.6 years and standard deviation of 6.2 years. The average self-reported annual mileage of the subjects was 8589 miles. All subjects had held a driver's license for at least four years; mean time since licensure was 10.3 years. All subjects had normal or corrected-to-normal visual acuity. Subjects were each paid \$8 per hour for a one-hour experiment.

Apparatus and Stimuli

Data were collected using the same driving simulator as what was used in Experiment 1.

Eye and head movements were collected with a Smart Eye Pro 5.5 system (SmartEye AB, 2004). This system consisted of three Sony XC HR50 monochrome cameras which were mounted on the dashboard of the car and two IR-illuminators attached to the two side cameras. The cameras fed information into software which located predefined characteristic points on the subject's face, and in this way determined where the subject's foveas were pointing. Data were analyzed with customized software written in Python and Matlab.

Driving Scenario

The simulated driving environment comprised a straight highway 16000 meters long with three lanes of traffic in each direction. Each lane was 3.6 meters wide. The two directions of the highway were divided by bushes and trees in the middle. There

was no traffic except the subject's vehicle. Thirteen speed limit signs of 45 MPH were posted along the right side of the road. The distance between adjacent speed limit signs was randomly sampled from a uniform distribution with a range from 500 to 1000 meters.

Heavy lateral wind began after the subjects had driven exactly 350 meters from the starting point of each trial. Wind velocity followed a pattern created from the sum of three sine waves, a manipulation inspired by Andersen & Ni (2005), who manipulated lead vehicle velocity using a combination of three sine waves in a car following task. The summation of three sinusoids was used to make the change of lateral wind difficult to predict. The amplitudes of the three sinusoids were 1000, 2000, and 1500 Newtons respectively, and their temporal frequencies were 0.117, 0.083, and 0.033 Hz. The phases of the first two sinusoids were assigned a random value from 0 to 1. The phase of the third sinusoid was set to the value that made the initial strength of wind zero. The random phase shift values made the lateral wind pattern differ from subject to subject. The directions of wind gusts varied between leftward and rightward, as determined by the sign of the summed sinusoids.

Loading Task

An auditory task manipulated drivers' level of cognitive load. The auditory materials were the same as that used in Experiment 1. Because Experiment 1 did not show much differences for the effects of a digit-ordering task and a digit-shadowing task, the digit-shadowing task was not used again in Experiment 2. In the low load condition, no auditory stimuli were played, and drivers performed only the driving task. In the high load condition, subjects were required to report back the four digits

in each set in ascending order. The high load condition thus imposed working memory demands (re-ordering the digits) that the low load condition did not.

Procedure

Upon arriving at the lab, subjects completed an informed consent form, a screening questionnaire inquiring about their driving experience and propensity for simulator sickness, and a demographic questionnaire. Subjects with at least four years of driving experience, normal or corrected-to-normal visual acuity, and no history of simulator sickness were allowed to participate in the experiment.

The subjects' primary task was to drive while maintaining an appropriate lane position and speed. Subjects were instructed to keep a steady lane position in the center lane and to drive at a speed of 45 MPH. After receiving a brief description of the experimental task, subjects completed a practice drive to familiarize themselves with the simulator and the driving scenario. They were free to ask questions during the practice drive. In the practice drive, subjects first drove in the low load (drive-only) condition then in the high load (dual-task) condition, with each condition lasting about three minutes. The experimental blocks began after subjects reported that they fully understood the task and were comfortable driving in the simulator. All subjects completed four drives, two in each task condition. The order of the four drives was counter-balanced across subjects in an ABAB design. Each drive lasted approximately ten minutes, and subjects were given a chance to rest between blocks.

Dependent Variables

Lane-keeping performance was calibrated using the average and standard deviation of lane position, steering reversal rate, steering holds (inactivity), and the

coherence value of steer wheel position and lateral wind strength. *Lane position* was measured as deviation in meters from the center of the subject's lane. *Steering reversal rate* measured drivers' efforts in adjusting the steering wheel's direction in order to maintain lane position. A steering reversal was defined as a change in steering direction with a velocity of more than 3.0 deg/s (Theeuwes, et al., 2002; Groot, et al., 2011). *Steering holds* were defined as periods of no steering activities, i.e., no change of steering wheel position, longer than 400 ms consecutively (Ranney, et al., 2005). The coherence value of steer wheel position and lateral wind strength measures the coupling of steer position and wind strength, with larger value indicating better steering adjustment in response to lateral wind. The coherence value was computed in the same way as Experiment 1.

Speed maintenance performance was assessed using the standard deviation of speed, speed manipulation frequency, and speed manipulation holds. Speed manipulation frequency and speed manipulation holds was defined in analogous to the steering reversal rate and steering holds frequency used for analysis of lateral control behavior (Ranney et al., 2005). The speed manipulation input was defined as the normalized accelerator input (0-1) value minus the normalized brake input value (0-1). The speed manipulation input ranged from -1 to 1, where -1 meant that the brake pedal was at its maximum depression, 0 meant that neither the accelerator nor the brake was depressed, and 1 meant that the accelerator pedal was at its maximum depression. The speed manipulation input was comparable to steering position in lateral lane-keeping. In analogy to the definition of steering reversal and steering holds, two variables were calculated based on the speed manipulation input. If the speed manipulation input changed value greater than three standard deviations in 83ms (or 5 consecutive data samples), this was treated as a *speed manipulation*. If the speed

manipulation input did not change for more than 400ms consecutively, it was treated as a *speed manipulation hold* (cf., Ranney et al., 2005).

Eye movement patterns were calibrated using the dispersion of fixations, which was defined as the standard deviation of horizontal and vertical fixation location.

Hypotheses

The rigidified steering hypothesis regards smaller lane variability under cognitive distractions as a performance loss. It predicts less frequent steering reversals and lower coherence between steering wheel position and lateral wind strength in the high load condition.

The visual enhancement hypothesis proposes that a concentration of gazes in the forward view improves the perceptual processing necessary for lateral control, therefore allowing enhanced tracking responses, producing smaller lane variability (Engström, et al., 2005; Östlund, et al., 2004). It predicts a narrowing of horizontal fixation dispersion under cognitive distraction, smaller lane variability, larger coherence between steering wheel position and lateral wind strength, and more frequent steering reversal rate. Enhanced visual processing in the forward view may also lead to better longitudinal performance.

The lateral prioritization hypothesis proposes that drivers shift attentional resources to lateral control in order to protect their lane-keeping performance (Beede & Kass, 2006; Engström et al., 2005) when under cognitive distraction. It predicts that cognitive load will reduce lane variability, increase the coherence between steering wheel position and lateral wind strength, increase the steering reversal rate, and compromise longitudinal performance.

The automatic steering hypothesis proposes that attention is shifted away from the automatic behaviors of steering under cognitive distractions, which allows less conscious interference of steering control (Kubose et al., 2006). Therefore, the automatic steering hypothesis expects that cognitive load will produce smaller lane variability, increase the coherence between steering wheel position and lateral wind strength, increase the steering reversal rate.

Results

Lane-Keeping

Cognitive load did not produce any significant changes in the average lane position, $t(17) = .43$, $p = .67$ ($M = 0.04\text{m}$, $SE = 0.02$ under dual-task conditions, and $M = 0.05\text{m}$, $SE = 0.02$ under drive-only conditions).

Lane variability can be measured using either the standard deviation of lane position (SDLP) or the root mean square error (RMSE) of lane position. Analysis of the SDLP and RMSE produced similar results. Therefore, only the data of the SDLP was reported here. The SDLP under dual-task conditions ($M = 0.44\text{m}$, $SE = 0.03$) was significantly smaller than that under drive-only conditions ($M = 0.47\text{m}$, $SE = 0.04$), $t(17) = 2.74$, $p = .01$.

Steering Control

Steering control behavior was further analyzed to explain the changes in lane-keeping performance. The steering reversal rate was significantly higher under dual-task conditions ($M = 1.31\text{ Hz}$, $SE = 0.08$) than drive-only conditions ($M = 1.17\text{ Hz}$, $SE = 0.06$), $t(17) = 4.80$, $p < .001$. The frequency of steering holds was smaller under

dual-task conditions ($M = 0.283$ Hz, $SE = 0.02$), compared to drive-only conditions ($M = 0.317$ Hz, $SE = 0.02$), $t(17) = 4.733$, $p < .001$.

Further analysis of the distribution of the steering reversal time interval was used to compare the four hypotheses. The rigidified steering hypothesis claims that drivers only steer intermittently when they were cognitively distracted. This intermittent steering behaviors would produce significant time gaps between steering reversals, which would reflect in larger numbers of long steering reversal intervals. The lateral prioritization hypothesis posits more effort in lane-keeping and higher steering reversal rate, and therefore, predicts that the mean steering reversal interval would be reduced.

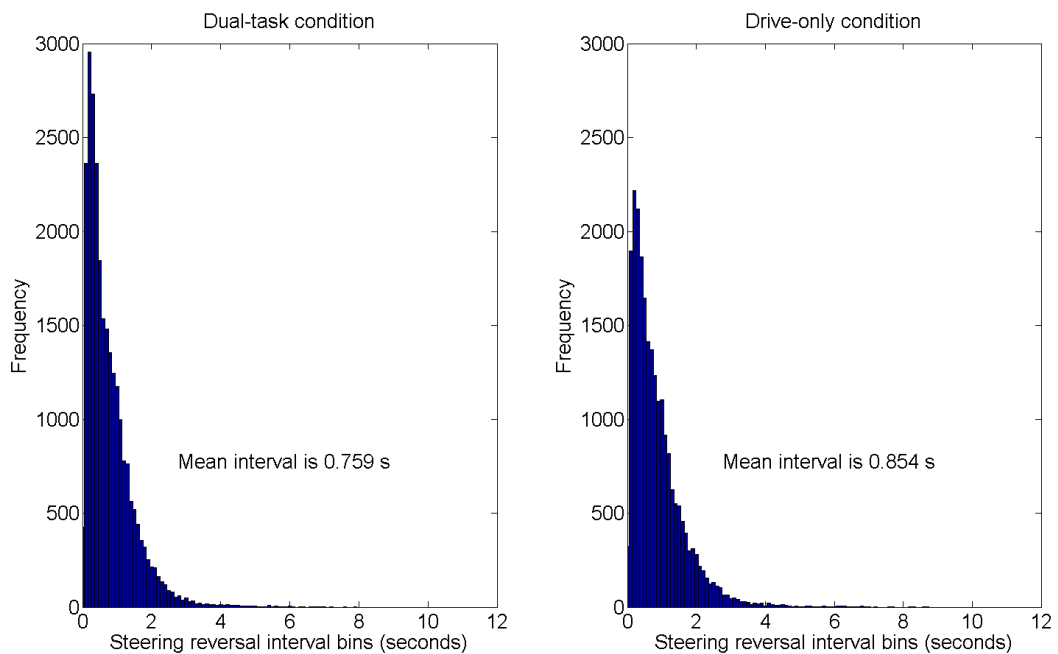


Figure 4. Distribution of steering reversal intervals under dual-task and drive-only conditions.

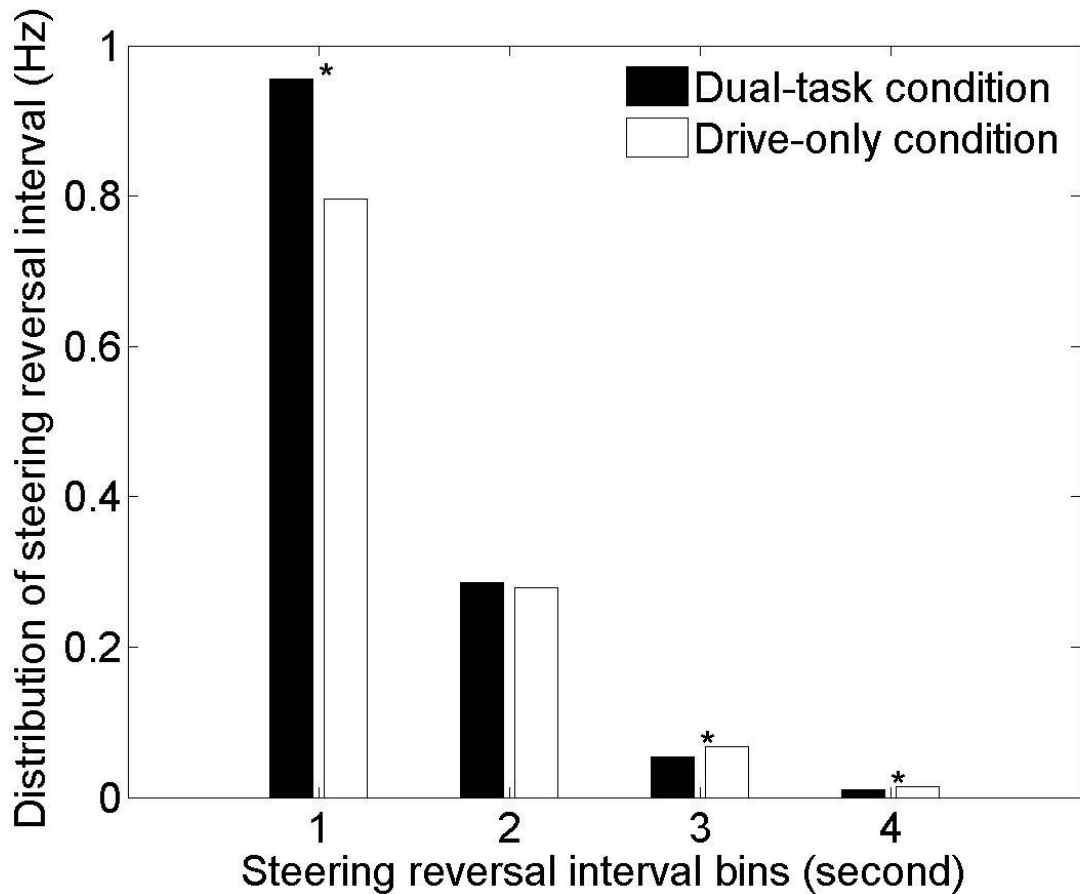


Figure 5. Comparisons of the steering reversal interval each ten time bins under dual-task and drive-only conditions (A star symbol indicates significant difference)

Figure 4 shows the distribution of steering reversal intervals under dual-task and drive-only conditions. Most the steering reversal intervals were below 4 seconds. Therefore, for statistical analysis, the steering reversal intervals were categorized into four bins of one second each. Figure 5 shows the frequency of steering reversal intervals in each time bins. The frequency of steering reversal intervals in each bin was treated as the dependent variable, and submitted to an ANOVA with time bin and cognitive load as within-subject factors. The main effects of both cognitive load and time bin were significantly, $F(1,17) = 22.71, p < 0.001$ and $F(3,51) = 101.416, p <$

0.001, respectively. Analysis also showed a significant interaction, $F(3,51) = 18.86$, $p < 0.001$.

