ABSTRACT

GEDEN, MICHAEL ALEXANDER. Two-track Mind: Perceptual Load and Driving Duration Moderate Mind Wandering. (Under the direction of Dr. Jing Feng).

A large portion of our day-to-day lives is spent with our heads in the clouds mind wandering. While often innocuous, there is mounting evidence that mind wandering may be dangerous and common during driving; however, little is known about where it may be particularly prevalent or dangerous. This dissertation explores two common environmental variables, perceptual load and driving duration, and their relationship with mind wandering rate and cost. In experiment I participants drove in two scenarios of differential perceptual loads, a simple rural drive with no extraneous objects and a more visually complex rural drive. Experiment II focused on the influence of an extended driving duration on mind wandering and its impact on vehicular control. Experiment III increased the perceptual load disparity by comparing a busy rural road to an urban drive and looked at the impact on cued/un-cued braking events in order to explore where mind wandering may be particularly dangerous. Increased perceptual load was found to be associated with decreased rates of mind wandering, and longer driving durations with an asymptotic rise in the rate of mind wandering. A number of driving detriments were found in association with mind wandering, including more variable driving speed, smaller headway distance, and a decreased safety margin during braking events. This study shows that environmental factors are critical in understanding mind wandering prevalence and cost. Improving understanding of the relationship of mind wandering and driving will help the future development of driver alert systems and their effective deployment.

Two-track Mind: Perceptual Load and Driving Duration Moderate Mind Wandering

by
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BIOGRAPHY

Michael Alexander Geden is a doctoral student in the Human Factors and Applied Cognition Program in the Psychology Department at North Carolina State University. Michael earned his Bachelor of Science in Psychology from the University of Florida prior to starting his graduate career. During graduate school, Michael researched mind wandering, or task-unrelated thoughts, and their impact on driving and reading, as well as the mechanisms through which inattention influences behavior. Michael also had the opportunity to work with the Laboratory of Analytical Sciences on researching the process of anticipatory thinking and intern with SAS on the learnability of their technical documentation.

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INTRODUCTION

Driving is one of the most dangerous activities that we do in our daily lives. In 2015, 35,092 people died in the US alone in motor vehicle accidents (NHTSA, 2016). One of the leading causes of motor accidents is distracted driving (NHTSA, 2010), in which an individual is engaged in a secondary task involving visual, auditory, manual, and/or cognitive resources. Phone use has been found in numerous laboratory (Strayer & Johnston, 2001) and naturalistic studies (VTTI, 2010) to increase crash risk, particularly during texting where the individual often must look away from the road. The additional cognitive load of the task is thought to play a particularly large part in the cost of distracted driving (Lamble, Kauranen, Laakso, & Summala, 1999). A safety hazard that has received less attention is internal distraction; more specifically mind wandering. Mind wandering occurs often, with some studies showing mind wandering constituting as much as 50% of our waking thoughts (Killingsworth & Gilbert, 2010), and around 39% during simulated driving (Yanko & Spalek, 2014). A number of costs have been found to associate with mind wandering as well, including decreased sensitivity to external stimuli (Smallwood, Beach, Schooler, & Handy, 2008) and decreased encoding of information (Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012; Smallwood, Baracaia, Lowe, & Obonsawin, 2003). Several post-hoc studies have presented strong evidence that mind wandering may present a significant risk to driving safety; these results should be interpreted with some caution as they rely on the accuracy of post-accident self-reports of thought content. Erie Insurance (2012) found that 62% of distracted driving fatalities were associated with mind wandering; a rate five times higher than talking or texting on one’s phone. In addition, Galéra et al. (2012) found that individuals who reported having distracting thoughts at the time of an accident were significantly more likely to be responsible for the accident.