Simple main effect analysis show that the frequency of steering reversal intervals was higher in the dual-task conditions ($M = 0.96$ Hz) than the drive-only conditions ($M = 0.80$ Hz), for the one second bin, $t(17) = 4.48$, $p < 0.001$. For the two second bin, the frequency of steering reversal intervals was numerically larger in the dual-task conditions ($M = 0.29$ Hz) than the drive-only conditions ($M = 0.28$ Hz), but not significant, $t(17) = 1.17$, $p = 0.26$. For the three second bin, the frequency of steering reversal intervals was smaller in dual-task conditions ($M = 0.05$ Hz) compared to the drive-only conditions ($M = 0.07$ Hz), $t(17) = 16.48$, $p < 0.001$. For the four second bin, the frequency of steering reversal intervals was smaller in dual-task conditions ($M = 0.0099$ Hz) compared to the drive-only conditions ($M = 0.0142$ Hz), $t(17) = 3.58$, $p = 0.002$. Data thus show that the frequency of steering reversal intervals below two seconds was increased by cognitive distraction while the frequency of intervals longer than two seconds was reduced. There were no signs of a distraction-induced increase in long periods of steering reversal intervals of the kind predicted by the rigidified steering hypothesis. Data instead support the lateral prioritization hypothesis, which predicts a decrease of the steering reversal intervals in the dual-task conditions.

Spectral Coherence Analysis

Spectral coherence analysis was used to measure drivers' steering response to lateral wind change. The coherence, delay and gain values were submitted to three separate two-way ANOVAs, with level of cognitive load (low vs. high) and the

frequencies of the three sinusoidal components of the lateral wind (0.117 vs. 0.083 vs. 0.033 Hz) as within-subject factors.

Figure 6 depicts the average coherence values for all three sinusoidal wind components as a function of cognitive load condition. Coherence was lower on average for the higher frequency components of the wind than for the lower frequency components, $F(2, 34) = 810.02, p < .001$. Of more interest, coherence increased reliably under dual-task conditions, $F(1, 17) = 5.96, p = .03$. Because these main effects were qualified by a significant interaction effect, $F(2, 34) = 4.06, p = .03$, simple effect tests explored the influence of cognitive load separately for each wind frequency component. For the 0.033Hz component, the simple effect of cognitive load was non-significant, $t(17) = 0.72, p = .48$. For the 0.083Hz component, coherence was significantly higher in the dual-task conditions ($M = 0.71, SE = 0.03$) than in the drive-only conditions ($M = 0.68, SE = 0.03$), $t(17) = 2.57, p = .02$. For the 0.117Hz component, the simple effect of load condition was not significant, $t(17) = 0.82, p = .43$. The null effects for the .033 and .117 Hz components were perhaps because these coherence values were near ceiling and floor, respectively.

Analysis of delay and gain both showed reliable main effects of wind frequency component, $ps < .001$, but no reliable main effects of cognitive loads and no interaction effects, all $ps > .15$.

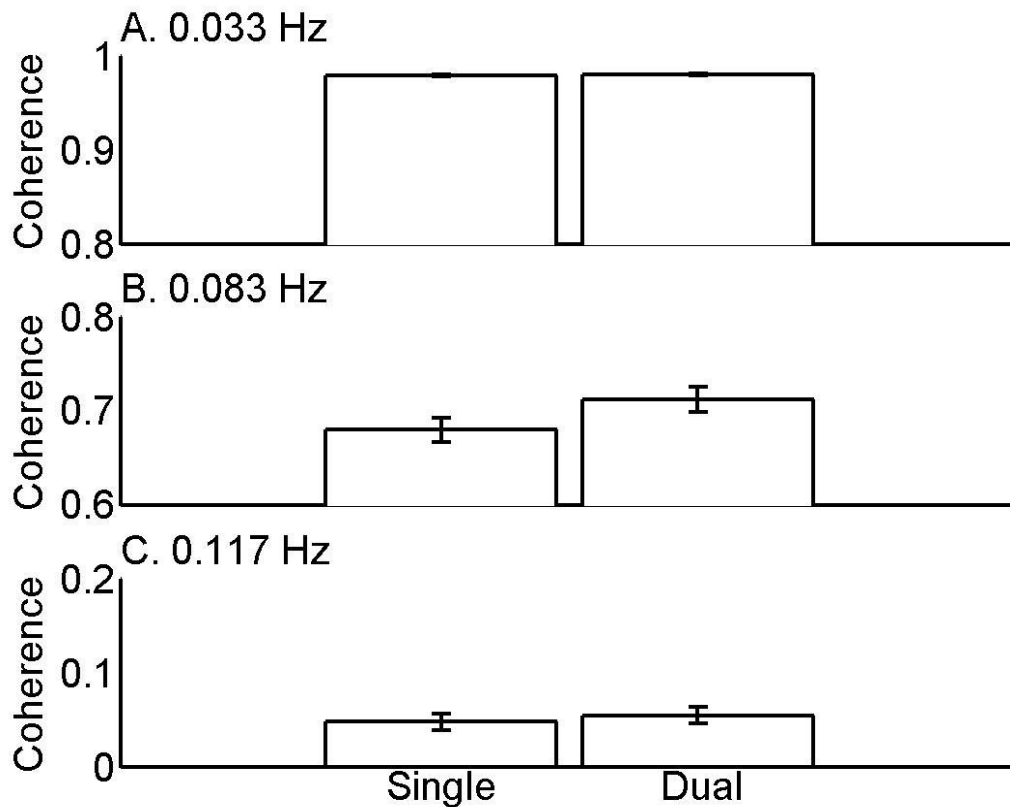


Figure 6. The average coherence of steering wheel position and lateral wind strength under different cognitive load condition. (A. Coherence for 0.033 Hz component; B. Coherence for 0.083 Hz component; C. Coherence for 0.117 Hz component. Please note the ranges of the Y-axis are different for the three graphs.)

Longitudinal Speed-Maintenance

The mean and standard deviation of speed were used to measure longitudinal performance. Mean speed was 45.96 MPH ($SE = 0.34$) under the dual-task conditions and 45.93 MPH ($SE = 0.39$) under the drive-only conditions, suggesting that drivers followed the experimental instructions to drive at the speed of 45MPH. Data showed no reliable differences in average speed between dual-task conditions and drive-only conditions, $t(17) = 0.31, p = .76$. However, the standard deviation of speed reliably

increased under the dual-task conditions ($M = 2.34$ MPH, $SE = 0.16$), compared to the drive-only conditions ($M = 2.06$ MPH, $SE = 0.15$), $t(17) = 2.32$, $p = .03$.

A pair of variables, analogous to the steering reversal rate and steering holds frequency used for analysis of lateral control behavior (Ranney, et. al., 2005), was calculated to analyze speed manipulation. The frequency of speed manipulation was reliably lower under the dual-task conditions ($M = 0.01$ Hz, $SE = 0.002$), relative to the drive-only conditions ($M = 0.02$ Hz, $SE = 0.003$), $t(17) = 4.463$, $p < .001$. The frequency of speed manipulation holds was marginally higher under the dual-task conditions ($M = 0.02$ Hz, $SE = 0.005$), than the drive-only conditions ($M = 0.01$ Hz, $SE = 0.004$), $t(17) = 2.055$, $p = .056$. Both results suggest that drivers were less active in manipulating speed when distracted, an effect opposite that seen in the lateral control data.

Fixation Dispersions

The visual enhancement hypothesis posits that perceptual processing in the forward view improves as a side effect of attentional narrowing under cognitive distractions. To test the possibility that attentional narrowing might have improved lateral control in the current experiment, we analyzed the dispersion of subjects' oculomotor fixations using standard deviation of horizontal and vertical fixation location. Paired-sample t-tests revealed no difference in the dispersion of fixation location between the dual-task conditions and the drive-only conditions, either horizontally ($M = 0.046$ m, $SE = 0.004$ for the dual-task conditions, $M = 0.045$ m, $SE = 0.006$ for the drive-only conditions), $t(17) = 0.317$, $p = .755$, or vertically ($M = 0.042$ m, $SE = 0.003$ for the dual-task conditions, $M = 0.038$ m, $SE = 0.003$ for the

drive-only conditions), $t(17) = 1.302$, $p = .210$. These effects give no evidence to support the visual enhancement hypothesis.

Discussion

This study replicated the findings of smaller lane variability under cognitive distractions in Experiment 1 and confirmed that the effect was apparently produced by drivers' more active steering behavior (cf., Östlund, et al., 2004) and lower frequency of steering holds (Ranney, et al., 2005). More novelly, changes in steering behaviors entailed a larger coherence between lateral wind strength and steering wheel position, an effect suggesting that distraction-induced reductions in the variability of lane position reflected a true performance gain in lane-keeping, rather than a performance loss. Notably, the increasingly active manipulation of steering wheel under the dual-task conditions was accompanied by an increase in the variability of velocity and a decrease in the frequency of speed manipulation.

Cognitive distraction has been shown to impair many aspects of driving, reducing the breadth of visual scanning (Recarte & Nunes, 2000, 2003), impairing the quality of attentional processing within an area of interest (Strayer et al., 2003), and increasing response time to hazards (Caird et al., 2008; Strayer & Johnston, 2001). The reduction of lane variability under cognitive distraction seems to be an outlier to the widespread impairment of driver performance under distraction. The rigidified steering hypothesis proposes that the reduction of lane variability is in fact a performance loss, resulting from neglect of the lateral control task (Mehler, et al., 2009; Reimer, 2009; Son, et al., 2010). However, contrary to the predictions of the

rigidified steering hypothesis, this study and other previous work have found that drivers steer more actively during distraction (Engström, et al., 2005; Östlund, et al., 2004; Ranney, et al., 2005). The current data extend earlier findings furthermore, by showing that distraction can improve the coherence between steering wheel position and lateral wind strength, again contrary to the predictions of the rigidified steering hypothesis. Experiment 2 also provided a unique measurement of the distribution of the steering reversal time intervals. Cognitive distraction reduced the intervals between steering reversal, which is opposite to the prediction of intermittent steering response pattern by the rigidified hypothesis.

How did drivers produce better lane-keeping performance under the dual-task conditions? According to existing literature, drivers might improve lane-keeping performance either through better visual processing (the visual enhancement hypothesis), less interferences of conscious control on the automatic steering behaviors (the automatic steering hypothesis), or actively prioritizing lateral lane-keeping (the lateral prioritization hypothesis) (Engström et al., 2005; Kubose et al., 2006; Liang & Lee, 2010).

The visual enhancement hypothesis explains the reduction of lane variability under cognitive distractions as a result of attentional narrowing in the central forward view (Recarte & Nunes, 2000, 2003; Harbluk, et al., 2007; He, et al., 2011; Liang & Lee, 2010; Victor, et al., 2005). Though superficially reasonable, however, the visual enhancement hypothesis contradicts with evidence suggesting that cognitive distraction compromises attentional processing even for information that is directly fixated (Strayer et al., 2001, 2003, 2007). Moreover, past work has found only a weak relationship between gaze concentration and lane variability (Liang & Lee, 2010).

Consistent with those findings, the current study revealed that lane variability and steering control improved with no concomitant changes in fixation dispersion, providing further evidence that better lane-keeping under cognitive distraction is not a by-product of attentional narrowing.

The automatic steering hypothesis regards smaller lane variability as a performance gain in lane-keeping resulting from less conscious control in the dual-task conditions. Lateral control for experienced drivers is an automatic process. This hypothesis argues that more resources for automatic behaviors may actually harm performance (Beilock & Carr, 2001; Beilock, et al., 2002). When a secondary task takes attention away, it allows less conscious interference on the automatic steering control, thereby producing straighter lane position. As an automatic process, the automatic steering hypothesis claims that drivers can automatically adjust the steering reversal rate according to the strength of lateral wind. This claim makes it hard to validate the automatic steering hypothesis with either lane variability or the steering reversal rate. However, the automatic steering hypothesis does not predict a trade-off of steering control and speed manipulation. Experiment 2 found that cognitive distraction increased the steering reversal rate and decreased speed manipulation frequency at the same time. Moreover, the automatic steering hypothesis assumes attention is shifted away from steering control. The resources originally allocated for steering control can be reallocated to the secondary task or other aspects of driving. If these resources are reallocated to speed maintenance, speed manipulation frequency may be increased and result in better speed maintenance performance. Thus, the automatic steering hypothesis will not expect a more inactivity of speed manipulation in the dual-task conditions.

The lateral prioritization hypothesis best explains the findings of Experiment 2 and of earlier work on lateral control under distraction. Here, when drivers engaged in an auditory digit ordering task, they became more active in steering control, as indicated by larger steering reversal rate, and smaller steering holds frequency, and reduction of steering reversal time intervals. At the same time, speed manipulation was reduced, as drivers made fewer speed control inputs and produced more periods of speed manipulation inactivity. These steering and speed manipulation behaviors together suggested that distracted drivers may have shifted resources from speed manipulation to lateral lane-keeping, and achieved smaller lateral variability by sacrificing longitudinal control. The lateral prioritization hypothesis is also supported by the findings of several earlier studies. For example, drivers doing a language production task concurrently produced smaller lane variability, and more variable speed and headway time when driving following a leading vehicle (Kubose et al., 2006). Beede and Kass (2006) also suggested that distracted drivers protected lane keeping performance by shedding peripheral tasks to maintain a straighter course.

Data in Experiment 2 are in favor the lateral prioritization hypothesis. However, findings so far cannot provide enough information to test the validity of the automatic steering hypothesis. We are still not confident about the underlying mechanisms how distracted drivers achieved a better lane-keeping performance.

EXPERIMENT 3: RESPONSE TIME TO LATERAL WIND AND LEADING VEHICLE BRAKE HAZARDS

Subjects in Experiment 1 and 2 drove under continuously varying lateral winds produced from a combination of three sinusoids. The wind manipulation provided data amenable to coherence analysis, but did not allow a direct measurement of response times to discrete lateral wind change. Studies of longitudinal vehicle control, conversely, often measure responses to sudden braking events by a lead vehicle (Alm & Nilsson, 1995; Lee, Vaven, Haake, & Bron, 2001; Strayer et al., 2003; Strayer et al., 2006). Such methodological differences complicate comparisons of lane-keeping and speed maintenance. Experiment 3 seeks to compare longitudinal and lateral performance, with and without distraction, in as direct a manner possible. Here, in place of the continuously varying lateral winds like those that have often been used in studies of lateral control (Kubose et al., 2006), we used a step-wise lateral wind, as shown in Figure 7. Lateral winds blew at random intervals and varying strengths. A steering manipulation opposite to the direction of lateral wind can be treated as a response to lateral event, producing measurement like RT and accuracy in traditional car following task. Besides the lateral wind events, drivers also need to drive following a leading vehicle, which brakes intermittently. The combination of lateral wind and brake events makes it possible to compare task prioritization in a common unit of RT and accuracy.

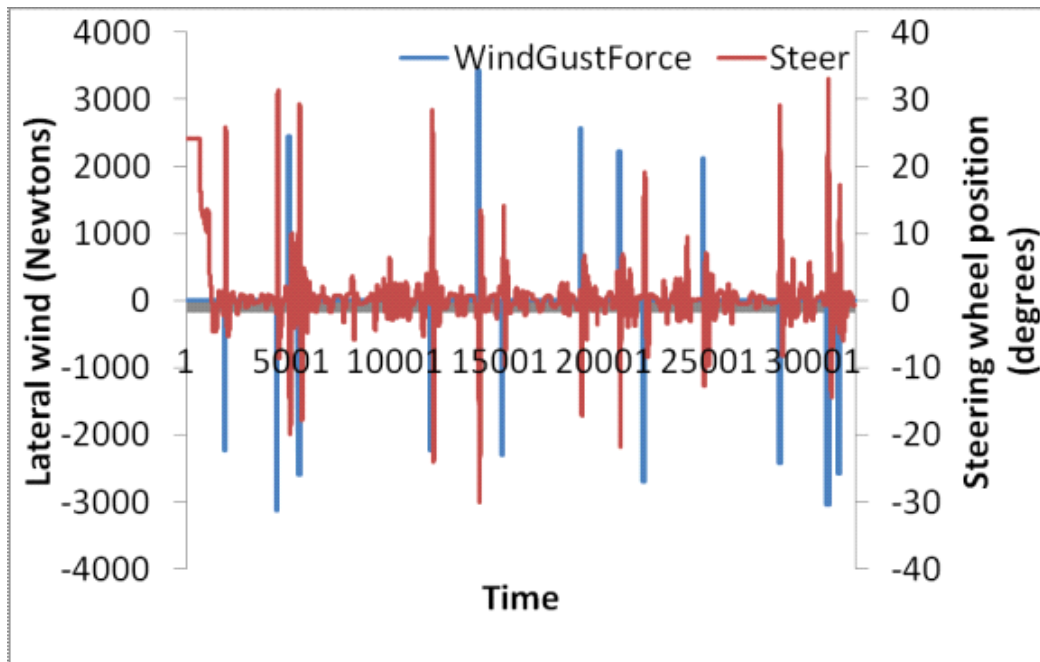


Figure 7. A sample of lateral wind used in the experiment. The (Note: the strength and direction of lateral wind and the time interval between adjacent wind gust are all randomized. The blue line shows the wind gust force curve. The red line shows a driver's steering response to lateral wind)

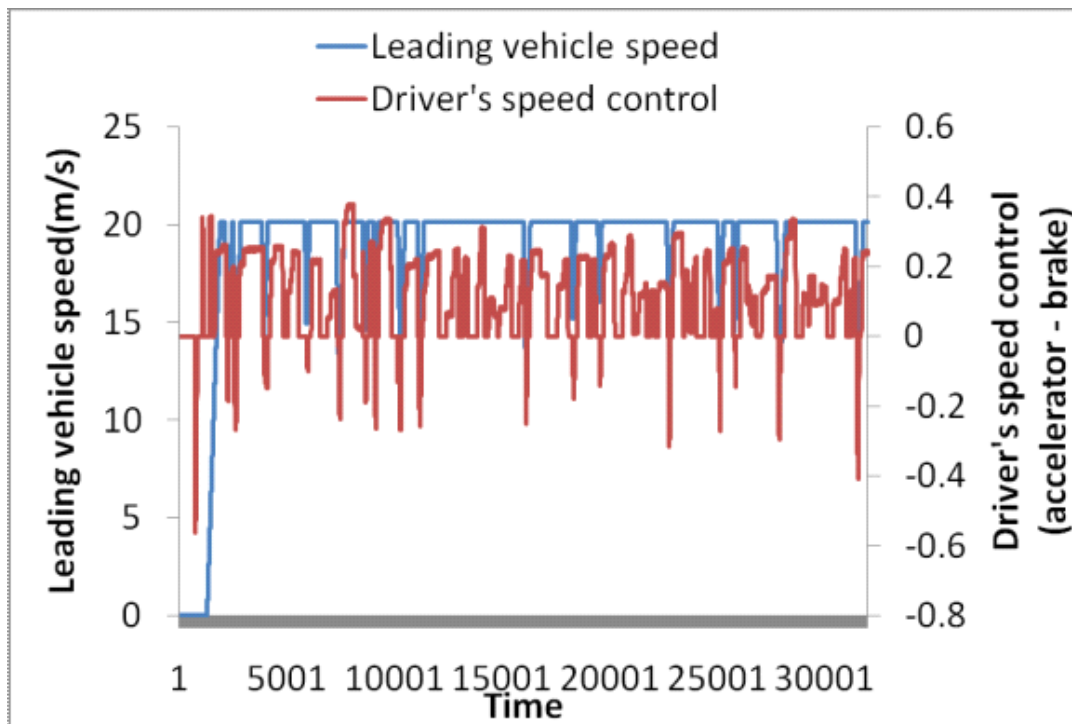


Figure 8. A sample of leading vehicle speed change and a driver's speed control. (Note: the blue line shows the leading vehicle speed; the red line shows a driver's brake response to leading vehicle brake events)

Method

Subjects

Twenty-two subjects (9 female and 13 male) were recruited through online advertisements and campus posters. The ages of the subjects ranged from 18 to 25 years, with a mean of 20.7 years and standard deviation of 1.5 years. The average self-reported annual mileage of the subjects was 6564 miles, with a standard deviation of 7151 miles. All subjects had held a driver's license for at least three years. The average time since licensure was 4.6 years. All subjects had normal or corrected-to-

normal visual acuity. Subjects were reimbursed either with cash at the rate of \$8 per hour for a one-hour experiment or in exchange of course credits.

Apparatus and Stimuli

Data were collected using the same driving simulator as what was used in Experiment 1 and 2.

Eye and head movements were collected with a Smart Eye Pro 5.8 system (SmartEye AB, 2004). This system consisted of five Sony XC HR50 monochrome cameras, which were equipped with two IR-illuminators and mounted on the dashboard of the car. The cameras fed information into software that located predefined characteristic points on the participant's face, and in this way determined where the participant's foveas were pointing. Data were analyzed with customized software.

Driving Scenario

The simulated driving environment consisted of a straight rural highway, three-lanes in each direction, with no intersections or turns. The route was 11600 meters long. Each lane was 3.6 meters wide. The speed limit of the road was 55MPH. Thirteen speed limit signs of 55MPH were posted on the right side of the road, with the distance between adjacent signs selected randomly from a uniform distribution ranging from 500 to 1000 meters. Parked vehicles along the roadside and pedestrians on the sidewalks also appeared occasionally.

The subject vehicle was initially positioned facing straight ahead in the center of the lane. Driving hazards, either heavy lateral wind gusts or leading vehicle brake events, began after the subjects had driven exactly 350 meters from the starting point of the trial. An event scheduler determined the occurrence of lateral wind gusts and

longitudinal brake events, with equal probability for both types of hazards. The duration of the hazard events and the time intervals between events follow independent delayed exponential distributions. The delayed exponential distribution has the advantage of being memoryless following the initial delay (Ahmad & Alwasel, 1999), making it difficult for subjects to predict the occurrence of next event or the duration of an ongoing event. The event duration was determined using equation (1), with an intercept of 1 second and an asymptotic value of 4 seconds. The time interval between adjacent events ranged from 2.5 seconds to 75 seconds, as determined by equation (2).

$$duration = 1 - \log((1 - e^{1-4}) * rand() + e^{1-4}) \dots\dots\dots(1)$$

$$interval = 2.5 - 12.5 * \log((1 - e^{\frac{2.5-75}{12.5}}) * rand() + e^{\frac{2.5-75}{12.5}}) \dots\dots\dots(2)$$

$$wind_strength = 2000 - 500 * \log((1 - e^{\frac{2000-3000}{500}}) * rand() + e^{\frac{2000-3000}{500}}) \dots(3)$$

For the lateral wind events, the strength of wind also followed a delayed exponential distribution, ranging from 1000 to 2000 Newtons, as determined by equation (3). The wind was strong enough to require active steering manipulations to maintain a steady and safe lane position. The direction of wind varied randomly between leftward and rightward, with equal probability. Figure 7 illustrates the duration and time interval of lateral wind gusts and a driver's steer response to lateral wind in a sample trial.

For the longitudinal event, drivers drove after a large commercial vehicle in the central lane of the highway. The leading vehicle drove at a target velocity of 45 MPH. During a braking event, the leading vehicle decelerated at a rate of 3.0 m/s until reaching the lower speed bound of 35 MPH, and resumed the speed of 45 MPH

afterwards. The duration of the brake events was determined using a delayed exponential distribution. The brake lights of the leading vehicle illuminated during a braking event. Figure 8 illustrates the duration and time interval of leading vehicle brake events and a driver's brake response behavior in a sample trial.

Loading Task

The cognitive load was manipulated by a digit-ordering task, which was exactly the same as that used in Experiment 2.

Procedure

Upon arriving at the lab, subjects completed an informed consent form, a screening questionnaire inquiring about their driving experience and propensity for simulator sickness, and a demographic questionnaire. Subjects with at least three years of driving experience, normal or corrected-to-normal visual acuity, and no history of simulator sickness were allowed to participate. The subjects' primary task was to drive while maintaining appropriate lane position and headway distance from the leading vehicle. Subjects were instructed to keep a steady lane position in the center lane and follow the lead vehicle with about 2s headway time.

After receiving a brief description of the experimental task, subjects completed two practice drives to familiarize themselves with the simulator and the driving environment. They were allowed to ask questions during the practice drives. The first practice drive lasted about 5 minutes, and was the same as the experimental blocks, except with additional auditory feedback about headway time. When headway time was shorter than 1.5 seconds, drivers would be told that "too close, please slow down"; when headway time was over 2.5 seconds, drivers would be told "too far,

please speed up". When drivers drove between 1.5 and 2.5 seconds, there would be no auditory feedback. The second practice drive lasted about 10 minutes, and let subjects drive in the same condition as the experimental blocks. Subjects first drove in the drive-only condition, then drove with the digit ordering task, with each condition lasting about five minutes. There was no auditory feedback about headway time in the second practice drive.

The experimental blocks began after subjects reported that they fully understood the task and were comfortable to drive in the simulator. All subjects completed four drives, two drives each for the drive-only and dual-task conditions. The order of the four drives was counterbalanced across subjects using an ABAB design. Each drive lasted approximately ten minutes. Subjects were given a chance to rest between blocks. There was no auditory feedback of headway time in experimental blocks.

Dependent Variables

Lateral performance was measured by the average and standard deviation of lane position, the steering reversal rate, the steering reversal time interval, and the steering response time to lateral wind. *Lane position* was measured as deviation in meters from the center of the subject's lane. Positive values indicate positions to the right of lane center, and negative values indicate positions to the left. *The steering reversal rate* gauged drivers' efforts in adjusting the steering wheel's to maintain lane position (MacDonald & Hoffmann, 1980). A steering reversal was defined as a change in steering direction with a velocity of more than 3.0 deg/s (Theeuwes, et al., 2002; Groot, et al., 2011). The *steering reversal time interval* is the time interval inbetween two adjacent steering reversals. The *steering response time* to lateral wind

was calculated as the time from the onset of a lateral wind gust until the time of the largest spike in the steering velocity curve within 2s time window.

Longitudinal performance was measured by the standard deviation of speed, the standard deviation of headway time, the brake response time and the brake response rate. *Headway time* was defined as the time in seconds from the subject vehicle to the lead vehicle. In the same way as the definition of the steering response time, the *brake response time* was calculated as the time from the onset of the leading vehicle's brake lights until the maximum depression of the brake pedal occurring within 2 seconds of the onset of the leading vehicle's brake. A brake response was operationally defined as a minimum of 1% depression of the brake pedal (Strayer et al., 2006). An absence of a braking depression within 2 seconds was classified as a failure to response. The percentage of braking response over the total number of leading vehicle brake events is defined as the brake response rate.

Eye movement patterns were assessed using the dispersion of fixation position, which was defined as the standard deviation of horizontal and vertical fixation location.

Hypotheses

The rigidified steering hypothesis posits that cognitive distraction shifts attention away from vehicle control, inducing inactive, intermittent, or unresponsive steering behaviors (Cliff, 1973; Coughlin & Dusek, 2009; Liang & Lee, 2010; Mehler, et al., 2009; Son, et al., 2010). Phrased differently, "a decrease in lateral position variability may represent a rigidified, compensatory behavior pattern to allow attention to shift to the secondary task" (Reimer, 2009). By this hypothesis, apparent distraction-induced improvements lane-keeping variability masks a performance loss. The steering

response time to lateral wind should therefore increase as cognitive distraction shifts resources away from steering control. The brake response time may also become poorer as a result of general distraction effects.

The lateral prioritization hypothesis explains the reduction in lane variability under distraction as a result of attentional resources being shifted from other subtasks to lateral control in an effort to protect lane keeping performance. Lateral control thus improves at a cost to other elements of performance, for example, car following. Therefore, the lateral prioritization hypothesis expects quicker steering response time to lateral wind, and longer brake response time.

The visual enhancement hypothesis proposes that lane keeping improves under cognitive distractions as a result of a narrower attentional focus on the roadway ahead (Engström, et al., 2005; Östlund, et al., 2004). Cognitive distractions reduce the breadth of the driver's oculomotor scanning (e.g., Harbluk, et al., 2007; He, et al., 2011; Liang & Lee, 2010; Recarte & Nunes, 2000, 2003; Victor, et al., 2005). A concentrated gaze pattern enhances perceptual response in the forward view, therefore, improving steering response (Engström et al., 2005; Östlund et al., 2004). Likewise, perception of brake hazards should be improved too as a result of gaze concentration. Therefore, the visual enhancement hypothesis expects quicker steering and brake response time.