Given the large body of work on mind wandering there is little doubt about its potential negative impact in safety critical environments; however, the challenges of its prevention, detection, and management are nontrivial. The typical method of prevention used for external distractions (e.g. texting, using GPS, etc.) is the removal of the distractor from the environment, a strategy which is not possible for mind wandering as the thought content varies in terms of stimulus-relatedness and temporal focus (retrospective, prospective; Smallwood, Nind, & O'Connor, 2009). It is also unlikely that an individual could stop themselves from mind wandering completely as a large portion of mind wandering occurs without the awareness of the individual (Smallwood, McSpadden, & Schooler, 2008). With the possibility of prevention unavailable, the next best option is detecting the occurrence of mind wandering and intervening, and for this reason there is a strong push to develop tools for detecting mind wandering in real time (Lerner, Baldwin, Higgins, Lee, & Schooler, 2015). This line of research is still young, however there is some work showing promising results using eye tracking (D'Mello, Cobian, & Hunter, 2013) and response times (Franklin, Smallwood, & Schooler, 2011).

As prediction methods develop, the next question will be how this information can be used effectively to decrease mind wandering and improve performance. One approach is to intervene every time an individual is caught mind wandering and remind them to focus on the task; there are a number of reasons to believe why this approach may not be effective. The primary drawback would be the high volume of alerts necessary to keep the individual focused given the ubiquitous nature of mind wandering (30-50% of thoughts). If we assume that thought content can only change once a minute (an untenable assumption) and that people are mind wandering 33% of the time, this would give the low estimate of around one alert every three minutes. The high volume and low apparent utility of the alerts would be an ideal setting for the “cry wolf” effect, where the driver disregards or distrusts the alerts (Sorkin, 1988; Breznitz, 1983) due to the high proportion of low apparent impact. The secondary drawback is that this approach assumes that no mind wandering would be ideal for performance, a questionable assumption given the high workload required to maintain vigilance (Warm, Parasuraman, & Matthews, 2008). Finally, algorithms may not be sensitive to the differences between mind wandering and task-related interference as they are both internal stimulus-independent thoughts, but unlike mind wandering, task-related interference can benefit overall performance (for example planning a route) at the cost of momentary safety. Considering these challenges, intervention would be better saved for situations in which mind wandering would be particularly dangerous or frequent, rather than simply every occurrence. In order for this style of intervention to be implemented a better understanding of the impact of environmental factors on mind wandering rate and cost is required.

The goal of this dissertation is to explore the influence of two environmental factors on the relationship of driving safety and mind wandering; perceptual load of the driving environment and driving duration. These factors were selected based on previous research connecting them to driving performance and mind wandering, as well as their ease of integration in possible future alert systems. Sensitivity of mind wandering rate to perceptual load conditions was found in Forster & Lavie (2009), in which the rate of mind wandering decreased as the visual complexity of the task increased. No work has looked into the impact of perceptual load on mind wandering costs, or perceptual load on mind wandering within a driving context. Some evidence for the potential moderation of perceptual load on mind wandering costs can be found by drawing a corollary to external distraction research, where high perceptual load scenarios can exacerbate external distraction detriments to braking events (Strayer, Drews, & Johnston, 2003;

Strayer & Johnston, 2001).

Task duration is another important factor in understanding mind wandering as tasks with an extended duration are associated with an increase in the rate of mind wandering (Smallwood, Obonsawin, & Reid, 2002; Smallwood et al., 2004). The change in rate can be understood from the vigilance, or sustained attention, perspective, in which vigilance performance decrements have been considered to be due to either fatigue and/or boredom (Scerbo, 2001), though the exact role of each is still debated due to disparate results in varying contexts. There exists support that both boredom (Game, 2007; Harris, 2000; Martin, Sadlo, & Stew, 2006) and fatigue (Burdett, Charlton, & Starkey, 2016) are associated with an increase in the rate of mind wandering and can negatively influence driving performance (Nilsson, Nelson, & Carlson, 1997; Matthews & Desmond, 2002; Du-Hou, Qun, Wei, & Hao-xue, 2010; Dahlen, Martin, Ragan, & Kuhlman, 2005). Task duration has a positive relationship with mind wandering and clear implications while driving, however, no research has been conducted looking at the form of this relationship or how it may impact mind wandering costs over time. Given the similar influences of both boredom and fatigue on mind wandering, the general intent will be to focus on how task duration in general influences the rate and cost of mind wandering, rather than the specific influence of each.