The automatic steering hypothesis assumes that cognitive distraction tasks take attention away from the automatic skills of steering control, therefore, allowing less interference from conscious control (Kubose et al., 2006). Steering control can be treated as an automatic process during eventless conditions, in which less attention can process better lane-keeping performance according to the automatic steering hypothesis. But during hazards, steering control is no longer an automatic process, but

controlled process, which requires attention efforts to perceive the change of lane position and cognitive processing to adjust the lane positions (Sanfey & Chang, 2008). Therefore, during hazards, with less attention allocated for lane-keeping, the automatic steering hypothesis predicts longer steering response times to unpredictable lateral wind hazards.

Figure 9 summarizes the theoretical predictions of steering response time to lateral wind gusts and brake response time to leading vehicle brake hazards under distraction condition.

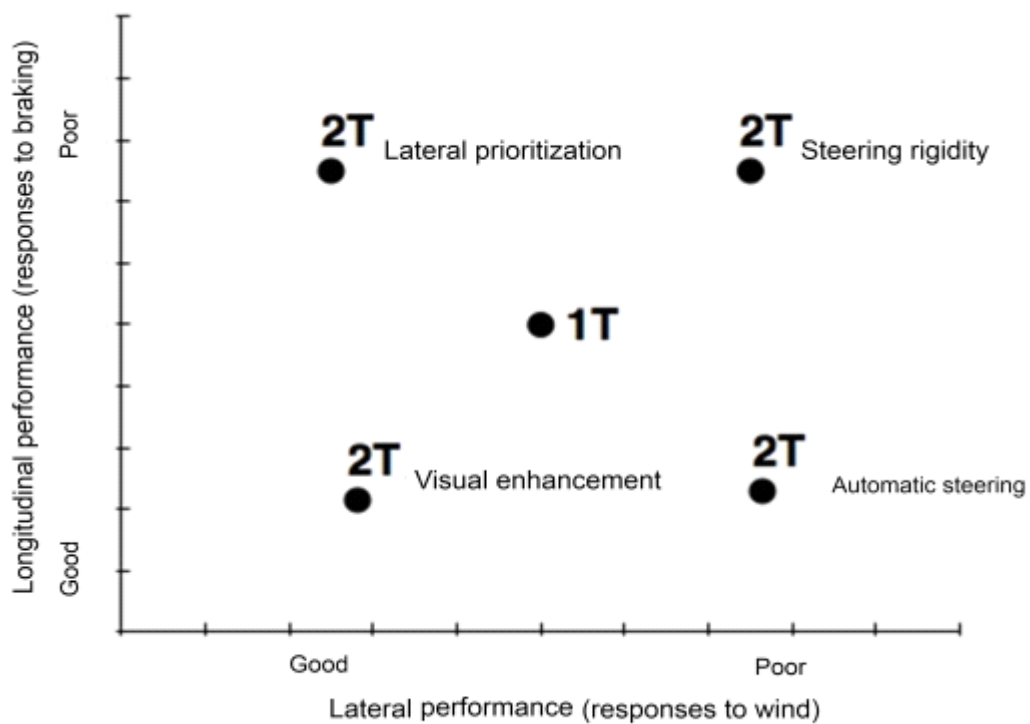


Figure 9. Theoretical predictions of lateral and longitudinal performance to hazards under distraction condition. (1T is for drive-only condition; 2T is the predicted performance under dual-task condition (driving paired with a digit ordering task). Four hypotheses, rigidified steering, lateral prioritization, visual enhancement, and automatic steering, expect quite different results.)

Results

Lane-Keeping

The average lane position did not differ significantly between the dual-task ($M = 0.003\text{m}$, $SE = 0.04$) and drive-only ($M = 0.014\text{m}$, $SE = 0.04$) conditions, $t(21) = 0.83$, $p = .42$. The average of the standard deviation of lane position was significantly smaller under dual-task conditions ($M = 0.33\text{m}$, $SE = 0.02$) than under drive-only conditions ($M = 0.35\text{m}$, $SE = 0.02$), $t(21) = 2.27$, $p = .03$.

Steering Control

The steering reversal rate was higher under dual-task conditions ($M = 0.57\text{ Hz}$, $SE = 0.03$) than drive-only conditions ($M = 0.40\text{ Hz}$, $SE = 0.03$), $t(21) = 4.09$, $p < .001$.

A further analysis asked whether changes in steering reversal rate during dual-task blocks were time-locked to performance of the loading task. For this, the steering reversal rates before and after the onset of the secondary auditory digits for all the dual-task condition trials were compared. The two measurements were calculated over the four second and a seven second time windows before and after the auditory stimulus onset. The auditory presentation time was 2.77 seconds on average, with a range of 2.48 seconds to 3.10 seconds. The four second time window after the auditory onset should have included time in which the four auditory digits were being presented. The seven second time window should be long enough to included the time necessary for the auditory digits to be played and much of the time necessary for subjects to finish ordering the digits. The rigidified steering hypothesis predicts that

the steering reversal rate before the auditory onset would have been higher than that after the auditory onset. In contrast, the lateral prioritization hypothesis predicts that the steering reversal rate before the auditory onset would have been smaller than that after auditory onset.

When a four second time window was used, the average steering reversal rate before auditory onset ($M = 0.545\text{Hz}$, $SE = 0.03$) was numerically smaller than that after auditory onset ($M = 0.559\text{Hz}$, $SE = 0.03$), though the difference was not statistically significant, $t(21) = 1.34$, $p = .20$. When a seven second time window was used, the steering reversal rate was significantly higher after the auditory onset ($M = 0.570\text{Hz}$, $SE = 0.03$) than that before ($M = 0.580\text{Hz}$, $SE = 0.03$), $t(21) = 2.82$, $p = .01$. Results thus showed that steering reversal rate was actually maintained or even increased when drivers were listening and ordering auditory digits.

The rigidified steering hypothesis and lateral prioritization hypothesis also have different predictions on the distribution of the time interval between adjacent steering reversal. The rigidified steering expects long period of steering inactivity during secondary task, which is reflected in more frequency of long steering reversal interval. In contrast, the lateral prioritization hypothesis proposes more efforts in steering control when drivers are cognitively distracted, which should manifest as a higher steering reversal rate and smaller average steering reversal interval.

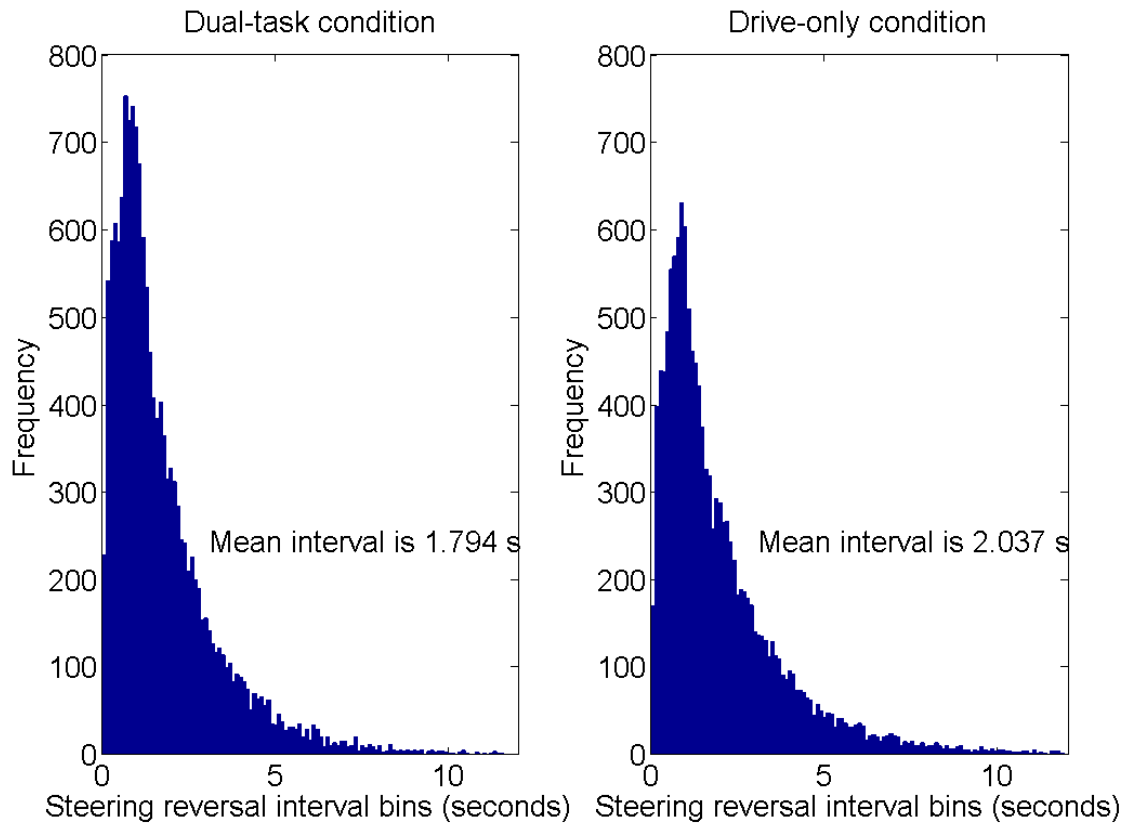


Figure 10. Distribution of steering reversal interval under dual-task and drive-only conditions.

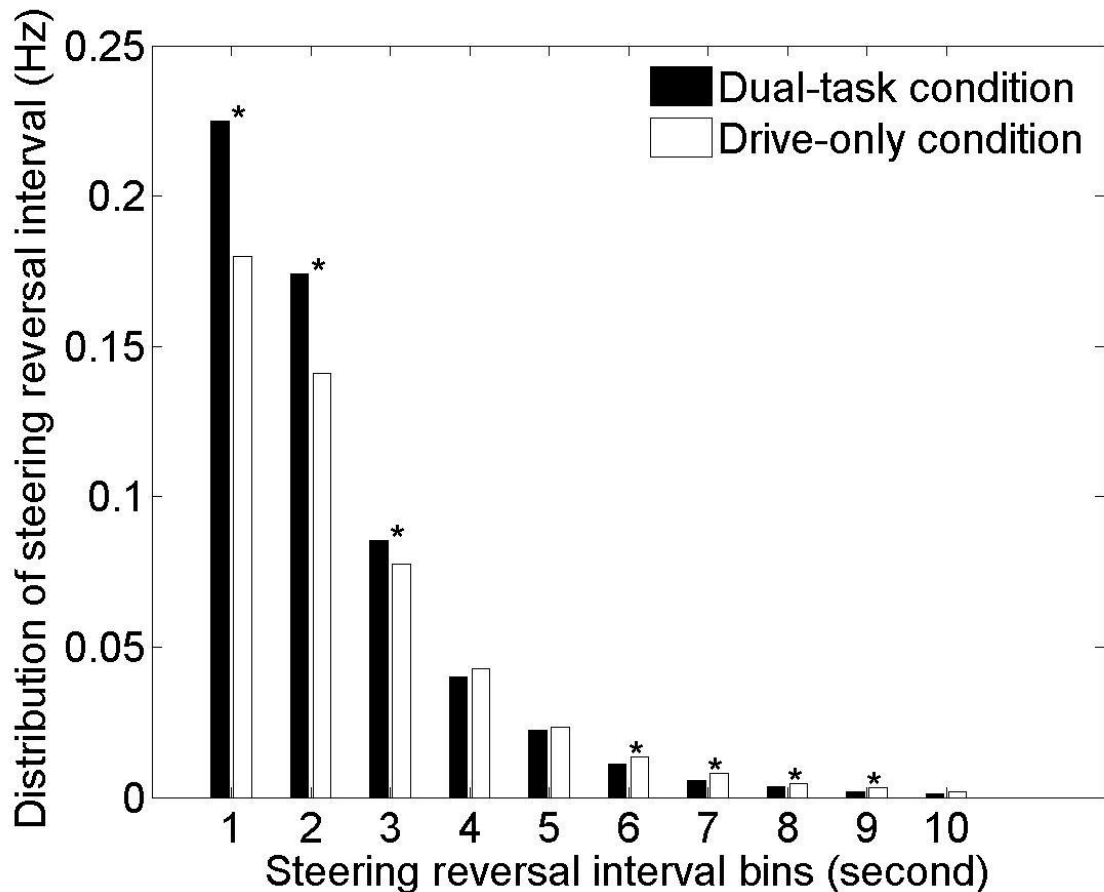


Figure 11. Comparisons of the steering reversal interval each ten time bins under dual-task and drive-only conditions (Asterisks indicate significant differences.)

As shown in Figure 10, most of the steering reversal intervals are below ten seconds (99.2% for the drive-only conditions and 99.5% for the dual-task conditions). Thus, the steering reversal intervals were categorized into ten time bins, each lasting one second. Figure 11 shows the frequency of steering reversal intervals in each time bins. The frequency of steering reversal intervals was submitted to repeated-measure analysis of variance, with cognitive load and time interval bins as within-subject factors. The main effects of both cognitive load and time bins were significantly, $F(1,21) = 17.04, p < 0.001$ and $F(9,189) = 91.54, p < 0.001$, respectively. Analysis also showed a significant interaction, $F(9,189) = 11.85, p < 0.001$.

Simple effects analyses showed that the frequency of steering reversal intervals was higher in the dual-task conditions than the drive-only conditions for the one, two, and three-second bin, all $ps < 0.01$. The frequency of steering reversal intervals was smaller in the dual-task conditions than the drive-only conditions for the longer time intervals, including interval bins of six, seven, eight, and nine-seconds, all $ps < 0.05$. The simple main effect of cognitive load for the time bins of four, five, and ten-seconds was not significant, all $ps > 0.10$. Data show that cognitive load resulted in more short steering reversal intervals (intervals smaller than three seconds) and fewer long steering reversal intervals (intervals longer than six seconds). Data, thus, support the lateral prioritization hypothesis, which expects a decrease of the steering reversal intervals in the dual-task conditions; data also argue against the rigidified steering hypothesis which expects more frequent long steering reversal intervals.