LITERATURE REVIEW

The literature review will begin with a description of the various methods used to measure mind wandering, leading into how awareness of one's thoughts is important both in catching mind wandering and its influence on task performance. Afterwards, the prevalence of mind wandering in a variety of contexts is discussed, along with what factors can influence the rate of mind wandering. The universal nature of mind wandering leads into an explanation of its crucial impact on task performance for a variety of tasks and driving in particular followed by an introduction of the role of perceptual load and task duration on driver performance. Some criticism is then given on the commonly used statistical methods in mind wandering research, with a proposed alternative method. Finally, there is a summary of the gap in the literature in relation to perceptual load and driving duration, and a brief overview of the proposed experiments

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Measuring Mind Wandering

One of the foremost challenges of researching mind wandering lies in the methodology of its measurement, as there is no direct way to measure what someone is thinking about. The two primary methods of measuring an individual's thought state are the self-caught method (Giambra, 1993) and the probe method (Giambra, 1995; Smallwood, Baracaia, Lowe, & Obonsawin, 2003). The self-caught method asks individuals to report whenever they notice themselves mind wandering. This method provides information about how individuals become aware of their internal distraction and provides insight into the role of meta-awareness in mind wandering regulation. The requirement of meta-awareness for reporting can be a limitation as well however, as the self-caught method is unable to detect mind wandering without awareness

(Schooler, Reichle, & Halpern, 2004), which occurs frequently (Smallwood, McSpadden, & Schooler, 2007). The probe-based method addresses this confound through asking individuals to report their current thought states at random intervals using an auditory or visual cue. The probe acts as an external instigation of meta-awareness, allowing for the detection of both mind wandering with and without awareness (Smallwood & Schooler, 2006). Estimates of the effect size of mind wandering costs may differ between the self-caught method and the probe-based method, as the self-caught method strictly compares on-task thoughts to mind wandering with awareness, while the probe-based method compares on-task thoughts to mind wandering with and without awareness.

A cost of these self-report methods is that only a small portion of the data collected can be used in analysis. In the self-caught method, data from around 3-15 seconds before their self-report is compared to the interval around 20 seconds after the report (He, Becic, Lee, & McCarley, 2011), as this period would be expected to be on-task. The probe method allows for the use of data from 0 to 10 or 15 seconds before a probe (Yanko & Spalek, 2014), and the probes typically occur approximately every minute in many studies. There is no theoretical reason for the use of these specific intervals, however with the current tools it is impossible to test the range at which we can be confident of their thoughts. As only a small portion of the total data can be used, and the state of mind wandering is a binary variable (i.e., mind wandering or on-task), acquiring sufficient power in an experiment can be challenging. This often leads researchers towards using simple paradigms, such as the sustained attention to response task (SART) or long rural roads in a driving simulator (He, Becic, Lee, & McCarley, 2011).

Another major limitation of both of these methods is that they are self-reports and can be heavily influenced by individual interpretation and social desirability biases. When an individual attempts to report their thoughts, they must classify if they were “task-related” or “task-unrelated”, something that is not always clear. For example, if while driving you start thinking about the shoes of a pedestrian located at a crosswalk, this is related to driving, but not tied to your performance, leaving room for the participant to interpret which it is. To address this, mind wandering studies often use a short series of examples to help standardize individual’s definitions of mind wandering and what it constitutes (Smilek, Carriere, & Cheyne, 2010), but no work has been done testing the influence of these examples on the reliability of reported mind wandering. The cost of the potential lowered reliability of these reports would be a decrease in reported effect size, as mind wandering and on-task reports would be mixed together, decreasing potential differences. More problematically is the negative impact of the social desirability bias on self-reports’ validity (Van de Mortel, 2008), as individuals tend to present a favorable image of themselves. It is likely that individuals see their inattention as negative, as not paying attention is often seen in a bad light. The cost of this bias would be the same as the lowered reliability of reports, decreasing potential power and effect size of mind wandering estimates.

A third limitation in the use of self-reports is the applicability of the method for real world problems. It would be impractical to ask individuals to report their thoughts constantly during driving, making prevention and intervention challenging. There is currently an initiative to develop mind wandering detection methods (Lerner et al., 2015) due to the insensitivity of subjective reports to attentional state as well as the potential of implementing interventions to mitigate the negative influence of mind wandering. One of the initial forays into this work was done by Franklin, Smallwood, & Schooler (2011), in which they developed a method of detecting mind wandering in real time based on response time fluctuations in reading while presenting participants with passages one word at a time. Their algorithm was able to detect mind wandering correctly approximately 72% of the time, however given the lack of continuous response time data on the road the generalizability of this method to driving environments is questionable. A more promising approach for driving contexts may be the use of eye trackers, which have already been successfully employed in managing other issues, such as warning systems for the fatigue (Ji, Zhu, & Lan, 2004; Horng, Chen, Chang, & Fan, 2004). A number of differences between mind wandering and on-task thoughts have been found using eye trackers, including eye movements (Uzzaman & Joordens, 2011), blinking (Smilek, Carriere, & Cheyne, 2010), and duration (Foulsham, Farley, & Kingstone, 2013; Reichle, Reineberg, & Schooler, 2010). One attempt at automatic mind wandering detection based on eye tracking was done by D'Mello, Cobian, & Hunter (2013) with moderate success. While there is much room for improvement, the potential of online mind wandering detection appears to be very possible, and along with it on the road support systems for managing mind wandering. It is worth noting that currently mind wandering detection is being compared to self-report responses as a way of testing accuracy, making the detection algorithms reliant on the assumption of the validity of the self-report methods themselves.

Meta-Awareness

A key component of mind wandering is meta-awareness (the awareness of one's own thoughts). Mind wandering is a form of spontaneous thought, related to creative thought and dreaming (Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016), with thoughts springing up with or without our intent. Individuals are often unaware of their mind wandering, and mind wandering without awareness can be more detrimental to task performance than mind wandering with awareness (Schooler, McSpadden, & Schooler, 2007; Smallwood, McSpadden, Luus, &

Schooler, 2008; Smallwood, McSpadden, & Schooler, 2008). These results conceptually make sense, as when an individual is less aware of their distraction, they will be less able to compensate for their diminished task-related attention. Support for this claim can be found through comparing mind wandering to external distractions. While engaging in an external distraction, drivers tend to drive slower with a larger headway distance (Rakauskas, Gugerty, & Ward, 2004), seemingly compensating for their decreased attention. This pattern is not seen during mind wandering, and in fact we see the opposite; while mind wandering individuals tend to drive faster with a decreased headway distance compared to when on-task (Yanko & Spalek, 2014).

One key difference between mind wandering and external distractions could be the ease of awareness of one's distraction. An external distraction provides a constant reminder of its presence through the senses acting as an environmental cue for awareness, while mind wandering has no physical form to remind the individual of its presence. As an example, while talking on the phone one has at least a combination of tactile and auditory feedback of their divided attention. During mind wandering no such cues are present, requiring the individual instead to monitor their current train of thought and compare it to their task goals. This presents an additional challenge in the regulation of mind wandering, as all awareness of the distraction must be maintained in working memory, and the engagement in metacognitive strategies becomes a competitor for attention.