Longitudinal Control

Drivers tended to adopt a longer headway time under dual-task conditions ($M = 2.06s$, $SE = 0.12$) than under drive-only conditions ($M = 1.97s$, $SE = 0.10$), though the effect reached only marginal significance, $t(21) = 1.85$, $p = 0.08$. The average of the standard deviation of headway time was higher under dual-task conditions ($M = 0.56s$, $SE = 0.03$), than under drive-only conditions ($M = 0.51s$, $SE = 0.03$), $t(21) = 2.53$, $p = 0.02$. The same pattern of effects was seen in analysis of headway distance. Data thus showed that high cognitive load tended to increase headway time and resulted in more variable headway time.

Drivers drove at similar average speeds under both dual-task ($M = 43.72\text{mph}$, $SE = 0.04$) and drive-only conditions ($M = 43.74\text{ mph}$, $SE = 0.05$), $t(21) = 0.46$, $p = 0.65$. There was no significant difference for the average standard deviation of speed

between dual-task conditions ($M = 4.44\text{mph}$, $SE = 0.13$) and drive-only conditions ($M = 4.35\text{ mph}$, $SE = 0.14$), $t(21) = 0.85$, $p = 0.41$. The lack of a load effect on speed likely obtained because the subject vehicle speed was largely determined by the speed of the leading vehicle.

The more variable headway times and distances in dual-task conditions suggests that longitudinal performance was impaired when drivers performed a cognitive auditory task while driving.

Response Time to Hazards

This section compares the steering response time and response rate to lateral wind gusts with the braking response time and response rate to the leading vehicle brake hazards. The steering response time and response rate are analogous to the braking response time and response rate measures in the traditional car-following task. The only difference is the hazardous events: in one case, the hazards are lateral wind gusts; in the other, the hazards are the sudden braking or slowdown of the leading vehicle. This gives a direct comparison of lateral lane-keeping and longitudinal car-following performance in common units.

In order to better understand the steering and braking response behaviors, a steering position and a speed profile were created by extracting a 10-s time window time locked to the onset of each leading vehicle brake and lateral wind events. This was inspired by the analysis of Strayer, Drews, and Crouch (2006). For this, the driving data from the 600 samples (i.e., 60 samples per second for ten seconds) following the onset of a hazard were entered into a matrix $X_{[j,1]}$, $X_{[j,2]}$, $X_{[j,3]}$, ..., $X_{[j,600]}$, in which j was the index of the occurrence of leading vehicle brake events or lateral wind onset events. Each driving profile was created by averaging across j for

each of the 600 time points.

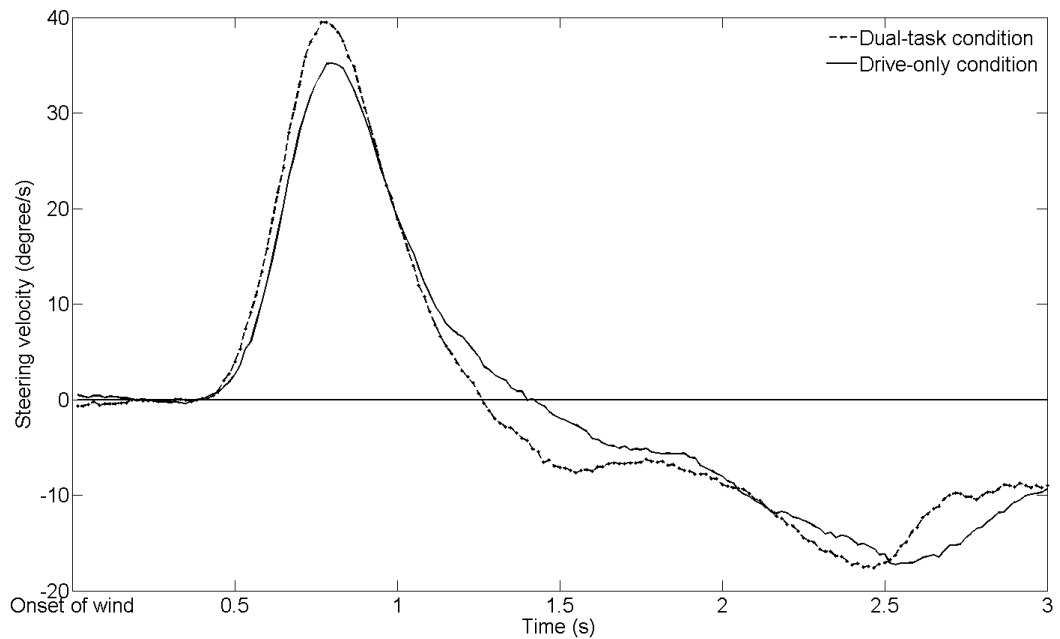


Figure 12. The steering velocity profile averaged across subjects

A steering response was defined as a steering manipulation with a minimum steering velocity of 3.0 deg/s (Theeuwes, Alferdinck, & Perel, 2002; Groot, Winter, Garcia, Mulder, Wieringa, 2011), and in the opposite direction which the wind was blowing. Figure 12 shows the steering velocity profiles under dual-task and drive-only conditions, combined over all the subjects and lateral wind hazard events. This figure suggests that the steering responses occurred in the time range of 0.5s to about 2.5s. Analyses using values of 2s, 2.5s, and 3s as the upper limit of steering response time produced similar patterns of results. Data based on an upper limit of 2s are reported here. After the preprocessing of steering velocity thresholding, the steering response time was defined as the length of time from the onset of lateral wind until the largest spike in the steering velocity curve within a 2s time window. A failure to generate a steering manipulation against the wind with steering velocity larger than

3.0 deg/s occurred within 2s time window following a wind gust was treated as non-response. The number of correct steering responses over the total number of lateral wind events was the steering response rate.

The steering response time was smaller in the dual-task conditions ($M = 0.85s$, $SE = 0.01$) than in the drive-only conditions ($M = 0.88s$, $SE = 0.02$), $t(21) = 2.58$, $p = 0.02$. The steering response rate was similar for the dual-task ($M = 0.79$, $SE = 0.02$) and drive-only ($M = 0.79$, $SE = 0.02$) conditions, $t(21) = 0.15$, $p = 0.88$. These data suggest that high cognitive load improved steering response to lateral wind gusts.

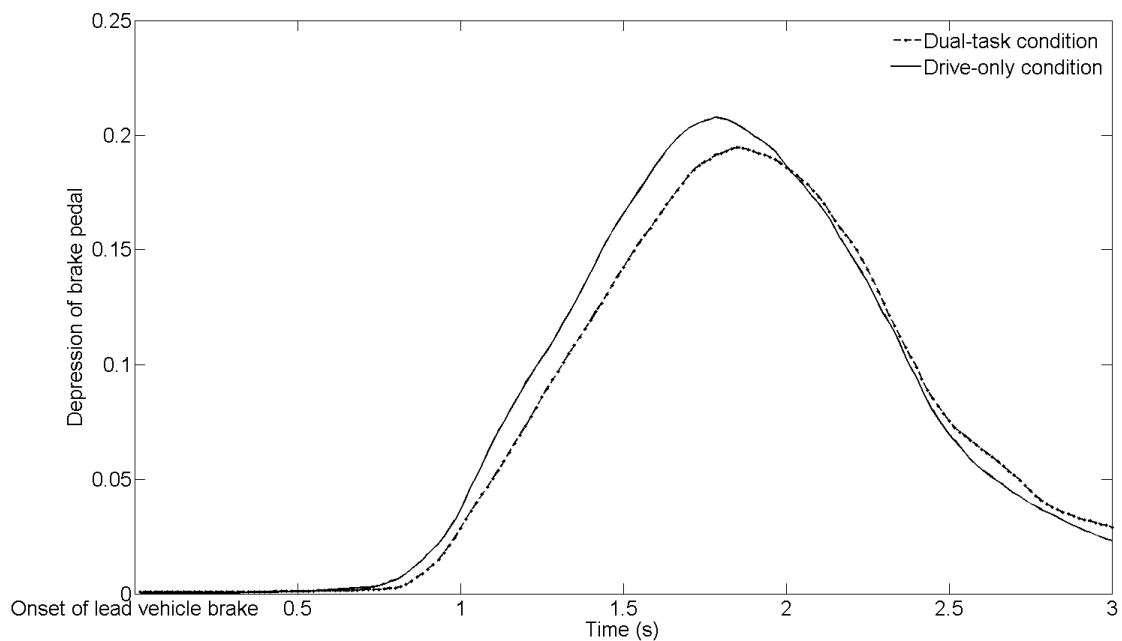


Figure 13. The brake profile averaged across subjects

Figure 13 shows the brake profiles under dual-task and drive-only conditions, combined over all the subjects and leading vehicle brake events. The brake response time was numerically longer in dual-task conditions ($M = 1.85s$, $SE = 0.02$) than in drive-only conditions ($M = 1.80s$, $SE = 0.03$), with a marginally significant main effect of cognitive load, $t(20) = 0.1.90$, $p = 0.07$. The brake response rate was

numerically but non-significantly smaller in dual-task conditions ($M = 0.61$, $SE = 0.06$) compared to drive-only conditions ($M = 0.63$, $SE = 0.06$), $t(20) = 0.61$, $p = 0.55$. Data thus gave no evidence of an improvement in longitudinal hazard responses under high cognitive load.

Fixation Dispersions

The visual enhancement hypothesis posits that perceptual processing in forward view improves as a side effect of attentional narrowing under cognitive distractions. To test the possibility that attentional narrowing might have improved lateral control in the current experiment, we analyzed the dispersion of subjects' oculomotor fixations using standard deviation of horizontal and vertical fixation location. Within-subject t-tests revealed no difference in the dispersion of fixation location between cognitive load conditions, either horizontally ($M = 0.29$, $SE = 0.03$ for dual-task conditions, $M = 0.28$, $SE = 0.03$ for drive-only conditions), $t(21) = 0.96$, $p = .35$, or vertically ($M = 0.28$, $SE = 0.03$ for dual-task conditions, $M = 0.26$, $SE = 0.03$ for drive-only conditions), $t(21) = 1.85$, $p = .08$.

Discussion

In Experiment 3, drivers drove along a straight lane while responding to sudden onset of lateral wind gusts or leading vehicle brake events. An auditory digit-ordering task was used to manipulate the cognitive load. Drivers produced smaller standard deviation of lane position when concurrently doing a digit-ordering task, an effect that was apparently achieved through more active steering manipulation. In contrast, longitudinal performance became poorer in dual-task conditions, with more variable

headway time and headway distance. More importantly, drivers responded quicker to lateral wind gusts when doing a digit-ordering task, but showed no improvements in their brake response times to sudden braking of the lead vehicle. These measurements together suggested that cognitive distraction improved lane-keeping performance and impaired car-following performance.

Similar as Experiment 1 and 2 in this dissertation and existing literature, drivers produced less variations in their lane position when performing a cognitive distraction task while driving (see also Becic et al., 2010; Brookhuis, et al., 1991; Kubose et al., 2006).

Since there is no common agreement about whether smaller lane variability indicates a performance gain or a performance loss in lane-keeping, we need to find support from other convergent measures. Experiment 3 implemented lateral wind hazards and car-following hazards, and uses the steering response time to the sudden onset of lateral wind as an alternative measure of lane-keeping performance.

Experiment 3 found an increase in the steering reversal rate in dual-task conditions, which suggested that drivers invested more efforts in adjusting lane positions. Data in Experiment 3 further showed that drivers responded quicker to lateral wind gusts. These data indicate that drivers had better response to lateral hazards under high cognitive load. Therefore, the smaller lane variation appears to be a true performance gain, as drivers put more efforts in lane-keeping and responded quicker to lateral wind hazards.

The present data sit poorly with the rigidified steering hypothesis, which treats smaller lane variability under distraction as an performance loss, reflecting an intermittent unresponsive steering pattern. If drivers only steer intermittently in high cognitive load, the steering reversal rate should be smaller, and the time interval

between steering reversal should be longer, than that under drive-only conditions. However, Experiment 3 found higher steering reversal rates and smaller steering reversal time intervals in dual-task conditions. Experiment 3 also compared the steering reversal rate before and after the onset of auditory task. There was no decrease, but a trend toward an increase in steering reversal rate after the onset of auditory task, compared to the time before the onset of auditory task. Higher steering reversal rates under high cognitive load have been also reported in several other studies (cf., Engström et al., 2005; Östlund, et al., 2004; Ranney, et al., 2005). Moreover, if cognitive distraction leads to unresponsive and intermittent steering behaviors, with less attention devoted to lane-keeping, longer response time to lateral hazards should result. However, Experiment 3 found that drivers responded quicker to lateral wind gusts in the dual-task conditions.

The visual enhancement hypothesis, which explains the smaller lane variation under cognitive load as a result of better visual processing when attention narrows in the central forward view, is not supported either. A smaller horizontal fixation dispersion in dual-task conditions, described as attentional narrowing, is found in many laboratory and on-road driving experiment (Harbluk, et al., 2007; He, et al., 2011; Liang & Lee, 2010; Recarte & Nunes, 2000, 2003; Victor, et al., 2005). The visual enhancement hypothesis proposes that more attention is devoted to process information in the central forward view when attention narrows in this area; therefore, improve attentional processing for information necessary for lane-keeping, such as lane markers. Though this hypothesis seems reasonable superficially, it contradicts with many existing studies which suggest that cognitive distraction impairs attentional processing of information, even if drivers had fixated directly on these objects (Strayer et al., 2001, 2003, 2007). Moreover, Liang and Lee (2010) only found a weak

relationship between gaze concentration and lane variability. Therefore, better lane-keeping performance under cognitive load does not seem to be explained by attentional enhancement hypothesis. Even if attentional enhancement hypothesis were a possible explanation, it could not explain the smaller lane variation found in Experiment 3 since no attentional concentration effects were found.

The automatic steering hypothesis, which regards steering as an automatized process which requires little attention, is not supported either. According to the automatic steering hypothesis, increasing the attention devoted to steering will degrade lane-keeping performance. By drawing attention away from the automatic skills of steering, a cognitive distracting task therefore improves automatic responses (Beilock & Carr, 2001; Beilock, Carr, MacMahon, & Starkes, 2002; Kubose et al., 2006). Steering response in an eventless period may be an automatic process, but steering response to sudden onset of lateral wind gusts is a controlled process, requiring attention resources (Sanfey & Chang, 2008). With less attention allocated for steering, the automatic steering hypothesis would expect longer steering response time to lateral wind hazards. However, drivers had quicker steering response time to lateral wind gusts, which indicated lane-keeping performance was actually improved in dual-task conditions, contrary to the prediction of automatic steering hypothesis.