Rate of Mind Wandering

A large body of work exists on the rate of mind wandering across a variety of tasks, particularly in educational settings such as lectures and reading (see Table 1). Across these studies we see a fairly stable mind wandering rate of around 30-40%, with similar rates in naturalistic studies compared to laboratory studies. A number of different factors can influence the rate of mind wandering, including perceptual load (Forster & Lavie, 2009), time (Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012), alcohol (Sayette, Reichle, & Schooler, 2009; Finnigan, Schulze, & Smallwood, 2007), difficulty (Feng, D'Mello, & Graesser, 2013; Grodsky & Giambra, 1990), practice (Mason, Norton, Horn, Wegner, Grafton, & Macrae, 2007), and age (McVay, Meier, Touron, & Kane, 2013; Krawietz, Tamplin, & Radvansky, 2012). The majority of these factors and their relationship with the rate of mind wandering can be explained through a cognitive resources perspective, in which as more cognitive resources are tied up in the primary task there are less available to freely engage in mind wandering. Numerous studies have found support for this perspective, with working memory capacity being a critical factor in regards to the rate of mind wandering (Rummel & Boywitt, 2014; McVay & Kane, 2009; 2012a; Kane et al., 2007).

There are two prominent theories on why mind wandering occurs; the control-failure hypothesis (McVay & Kane, 2010) and the global availability hypothesis (Smallwood, 2010). The control-failure hypothesis states that mind wandering occurs due to a failure in executive control to maintain goal-relevant information and inhibit the spontaneously generated internal thoughts. This theory differs from the global availability hypothesis in that it claims that mind wandering does not consume any executive resources itself, while the global availability hypothesis states that as mind wandering enters consciousness it by definition consumes global resources. A clear victor among the two theories has not been found, but there is no question of the importance of the executive function in the generation of mind wandering (Teasdale et al., 1995). Neurological support for this claim can be found in Christoff, Gordon, Smallwood, Smith,

& Schooler (2009) in which mind wandering was associated with increased activation in the dorsal anterior cingulate cortex (ACC) and the medial prefrontal cortex (PFC); the two regions considered to be the primary centers for the executive network (Posner & Rothbart, 1998; Botvinick, Braver, Barch, Carter, & Cohen, 2001). The executive function is thought to also be important in the detection of mind wandering through an individual’s meta-awareness (Schooler, Smallwood, Christoff, Handy, Reichle, & Sayette, 2011), allowing them to regulate their thought content.

The rate of mind wandering is sensitive to a number of environmental and individual factors. Three environmental factors that are of particular interest to driving contexts are perceptual load, task difficulty, and time on a variety of scales. As the perceptual complexity of an environment increases, the rate of mind wandering decreases (Forster & Lavie, 2009). This result is similar to how the rate of mind wandering decreases as the difficulty of the task increases (Smallwood & Schooler, 2006); increased resource demand for the primary task takes resources away from engaging in mind wandering. Another result that becomes intuitive with the cognitive resources perspective is decreased rate of mind wandering during more challenging tasks compared to easier tasks (McKiernan, D’Angelo, Kaufman, & Binder, 2006). Temporal factors impact the rate of mind wandering along both a long and short time-scale. Along the longer time scale more practiced tasks have a higher rate of mind wandering (Teasdale et al., 1995) as individual’s expertise grows and they require less cognitive resources to maintain a particular performance level. Practice effects are asymptotic with time with decreasing improvements with additional exposure after a certain amount of experience. Given that the average amount of time spent driving per day in the US is 47.1 minutes (Triplett, Santos, Rosenbloom, & Tefft, 2016), most individuals after a few years could be considered experts with negligible improved driving with additional practice. The primary focus of this research was on short time-scale factors instead, as these generalize to all drivers and could be eventually used with interactive systems.

Maintaining vigilance, or sustained attention, on a single task for an extended duration is challenging and often associated with performance decrements as the task drags on. Along this shorter time-scale, the rate of mind wandering increases with longer task durations (Smallwood, Obonsawin, & Reid, 2002; Smallwood et al., 2004; McVay & Kane, 2009). The two primary explanations for these vigilance decrements are fatigue (Helton & Russell, 2011; Mast & Heimstra, 1964) and/or boredom/mindlessness (Pattyn, Neyt, Henderickx, & Soetens, 2007; Kass, Vodanovich, Stanny, & Taylor, 2001; Thackray, Bailey, & Touchstone, 1977), depending on the task and user characteristics. The rate of mind wandering increases with both fatigue (Burdett et al., 2016; Körber, Cingel, Zimmermann, & Bengler, 2015) and boredom (Game, 2007; Harris, 2000; Martin, Sadlo, & Stew, 2006), however, the mechanism through which these factors influence mind wandering may differ. Fatigue is thought to occur through resource depletion (Helton & Warm, 2008; Warm, Parasuraman, & Matthews, 2008; Parasuraman, Warm, & Dember, 1987), where maintaining attention over time demands and drains cognitive resources. Fatigue then negatively influences working memory and executive functioning (Persson, Welsh, Jonides, & Reuter-Lorenz, 2007; Lorist, Boksem, & Ridderinkhof, 2005; Van der Linden, Frese, & Meijman, 2003), and can inhibit attentional processing (Van der Linden & Eling, 2006).

Boredom is a multi-faceted construct considered on both a state and trait-based level that can be defined as “the aversive experience of wanting, but being unable, to engage in satisfying activity” (Eastwood, Frischen, Fenske, & Smilek, 2012). Tasks that lack challenge (Van Tilburg

& Igou, 2012) and/or appear trite (Fahlman, Mercer, Gaskovski, Eastwood, & Eastwood, 2009; Van Tilburg & Igou, 2012) are more likely to elicit boredom. Boredom is associated with difficulty in maintaining sustained attention on task (Pattyn, Neyt, Henderickx, & Soetens, 2008; Scerbo, 1998; Thackray, Bailey, & Touchstone, 1977), poor temporal estimation (Danckert & Allman, 2005), increased stress (Scerbo, 1998), and decreased task performance (Malkovsky, Merrifield, Goldberg, & Danckert, 2012; Kass, Vodanovich, Stanny, & Taylor, 2001). As an individual loses the ability to sustain attention on their task, both due to decreasing motivation and cognitive resources, they become more likely to mind wander (Eastwood, Frischen, Fenske, & Smilek, 2012; Game, 2007; Harris, 2000; Martin, Sadlo, & Stew, 2006), though the direction of this relationship is currently unclear.

Table 1

Mind Wandering Rate across Tasks

Study	Task	Percentage
Feng, D’Mello, & Graesser (2013)	Reading (Easy)	36.2%
---	Reading (Difficult)	42.3%
Foulsham, Farley, & Kingstone (2013)	Reading	39.0%
Jackson & Balota (2012)	Reading (Young)	30.0%
---	Reading (Old)	14.0%
Kane et al. (2007)	Naturalistic (US)	30.0%
Killingsworth & Gilbert (2010)	Naturalistic (US)	46.9%
Lindquist & McLean (2011)	Lecture	33.0%
McVay & Kane (2012b)	STROOP	31.9%
---	SART	27.3%
---	Reading	51.1%
Risko et al. (2012)	Lecture	41.0%
Risko et al. (2013)	Lecture	24.3% | 37%
Song & Wang (2012)	Naturalistic (China)	24.4%
Unsworth & McMillan (2013)	Reading	42.5%
Yanko & Spalek (2014)	Driving (simulated)	39.0%

General Mind Wandering Costs

The impact of mind wandering on behavior is largely task-specific, however there are some general findings that appear to be consistent. Mind wandering is typically associated with weaker informational encoding (Smallwood, 2011; Smallwood, Fishman, & Schooler, 2007), increased response time variability (Bastian & Sucker, 2013; McVay & Kane, 2012; Seli, Cheyne, & Smilek, 2013), and increased visual tunneling (He, Becic, Lee, & McCarley, 2011; Uzzaman & Joordens, 2011). The predominant explanation provided for how mind wandering negatively influences behavior is the perceptual decoupling hypothesis (Antrobus, Singer, Goldstein, & Fortgang, 1970), which states that as attention shifts inwards it is decoupled from monitoring the external environment. Numerous neurological studies have found evidence supporting this claim, with decreased processing of external stimuli during mind wandering episodes (Smallwood, Beach, Schooler, & Handy, 2008; Barron, Riby, Greer, & Smallwood, 2011).