The lateral prioritization hypothesis is most congruent with current findings of an increase in lateral lane-keeping performance with a decrease in longitudinal car-following performance (see also Kubose et al., 2006). This hypothesis suggests that drivers invest more efforts in lane-keeping when they are distracted to achieve a safer zone within the lane (Engström et al., 2005). Data in Experiment 3 showed that distracted drivers had quicker steering response time to the sudden onset of lateral wind, which suggests better lane-keeping performance. Higher steering reversal rate

in dual-task condition suggests that drivers indeed invested more efforts in lane-keeping when they were distracted, as claimed by the lateral prioritization hypothesis. Analysis of car-following performance further confirmed that prioritization of lane-keeping comes with a cost of longitudinal performance. Headway time to leading vehicle became more variable under dual-task conditions.

GENERAL DISCUSSION

This dissertation project explored the lane-keeping performance changes that result when drivers are distracted by cognitive tasks and probed their underlying mechanisms. The two major research questions were: First, does smaller lane variability under cognitive distractions indicate a performance loss or a performance gain in lane-keeping? Second, what is the mechanism by which cognitive distraction induces less lane variability? Four hypotheses, rigidified steering, visual enhancement, lateral prioritization, and automatic steering, were compared using three simulated-driving studies.

Finding Summary

Table 2 summarizes the findings of the three experiments. For all the three experiments, a digit-ordering task was used to manipulate the cognitive load.

Table 2. Summary of the findings in three experiments

	Experiment 1	Experiment 2	Experiment 3
Distraction task	Digit ordering task	Digit ordering task	Digit ordering task
Lane-keeping task	Keep steady lane position under unpredictable heavy lateral wind (sum of three sine waves)	Keep steady lane position under unpredictable heavy lateral wind (sum of three sine waves)	Keep steady lane position under unpredictable heavy lateral wind
Longitudinal task	None (speed is maintained by a cruise control system)	Maintain a speed of 45mph	Maintain a speed of 45mph, respond to leading vehicle brake events
Lane-keeping performance	- Smaller lane variability - Higher coherence of steering and wind	- Smaller lane variability - Higher coherence of steering and wind	- Smaller lane variability
Steering behaviors	- Higher steering reversal rate	- Higher steering reversal rate	- Shorter steering response time - Higher steering reversal rate
Longitudinal performance	- None	- More variable speed	- More variable headway time
Eye scanning	- No gaze concentration	- No gaze concentration	- No gaze concentration

Experiment 1 asked drivers to drive under heavy lateral wind (the sum of three sinusoid waves) with the assistance of a cruise control system. Distracted drivers produced smaller lane variability and a higher steering reversal rate. Spectral analysis showed that the coherence value of lateral wind and steering wheel position was higher under dual-task conditions than under drive-only conditions. Thus, Experiment 1 suggested that the smaller lane variability under cognitive distraction indicates a performance gain in lane-keeping.

Experiment 2 extended the findings of Experiment 1 by introducing a speed maintenance task, and explored the possible mechanisms of lane-keeping performance change. Drivers in Experiment 2 were asked to keep a steady lane position under heavy lateral wind while maintaining a speed of 45 MPH. Experiment 2 replicated the finding of Experiment 1: drivers produced smaller lane variability and higher coherence between lateral wind and steering wheel position. Additionally, Experiment 2 found that the cognitive distraction task impaired speed maintenance, as shown in more variable speed in dual-task conditions. Experiment 2 also introduced two sets of variables to compare drivers' efforts in adjusting steering and speed. Drivers were more active in adjusting steering wheel position and less active in adjusting speed when they were in dual-task conditions. Drivers' increasing efforts in steering adjustment and decrease in speed manipulation suggested that drivers under distractions may achieve better lane-keeping performance by prioritizing lane-keeping performance.

Experiment 3 was devoted to exploring the underlying mechanisms of lane-keeping performance change. Inspired by the car-following paradigm, Experiment 3 implemented leading vehicle brake hazards and heavy lateral wind onset hazards.

Brake response time to leading vehicle brake hazards and steering response time to lateral wind onset provided a direct comparison of the car-following and lane-keeping performance. Experiment 3 found smaller lane variability under dual-task conditions. More importantly, the steering response time to lateral wind onset was reduced and steering reversal rate was increased under dual-task condition. Longitudinal performance was impaired, as evident in more variable headway time. Data thus supported the lateral prioritization hypothesis, which suggests that drivers put more efforts in steering adjustment when they engaged in a cognitive distraction task.

Discussion

In the three experiments in this dissertation project, and many other studies (Becic, Dell, Bock, Garnsey, Kubose, Kramer, 2010; Brookhuis, et al., 1991; Horrey & Simons, 2007; Horrey & Wickens, 2004; Kubose et al., 2006; Liang & Lee, 2010;), have found that cognitive distraction tasks reduce lane variability (However, see Horrey, Lesch, Garabet (2009), Just, Keller, Cynkar (2008), and Salvucci & Beltowska (2008) for findings of larger lane variability under cognitive distractions).

The finding of smaller lane variability under cognitive distraction is counterintuitive. On one hand, smaller lane variability should reduce the risks of lane excursions or collisions with vehicles in the neighboring lanes. Therefore, smaller lane variability should be taken as a performance gain. On the other hand, cognitive distraction tasks are known to cause performance losses in many other aspects of driving, for example, narrowing of visual scanning (Recarte & Nunes, 2000; Hammel et al. 2002), slower response to traffic events and emergency (Hancock et al., 2003; Patten et al. 2004; Strayer et al., 2003; Strayer and Johnston, 2001), more variable

speed control (Horrey & Wickens, 2004), and poor attentional processing of driving related information in the scene (Simons & Chabis, 1999; Strayer & Johnston, 2001; Strayer et al., 200; Strayer et al., 2007). Intuitively, cognitive distraction tasks should impair lane-keeping too.

Then, does the smaller lane variability under cognitive distractions indicate a performance gain or a performance loss in lane-keeping? Because researchers have debated the performance implication of smaller lane variability, this dissertation project sought several alternative ways to measure lane-keeping performance. In Experiment 1 and 2, a spectral coherence analysis of steering wheel and lateral wind was used to measure lane-keeping performance. The lateral wind in Experiment 1 and 2 was made of a combination of three sinusoid waves. The spectral coherence analysis had lateral wind strength and reversed steering wheel position as inputs, and generates a coherence value, which measured the coupling of steering wheel and lateral wind, with higher coherence value indicated better performance steering response to lateral wind. In both Experiment 1 and 2, coherence values were higher in dual-task conditions, compared to drive-only conditions. The spectral coherence analysis suggested that distracted drivers had better steering response to lateral wind. Experiment 3 measured lane-keeping performance using the steering response time to the onset of lateral wind hazard. The steering response time was smaller in the dual-task conditions, relative to drive-only conditions. Moreover, in all three experiments, the steering reversal rate was higher in dual-task conditions, which suggested that distracted drivers invest more efforts in steering adjustment. The higher coherence of steering and lateral wind, quicker steering response time to lateral wind, and higher steering reversal rate all suggest that smaller lane variability under cognitive distractions indicates a performance gain of lane-keeping.

The rigidified steering hypothesis, which interprets smaller lane variability as an indicator of performance loss, was not supported. The rigidified steering hypothesis predicts smaller steering reversal rate under dual-task conditions. However, in all three experiments, the steering reversal rate was higher in dual-task conditions. Higher steering reversal rates under cognitive distraction have also been reported in several other studies (Engström, et al. , 2005; Östlund, et al. , 2004; Ranney et al., 2005). The rigidified steering hypothesis also proposes that attention resources are shifted away from steering control. With less resources invested in steering, steering responses to lateral wind should be delayed. In fact, data showed better steering responses to lateral wind in all three experiments. In Experiment 1 and 2, the coherence of steering wheel position and lateral wind strength was higher in dual-task conditions, which suggests better coupling of steering and lateral wind under cognitive load. In Experiment 3, distracted drivers produced quicker steering response time to the sudden onset of lateral wind. Therefore, smaller lane variability should not be an indicator of performance loss in lane-keeping, contrary to the claim of the rigidified steering hypothesis.

Then, how do distracted drivers achieve a better lane-keeping performance? According to the literature, drivers may achieve this by three possible mechanisms, that is, the visual enhancement hypothesis, automatic steering hypothesis, and lateral prioritization hypothesis.

First, according to the visual enhancement hypothesis, distracted drivers may improve lane-keeping by narrowing visual scanning window, thereby, improving perceptual processing of scenes in the forward views (Engström, et al. , 2005; Östlund, et al. , 2004). Narrowing of visual scanning window under cognitive load conditions has been reported in several studies (Recarte & Nunes, 2000,2003). The

distribution of focused attention in three-dimensional space is ellipsoidal, with higher attentional processing ability in the forward view and at closer distance (Anderson, 1990; Anderson & Kramer, 1993). Therefore, narrower visual scanning might improve the processing of information in the forward view, allowing better steering adjustments to keep a more stable lane position.

Although plausible, the visual enhancement hypothesis is not supported by experiments in this dissertation or several previous studies. The visual enhancement hypothesis interprets smaller lane variability as a by-product of an attentional narrowing effect. However, in Experiments 2 and 3, lane variability was reduced under dual-task conditions without an attention narrowing effect (Experiment 1 did not collect eye scanning patterns). The standard deviation of horizontal fixation position was unchanged for dual-task conditions and drive-only conditions. Therefore, the smaller lane variability in Experiment 2 and 3 could not have resulted from visual enhancement caused by gaze concentration. Furthermore, supposing visual enhancement did play a role in the smaller lane variability in Experiment 2 and 3, it should have had positive effects on both steering response and speed manipulation. Experiment 2 and 3 actually showed that a digit-ordering task improved steering responses to lateral wind while compromising longitudinal performance.

Moreover, the visual enhancement hypothesis also sits poorly with existing findings, i.e., inattention blindness and neural activations. The visual enhancement hypothesis posits better processing of visual information under cognitive load. However, cognitive distraction actually causes poor recognition memory of driving scenes. Strayer et al. (2001, 2003, 2007) reported that drivers engaging in a cell phone conversation often failed to recognize objects in the driving scenes, even if they had fixated on these objects directly, potentially suggesting a form of inattentional

blindness. Neuroscience studies further showed that the amplitude of P300 of ERP waves, which reflects high-level cognitive processing of visual information, was reduced by half when drivers were engaging in a cell phone conversation as compared to drive-only conditions (Strayer et al., 2007). A study using functional magnetic resonance imaging showed that the parietal lobe activation, which is involved in the processing of spatial information, was decreased by 37% when participants were concurrently listening to sentences in response to a simulated driving task relative to single-task driving conditions (Just et al., 2008). The reduced cortical activation in response to driving information argues against the visual enhancement hypothesis, which predicts better attentional processing under dual-task condition. Even if visual enhancement does contribute to the improvement of lane-keeping performance, finally, its influence is evidently small. Liang and Lee (2010) reported that gaze concentration, measured using the product of standard deviation of the horizontal and vertical fixation location, could only explain only 10% variance of steering error and 5% of the variance in lane position.

Second, according to the automatic steering hypothesis, distracted drivers may improve lane-keeping by shifting attentional resources away from steering, which allows less interference from conscious control (Kubose et al., 2006). Studies showed that more attention may be detrimental for highly practiced and automatic sensorimotor skills (Beilock et al., 2001; Beilock et al., 2002). For example, experienced golfers produced better putting performance in dual-task conditions, compared to skill-focused conditions. Experienced soccer players also performed better in the dual-task conditions when using their dominant right foot (Beilock, Carr, MacMahon, Starkes, 2002). Similarly for driving, steering control might be treated as an automatic skill. According to the logics of the automatic steering hypothesis,

steering control will be better in the dual-task conditions, in which the cognitive task takes attention away from steering. This hypothesis regards smaller lane variability as a performance gain, resulting from better automatic steering. One elementary assumption of the automatic steering hypothesis is that attention is shifted away from steering in dual-task condition. With less attention allocated to steering, the automatic skill of steering is improved.

The automatic steering hypothesis can claim that drivers can automatically adjust steering reversal rate according to the needs of lane-keeping. Thus, it is hard to test the automatic steering hypothesis with either lane variability or steering reversal rate. Nevertheless, the steering response time to lateral wind onset in Experiment 3 provides a good way to test the automatic steering hypothesis. Steering control under eventless period may be treated as an automatic process, but steering response to sudden unexpected events, for example, lateral wind gusts, is a controlled process, requiring attention resources (Sanfey & Chang, 2008). The automatic steering hypothesis assumes less attention devoted to steering under dual-task conditions. Therefore, this hypothesis expects longer steering response time to sudden onset of lateral wind. However, Experiment 3 shows that steering response time to lateral wind was actually reduced in dual-task conditions. Data thus argue against the automatic steering hypothesis.

Third, according to the lateral prioritization hypothesis, distracted drivers improve lane-keeping by actively prioritizing lateral control (Engström, et al. , 2005; Kubose et al., 2006). Driving may be treated as a satisficing process, and drivers have a subjective safety margin (Boer, 2000). The lateral prioritization hypothesis is most congruent with the three experiments in this dissertation project, and with existing studies. With the shifts of attentional resources from other subtasks of driving to lane-

keeping, the lateral prioritization hypothesis predicts an improvement in lane-keeping performance and a loss of performance in other aspects of driving, for example, speed maintenance and car-following. These predictions are confirmed in the three studies. First, lane-keeping performance was improved in dual-task conditions, with higher coherence values of steering position and lateral wind in Experiments 1 and 2, and quicker steering response time to sudden onset of lateral wind in Experiment 3. Second, distracted drivers consistently invested more efforts in lane-keeping, producing higher steering reversal rates in dual-task conditions in all three experiments. Moreover, the performance improvement of lane-keeping comes with a loss of longitudinal performance. Drivers in dual-task conditions produced more variable speed in Experiment 2, and larger standard deviation of headway time in Experiment 3. The more active steering control seen in dual-task conditions was accompanied with a decrease in speed manipulation frequency in Experiment 2. An increase in lane-keeping performance and a decrease in longitudinal performance suggest a prioritization strategy of drivers engaging in a cognitive distraction task. The lateral prioritization hypothesis also finds support in many existing studies (Alm & Nilsson, 1994; Becic, et al., 2010; Beede & Kass, 2006; Engström, et al., 2005; Kubose et al., 2006; Liang & Lee, 2010; Östlund et al., 2004; Seppelt & Wickens, 2003; Victor, et al., 2005). Several studies have shown that improvements in lane keeping in dual-task conditions often accompany an impairment of longitudinal driving performance. For example, Kubose et al. (2006) found that a language production task reduced the lane variability, and increased the standard deviation of velocity and headway time in the high load conditions. Other research has suggested that as driving risks increase, drivers may prioritize driving performance. For example, Becic et al. (2010) found that driver's storytelling performance decreased as

the difficulty of driving increased. They suggested that drivers prioritized the driving tasks even when talking. Drivers are likely to prioritize the visual guidance of lane-keeping over recognition of peripheral objects, planning tasks, and speed maintenance (Seppelt & Wickens, 2003; Victor, et al., 2005). More interestingly, task priority indeed influences variability in lane keeping. Horrey, Wickens and Consalus (2006) reported that variability in lane keeping was the lowest when drivers were prioritizing the driving task, compared to equal prioritization of driving and in-vehicle distraction task, and prioritization of an in-vehicle distraction task.

Thus, data from the current three experiments and existing studies suggest that drivers achieve better lane-keeping performance by actively prioritizing lateral control. Then, how do drivers prioritize lane-keeping? Drivers may prioritize lane-keeping in either or a combination of two ways.

First, drivers can prioritize lane-keeping by increasing their overall arousal level. Under easy driving conditions, drivers may not use all available resources in driving, as long as they stay in their comfortable safety zone (Boer, 2000). When driving demand increases or when a cognitive distraction task raises driving risk, drivers can protect their driving performance by increasing the overall arousal level, investing more efforts in driving. Increases of arousal level have been confirmed in many studies, which have shown that drivers report higher workload in dual-task conditions (Alm & Nilsson, 1995; Brookhuis, de Vries, & de Waard, 1991; Rakauskas, et. al., 2004; Reimer, et. al., 2009). For example, drivers reported higher workload when talking with a passenger or over the cellular phone, compared to drive-only conditions (Lalberge, Scialfa, White, Caird, 2004).

Second, drivers can prioritize lane-keeping by compromising other aspects of driving, such as , visual scanning and speed control. Drivers engaging in a cognitive

distraction task may be more concerned about their lane position, therefore, shift resources from other subtasks of driving to lane-keeping. This compensatory strategy of lane-keeping can allow drivers to keep a straighter lane position, but at the cost of further performance decrement in other aspects of driving. For example, in Experiment 2 and 3, drivers engaging in a digit-ordering task invested more efforts in lane-keeping with higher steering reversal rate, in the meanwhile, they reduced speed manipulation frequency.

Future Research

This dissertation tries to compare four hypotheses about smaller lane variability under cognitive distractions. Though I have accumulated some solid evidence in favor of the lateral prioritization hypothesis, it is not enough to draw a decisive conclusion on all alternative explanations. For example, the smaller lane variability in three experiments was found independent of a gaze concentration effect, therefore, cannot be explained by a visual enhancement hypothesis. However, the visual enhancement hypothesis may still play a role in the improvement of lane-keeping performance when gaze concentration effect actually does happen, although its contribution may be small (Liang & Lee, 2010) and it appears to be at odds with the inattentional blindness phenomenon in driving (Strayer, et al., 2001, 2003, 2007). Future studies should examine the possibility of visual enhancement hypothesis and automatic steering hypothesis more closely, for example, by using an object recognition or detection task to examine whether cognitive distraction tasks improve visual processing in the forward view, as claimed by the visual enhancement hypothesis.

Future studies should also measure secondary task performance and workload. This research shows that drivers prioritize lane-keeping by sacrificing other aspects of driving, for example, speed maintenance. Previous studies suggest that drivers may also prioritize lane-keeping performance by reducing secondary task performance, or increasing overall workload. Future studies can compare secondary task performance when it is carried out alone with when drivers do secondary task and driving concurrently to test whether drivers moderate secondary task performance to prioritize lane-keeping. Measurement of workload in the future studies can show whether drivers increase overall arousal level to protect lane-keeping performance.

Future studies may also consider using cognitive modeling, for example, the Threaded Cognition model based on ACT-R or Queuing Network model, to validate behavioral findings. Salvucci and colleagues successfully modeled an increase of lane variability by a memory rehearsal task using the ACT-R framework (Salvucci & Beltowska, 2008; Salvucci & Taatgen, 2008). They proposed independent threads for a secondary task, steering and speed manipulation. If by adjusting the priority of threads scheduling, the Threaded Cognition model can fit both an increase and a decrease of lane variability under different task priority instructions, for example, the data reported by Horrey et al. (2006). This will provide a theoretical test of the lateral prioritization hypothesis from a cognitive modeling approach.

REFERENCES

- Ahmad, I.A. & Alwasel, I. A. (1999). A goodness-of-fit test for exponentiality based on the memoryless property. *Journal of the Royal Statistical Society: Series B*, 61(3), 681-689.
- Alm, H. , & Nilsson, L.(1994). Changes in driver behaviour as a function of handsfree mobile phones: A simulator study. *Accident Analysis and Prevention*, 26 (4), 441–451.
- Alm, H., & Nilsson, L. (1995). The effects of a mobile telephone task on driver behaviour in a car following situation. *Accident Analysis & Prevention*, 27(5), 707-715.
- Andersen, G.J. (1990). Focused attention in three-dimensional space. *Perception & Psychophysics* 47, 112–120.
- Andersen, G.J., & Kramer, A.F. (1993). Limits of focused attention in three-dimensional space. *Perception & Psychophysics*, 53(6):658-667.
- Andersen, G. J., & Ni, R. (2005). The spatial extent of attention during driving. *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 395-400.
- AT&T Labs Natural Voices. Retrieved from <http://www2.research.att.com/~ttsweb/tts/demo.php>
- Baddeley, A.D. (1986). *Working Memory*. Oxford University Press, Oxford.
- Baddeley, A.D. (1996). Exploring the central executive. *The Quarterly Journal of Experimental Psychology*, 49, 5–28.

- Baddeley, A. D. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience*, 4(10), 829-839.
- Barickman, F.S., Smith, L., & Jones, R. (2007). Lane departure warning system research and test development. *Proceedings of the 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France, June 18-21, 2007*. Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration.
- Becic, E., Dell, G.S., Bock, K., Garnsey, S. M., Kubose, T., & Kramer, F. (2010). Driving impairs talking. *Psychonomic Bulletin & Review*, 17(1), 15-21.
- Beede, K.E., & Kass, S.J. (2006). Engrossed in conversation: The impact of cell phones on simulated driving performance. *Accident Analysis and Prevention*, 38, 415-421.
- Bellinger, D. B., Budde, B. M., Machida, M., Richardson, G. B., & Berg, W. P. (2009). The effect of cellular telephone conversation and music listening on response time in braking. *Transportation Research: Part F*, 12 (6), 441-451.
- Boer, E.R. (2000). Behavioral entropy as an index of workload. *44th Annual Meeting of the Human Factors and Ergonomics Society (HFES2000)*, San Diego, CA, July 30 - August 4, 2000.
- Briem, V. , & Hedman, L.R. (1995). Behavioral effects of mobile telephone use during simulated driving. *Ergonomics*, 38, 2536–2562.
- Brookhuis, K. A., de Vries, G., & de Waard, D. (1991). The effects of mobile telephoning on driving performance. *Accident Analysis and Prevention*, 23 (4), 309-316.

- Brookhuis, K. A., & de Waard, D. (1993). The use of psychophysiology to assess driver status. *Ergonomics*, 36, 1099–1110.
- Brookhuis, K., de Waard, D., & Mulder, B. (1994). Measuring driving performance by car-following in traffic, *Ergonomics*, 37(3), 427-434.
- Brookhuis, K. A., & de Waard, D. (2001). Assessment of drivers' workload: Performance and subjective and physiological indexes. In P.A. Hancock & P. A. Desmond (Eds.), *Stress, Workload, and Fatigue* (pp. 321–333). Mahwah, NJ: Erlbaum.
- Brown, I. D., Tickner, A. H., & Simmonds, D. C. V. (1969). Interference between concurrent tasks of driving and telephoning. *Journal of Applied Psychology*, 53 (5), 419-424.
- Caird, J., Willness, C., Steel, P., & Scialfa, C. (2008). A meta-analysis of the effects of cell phones on driver performance. *Accident Analysis and Prevention*, 40(4), 1282-1293.
- Cliff, R. C. (1973). Attention sharing in the performance of a dynamic dual task. *IEEE Transactions on Systems, Man and Cybernetics*, SMC-3 (3), 241-248.
- Consiglio, W., Driscoll, P., Witte, M., & Berg, W.P.(2003). Effect of cellular telephone conversations and other potential interference on reaction time in a braking response. *Accident Analysis and Prevention*, 35, 495-500.
- Cooper, J., & Strayer, D. (2008). Effects of simulator practice and real-world experience on cell-phone-related driver distraction. *Human Factors*, 50(6), 893-902.
- Dastrup, E., Lees, M., Bechara, A., Dawson, J., & Rizzo, M. (2010). Risky car following in abstinent users of MDMA. *Accident Analysis and Prevention*, 42(3), 867-873.

- Dingus, T., McGehee, D., Hulse, M., Manakkal, N., Mollenbauer, M., & Fleischman, R.(1995). Travtek Evaluation Task C3—Camera Car Study, Performance and Safety Sciences, Inc., Iowa City.
- Dingus, T.A., Klauer, S.G., Neale, V.L., Petersen, A., Lee, S.E., & Sudweeks, J.(2006). The 100-Car Naturalistic Driving Study, Phase II—Results of the 100-Car Field Experiment (Report No. DOT HS 810 593), Washington, D.C. National Highway Traffic Safety Administration, 2006.
- DriveSafety. (2004). Company website. Retrieved from <http://www.drivesafety.com>.
- Endsley, M.R. (1995). Towards a theory of situation awareness in dynamic systems. *Human Factors*, 37, 32–64.
- Engström, J., Johansson, E., & Östlund, J. (2005). Effects of visual and cognitive load in real and simulated motorway driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8, 97-120.
- Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, 40, 225-240.
- Green, P., Hoekstra, E., & Williams, M.(1993). On-the-Road Tests of Driver Interfaces: Examination of a Route Guidance System and a Car Phone, University of Michigan Transport Research Institute, Washington, D.C.
- Green, P. (2004). Driver distraction, telematics design, and workload managers: Safety issues and solutions. Society of Automotive Engineers, Paper No. 2004-21-0022.

- Greenberg, J., Tijerina, L., Curry, R., Artz, B., Cathey, L., Grant, P., Kochlar, D., Kozak, K., & Blommer, M. (2003). Evaluation of driver distraction using an event detection paradigm. *Journal of the Transportation Research Board*, 1843, 1–9.
- Groot, S., Winter, J. C. F., López-García, J. M., Mulder, M., & Wieringa, P. A. (2011). The effect of concurrent bandwidth feedback on learning the lane keeping task in a driving simulator. *Human Factors*, 53, 50-62.
- Haigney, D. , & Westerman, S. J. (2001). Mobile (cellular) phone use and driving: A critical review of research methodology. *Ergonomics*, 44(2), 132–143.
- Harbluk, J. L., Noy, Y. I., Trbovich, P. L., & Eizenman, M. (2007). An on-road assessment of cognitive distraction: impacts on drivers' visual behavior and braking performance. *Accident Analysis and Prevention*, 39(2), 372–379.
- Hazeltine, E., Ruthruff, E., & Remington, R. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, 52(4), 291-345.
- He, J., & McCarley, J. S. (2011). Effects of cognitive distraction on lateral lane keeping performance. *Proceedings of Human Factors and Ergonomics Society*, CA.
- He, J., Becic, E., Lee, Y.C., & McCarley, J. S. (2011). Mind wandering behind the wheel: Performance and oculomotor correlates. *Human Factors*, 53(1),13-21.
- Horrey, W., Lesch, M., & Garabet, A. (2009). Dissociation between driving performance and drivers' subjective estimates of performance and workload in dual-task conditions. *Journal of Safety Research*, 40(1), 7-12.
- Horrey, W., & Simons, D. (2007). Examining cognitive interference and adaptive safety behaviours in tactical vehicle control. *Ergonomics*, 50(8), 1340-1350.

- Horrey, W., & Wickens, C. (2006). Examining the impact of cell phone conversations on driving using meta-analytic techniques. *Human Factors*, 48(1), 196-205.
- Horrey, W., Wickens, C., & Consalus, K. (2006). Modeling drivers' visual attention allocation while interacting with in-vehicle technologies. *Journal of Experimental Psychology: Applied*, 12(2), 67-78.
- Horswill, M.S., & McKenna, F.P. (1999). The development, validation, and application of a video-based technique for measuring an everyday risk-taking behavior: driver's speed choice. *Journal of Applied Psychology*, 84 (6), 977-985.
- Hurts, K. (2011). Driver distraction, crosstalk, and spatial reasoning. *Transportation Research Part F*, (14),300–312.
- Iowa Comprehensive Highway Safety Plan (2006). Retrieved September, 10, 2011. http://www.iowadot.gov/traffic/chsp/pdfs/chsp_final_20070420.pdf
- Jamson, A., & Merat, N. (2005). Surrogate in-vehicle information systems and driver behaviour: Effects of visual and cognitive load in simulated rural driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, 8, 79-96.
- Janacek, G.J., 2008. Spectral analysis. In: *Encyclopedia of Biostatistics*, second ed. JohnWiley & Sons, Inc., New York.
- Jancke, L., Musial, F., Vogt, J., and Kalveram, K.T. (1994). Monitoring radio programs and time of day effect simulated car-driving performance. *Perceptual and Motor Skills*, 79, 484–486.
- Just, M.A., Keller, T.A., & Cynkar, J.A. (2008). A decrease in brain activation associated with driving when listening to someone speak. *Brain Research*, 1205, 70-80.
- Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, N.J.: Prentice Hall.

- Kass, S.J., Cole, K.S., & Stanny, C.J. (2007). Effects of distraction and experience on situation awareness and simulated driving. *Transportation Research F: Psychology and Behaviour*, 10, 321–329.
- 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 (No. DOT HS 810 594). Washington, DC: National Highway Traffic Safety Administration.
- Kramer, A. F., Larish, J., & Strayer, D. L. (1995). Training strategies for attentional control in dual-task settings: A comparison of young and old adults. *Journal of Experimental Psychology: Applied*, 1, 50-76.
- Kubose, T. T., Bock, K., Dell, G. S., Garnsey, S. M., Kramer, A. F., & Mayhugh, J. (2006). The effects of speech production and speech comprehension on simulated driving performance. *Applied Cognitive Psychology*, 20, 43-63.
- Laberge, D. (1983). Spatial extent of attention to letters and words. *Journal of Experimental Psychology: Human Perception & Performance*, 9, 371-379.
- Laberge, J., Scialfa, C., White, C., and Caird, J.(2004). Effects of passenger and cellular phone conversations on driver distraction. *Transportation Research Record: Journal of the Transportation Research Board*, 1899, 109–116.
- Lamble, D., Kauranen, T., Laasko, M., & Summala, H.(1999).Cognitive load and detection thresholds in car following situations: Safety implications for using mobile (cellular) telephones while driving. *Accident Analysis and Prevention*, 31, 617-623.
- Langham, M., Hole, G., Edwards, J., & O'Neil, C.(2002). An analysis of 'looked but failed to see' accidents involving parked police vehicles. *Ergonomics*, 45 (3), 167-185.

- Lansdown, T.C. (2002). Individual differences during driver secondary task performance: Verbal protocol and visual allocation findings. *Accident Analysis and Prevention*, 34, 655–662.
- Lee, J. D., McGehee, D. V., Brown, T. L., & Reyes, M. L. (2002). Collision warning timing, driver distraction, and driver response to imminent rear-end collisions in a high-fidelity driving simulator. *Human Factors*, 44(2), 314-334.
- Lee, J. D., Vaven, B., Haake, S., & Brown, T. L. (2001). Speech-based interaction with in-vehicle computers: The effects of speech-based E-mail on drivers' attention to the roadway. *Human Factors*, 43, 631–640.
- Levy, J., Pashler, H., & Boer, E. (2006). Central interference in driving: Is there any stopping the psychological refractory period? *Psychological Science*, 17(3), 228-235.
- Liang, Y., & Lee, J. (2010). Combining cognitive and visual distraction: Less than the sum of its parts. *Accident Analysis and Prevention*, 42(3), 881-890.
- Lien, M., Ruthruff, E., & Johnston, J. (2006). Attentional limitations in doing two tasks at once : The search for exceptions. *Current Directions in Psychological Science*, 15(2), 89-93.
- Loftus, G. R. & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, 1, 476-490.
- Mack, A., & Rock, I. (1998). *Inattention blindness*. Cambridge, MA: MIT Press.
- MacDonald, W.A. & Hoffmann, E.R. (1980). Review of relationships between steering wheel reversal rate and driving task demand. *Human Factors*. 22(6): 733-739.

- Marcotte, T. D., E. Roberts, et al. (2003). Test-retest reliability of standard deviation of lane position as assessed on a PC based driving simulator. *2nd International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*.
- Mazzae, E. N., Goodman, M., Garrott, W. R., and Ranney, T. A. (2005). NHTSA's research program on wireless phone driver interface effects. *In Proceedings of the 19th International Technical Conference on the Enhanced Safety of Vehicles*, National Highway Traffic Safety Administration, Washington, D.C., 2005.
- McCarley, J., Vais, M., Pringle, H., Kramer, A., Irwin, D., & Strayer, D. (2004). Conversation disrupts change detection in complex traffic scenes. *Human Factors*, 46(3), 424-436.
- McKnight, A.J. ,& McKnight, A.S. (1993). The effect of cellular phone use upon driver attention. *Accident Analysis and Prevention*, 25(3), 259:265.
- Mehler, B., Reimer, B., Coughlin, J.F., & Dusek, J.A. (2009). The Impact of incremental increases in cognitive workload on physiological arousal and performance in young adult drivers. *Transportation Research Record*, 2138, 6-12.
- Meyer, D. E., & Kieras, D. E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part 1. *Psychological Review*, 104(1), 3.
- Most, S., Simons, D., Scholl, B., Jimenez, R., Clifford, E., & Chabris, C. (2001). How not to be seen: The contribution of similarity and selective ignoring to sustained inattention blindness. *Psychological Science*, 12(1), 9-17.

- Most, S. B., Scholl, B. J., Clifford, E., & Simons, D. J. (2005). What you see is what you set: Sustained inattention blindness and the capture of awareness. *Psychological Review*, 112(1), 217-242.
- Navon, D., & Gopher, D. (1979). On the economy of the human processing system. *Psychological Review*, 86, 214–255.
- Navon, D., & Miller, J. (1987). Role of outcome conflict in dual task interference. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 435-448.
- Navon, D., & Miller, J. (2002). Queuing or sharing? A critical evaluation of the single-bottleneck notion. *Cognitive Psychology*, 44(3), 193-251.
- Norman, D.A. ,& Bobrow, D.G. (1975). On data-limited and resource limited processes. *Cognitive Psychology*, 7,44-64.
- Nunes, L.M., & Recarte, M.A. (2005). Speed, traffic complexity, and visual performance: A study on open road. In G. Underwood (Ed.), *Traffic and Transport Psychology: Theory and Application* (pp. 339–354). Amsterdam: Elsevier.
- Osman, A., & Moore, C.M. (1993). The locus of dual-task interference: Psychological refractory effects on movement-related brain potentials. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 1292–1312.
- Östlund, J. Carsten, O., Merat, N., Jamson, S., Janssen, W., & Brouwer, R., et al. (2004). Deliverable 2—HMI and safety-related driver performance. *Human Machine Interface And the Safety of Traffic in Europe (HASTE) Project*, Report No. GRD1/2000/25361 S12.319626.

- Pashler, H. (1990). Do response modality effects support multiprocessor models of divided attention. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 826 - 842.
- Pashler, H., Carrier, M., & Hoffman, J. (1993). Saccadic eye movements and dual-task interference. *Quarterly Journal of Experimental Psychology*, 46, 51-82.
- Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin*, 116(2), 220-244.
- Pashler, H., & Johnston, J. C. (1998). Attentional limitations in dual-task performance. In H. Pashler (Ed.), *Attention*, Psychology Press/Erlbaum (Uk) Taylor & Francis, Hove, England, 155-189.
- Patten, C.J.D., Kircher, A., Östlund, J., & Nilsson, L. (2004). Using mobile telephones: cognitive workload and attention resource allocation. *Accident Analysis and Prevention*, 36(3), 341–350.
- Pohlmann, S., & Traenkle, U. (1994). Orientation in road traffic: Age-related differences using an in-vehicle navigation system and a conventional map. *Accident Analysis and Prevention*, 26, 689-702.
- Poysti, L., Rajalin, S., & Summala, H. (2005). Factors influencing the use of cellular (mobile) phone during driving and hazards while using it. *Accident Analysis and Prevention*, 37, 47–51.
- Radeborg, K., Briem, V., & Hedman, L.R. (1999). The effect of concurrent task difficulty on working memory during simulated driving. *Ergonomics*, 42 (5),767-777.
- Ranney, T. A., Harbluk, J.L., & Noy, Y.I. (2005). Effects of voice technology on test track driving performance: Implications for driver distraction. *Human Factors*, 47(2), 439-454.

- Rakauskas, M., Gugerty, L., & Ward, N. (2004). Effects of cell phone conversation on driving performance with naturalistic conversations. *Journal of Safety Research, 35*, 453-464.
- Recarte, M., & Nunes, L. (2000). Effects of verbal and spatial-imagery tasks on eye fixations while driving. *Journal of Experimental Psychology: Applied, 6*(1), 31-43.
- Recarte, M., & Nunes, L. (2003). Mental workload while driving: Effects on visual search, discrimination, and decision making. *Journal of Experimental Psychology: Applied, 9*(2), 119-137.
- Redelmeier, M.D. ,& Tibshirani, R.J. (1997). Association between cellular-telephone calls and motor vehicle collisions. *The New England Journal of Medicine, 336*, 453-458.
- Reed, M.P. , & Green, P.A.(1999). Comparison of driving performance on-road and in a low-cost simulator using a concurrent telephone dialling task. *Ergonomics, 42* (8), 1015–1037.
- Reimer, B. (2009). Cognitive task complexity and the impact on drivers' visual tunneling. *Transportation Research Record, 2138*, 13-19.
- Reimer, B., Mehler, B., Coughlin, J.F., Godfrey, K., & Tan, C. (2009). An on-road assessment of the impact of cognitive workload on physiological arousal in young adult drivers. *Proceedings of the 1st International Conference on Automotive User Interfaces and Interactive Vehicle Applications*. Essen, Germany, 115-118.
- Regan, M. A., Lee, J. D., & Young, K. L. (2008). *Driver Distraction: Theory, Effects, and Mitigation*. CRC Press.

- Rizzo, M., Stierman, L., Skaar, N., Dawson, J.D., Anderson, S.W., & Vecera, S.P. (2004). Effects of a controlled auditory-verbal distraction task on older driver vehicle control. *Journal of the Transportation Research Board*, 1865, 1-6.
- Salvucci, D. D., & Beltowska, J. (2008). Effects of memory rehearsal on driver performance: Experiment and theoretical account. *Human Factors*, 50, 834–844.
- Salvucci, D., & Taatgen, N. (2008). Threaded cognition: An integrated theory of concurrent multitasking. *Psychological Review*, 115(1), 101-130.
- Salvucci, D. D. (2005). A multitasking general executive for compound continuous tasks. *Cognitive Science*, 29, 457-492.
- Seppelt, B., & Wickens, C. D. (2003) In-Vehicle Tasks: Effects of Modality, Driving Relevance, and Redundancy. Technical Report AHFD-03-16/GM-03-2. Savoy, IL: University of Illinois, Aviation Human Factors Division.
- Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattention blindness for dynamic events. *Perception*, 28, 1059-1074.
- Sodhi, M., Reimer, B., & Llamazares, I. (2002). Glance analysis of driver eye movements to evaluate distraction. *Behavior Research Methods, Instruments and Computing*, 34, 529–538.
- Son, J., Reimer, B., Mehler, B., Pohlmeier, A.E., Godfrey, K.M., Orszulak, J., Long, J. Kim, M.H., Lee, Y.T., & Coughlin, J.F. (2010). Age and cross-cultural comparison of drivers' cognitive workload and performance in simulated urban driving. *International Journal of Automotive Technology*, 11(4), 533-539.
- Spence, C., & Ho, C. (2008). Multisensory interface design for drivers: Past, present and future. *Ergonomics*, 51(1), 65–70.

- Spence, C., & Read, L. (2003). Speech shadowing while driving: On the difficulty of splitting attention between eye and ear. *Psychological Science*, 14(3), 251–256.
- Spijkers, W., Heuer, H., Steglich, C., & Kleinsorge, T. (2000). Specification of movement amplitudes for the left and right hands: Evidence for transient parametric coupling from overlapping-task performance. *Journal of Experimental Psychology: Human Perception and Performance*, 26, 1091–1105.
- Sanfey, A. G. & Chang, L.J. (2008). Multiple systems in decision making. *Annals of the New York Academy of Sciences*, 1128, 53-62.
- Strayer, D., & Drews, F. (2007). Cell-phone-induced driver distraction. *Current Directions in Psychological Science*, 16(3), 128-131.
- Strayer, D. L., Drews, F. A., & Crouch, D. J.(2006). A comparison of the cell phone driver and the drunk driver. *Human Factors*, 48, 381-391.
- Strayer, D.L., & Drews, F. A. (2004). Profiles in driver distraction: Effects of cell phone conversations on younger and older drivers. *Human Factors*, 46, 640-649.
- Strayer, D., Drews, F., & Johnston, W. (2003). Cell phone-induced failures of visual attention during simulated driving. *Journal of Experimental Psychology : Applied*, 9(1), 23-32.
- Strayer, D., & Johnston, W. (2001). Driven to distraction: Dual-task studies of simulated driving and conversing on a cellular telephone. *Psychological Science*, 12(6), 462-466.
- Theeuwes, J., Alferdinck, J. W. A. M., & Perel, M. (2002). Relation between glare and driving performance. *Human Factors*, 44, 95–107.

- Victor, T., Harbluk, J., & Engström, J. (2005). Sensitivity of eye-movement measures to in-vehicle task difficulty. *Transportation Research Part F- Traffic Psychology and Behavior*. 8(2), 167-190.
- Wann J.P., & Swapp D.K. (2000) Why you should look where you are going. *Nature Neuroscience*, 3, 647-648.
- Wang, J., & Knipling, R. R. (1994). *Single Vehicle Roadway Departure Crashes: Problem Size Assessment and Statistical Description*. DOT HS 808 113.
- Welford, A. T. (1952). The ‘‘psychological refractory period’’ and the timing of high speed performance—A review and a theory. *British Journal of Psychology*, 43, 2–19.
- Wickens, C.D. (1984). Processing resources in attention, in R. Parasuraman & D.R. Davies (Eds.), *Varieties of attention*, (pp. 63-102). New York: Academic Press.
- Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical Issues in Ergonomics Science*, 3(2), 159-177.
- Wikman, A., Nieminen, T., & Summala, H. (1998), Driving experience and time-sharing during in-car tasks on roads of different width. *Ergonomics*, 41 (3), 358–372.
- Wierwille, W.W., Antin, J.F., Dingus, T.A., & Hulse, M.C. (1988). Visual attentional demand of an in-car navigation display system. In A.G. Gale et al., (Eds.), *Vision in Vehicles— II* (pp. 307–316). Amsterdam: Elsevier
- Wierwille, W.W., 1993. Visual and manual demands of in-car controls and displays. In: B. Peacock and W. Karwowski, eds. *Automotive ergonomics*. Washington, DC: Taylor & Francis, 299–320.

- Wilson M, Chattington M, Marple-Horvat DE (2008). Eye movements drive steering: reduced eye movement distribution impairs steering and driving performance. *Journal of Motor Behavior*, 40(3),190-202.
- Yei-Yu Yeh, & Wickens, C. (1988). Dissociation of performance and subjective measures of workload. *Human Factors*, 30(1), 111-120.
- Zwahlen, H.T., Adams, C.C., & Schwartz, P.J. (1988). Safety aspects of cellular telephones in automobiles, *Proceedings of the ISATA Conference*, ISATA, Florence, Italy.
- Zylstra, B., Tsimhoni, O., Green, P., & Mayer, K.(2004). Driving performance for dialing, radio tuning, and destination entry while driving straight roads (Technical Report UMTRI-2003-35). Ann Arbor, MI: The University of Michigan Transportation Research Institute.