A drawback of the perceptual decoupling hypothesis is that while it maintains strong support, it is very vague. For example, if a mind wandering episode is predominantly visual or auditory, would we expect same modality interference as we would in external distraction as according to multiple resource theory (Wickens, 2008)? Is the decoupled attention influencing all stimuli in a similar, global fashion, or does it differentially impact stimuli depending on their goal relevance? There has been some additional work attempting to pinpoint the impact of mind wandering on specific attentional processes, primarily sustained attention. Sustained attention is how individuals maintain focus on a region or stimuli for a prolonged period of time, and lapses of sustained attention can pose a safety risk for a number of tasks (Edkins & Pollock, 1997; Scott, Rogers, Hwang, & Zhang, 2006).

A sizable body of work has been conducted on the impact of mind wandering on sustained attention using the Sustained Attention to Response Task (SART; Robertson, Manly, Baddeley, & Yiend, 1997), a go no-go task in which a response is withheld upon the presentation of a rare target (Mrazek, Smallwood, & Schooler, 2012; Christoff, Gordon, Smallwood, Smith, & Smallwood, 2009; Stawarczyk, Majerus, Maj, Van der Linden, & D'Argembeau, 2011). A number of performance detriments have been found on the SART during mind wandering including extreme reaction times (McVay & Kane, 2012a) and lower accuracy (McVay & Kane, 2009). The SART has been extensively used in neurological studies (Dockree, Kelly, Roche, Hogan, Reilly, & Robertson, 2004; Manly et al., 2004) with high convergent validity with the Cognitive Failures Questionnaire (CFQ; Broadbent, Cooper, FitzGerald, & Parkes, 1982) and the Attention-Related Cognitive Errors Scale (ARCES; Smilek, Carriere, & Cheyne, 2010), however some serious reservations have been raised about the validity of the paradigm in actually measuring sustained attention (Helton, 2009; Helton, Kern, & Walker, 2009; Stevenson, Russell, & Helton, 2011). The criticism lies in the fact that the SART appears to predominantly measure response inhibition rather than sustained attention, as the individuals are aware that they are making an incorrect response at the time. With this criticism in mind, mind wandering appears to have a negative impact on response inhibition, however less is known about its influence on other attentional mechanisms, such as selective attention and inattentional blindness.

In addition to the decreased processing of external stimuli, mind wandering also decreases encoding of information. This effect has primarily been studied in the context of reading (Feng, D'Mello, & Graesser, 2013; Unsworth & McMillan, 2013), however some work has used memory paradigms (Thomson, Smilek, & Besner, 2014) and lectures (Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012). One theory for how mind wandering influences informational encoding is the cascade model of inattention (Smallwood, 2011), which claims that as information is processed sequentially, detriments compound from earlier stages. This theory was created within the context of reading, however it generalizes well to other contexts. First, mind wandering decreases the processing of external stimuli. The loss of information from this stage results in less information available for processing of task-relevant features. Finally, this results in decreased encoding of information as less information is available.

Mind Wandering Costs on Driving

There is a limited body of work on the impact of mind wandering on driving, likely a consequence of the many methodological challenges involved in the research; primarily attaining sufficient power and gathering mind wandering data within naturalistic settings in a safe manner. Laboratory studies are challenged to create driving scenarios simple enough that mind wandering occurs in a high enough rate, while maintaining enough complexity for the experiment to be sensitive to changes in driving performance. This constraint has resulted in most mind wandering studies employing the use of simple rural roads to acquire adequate power (see Table 2). While mind wandering behind the wheel, individuals have narrowed vision, slower response time to unexpected events, shorter headway distance (He et al., 2011; Yanko & Spalek, 2014), and slower speed (Baldwin et al., 2017). Support for the general simplification of eye movement during mind wandering can be found outside the driving domain as well (Uzzaman & Joordens, 2011).

Further evidence for the detrimental impact of mind wandering on driving safety has been provided by Erie Insurance (2012) and Galéra et al. (2012). Erie Insurance (2012) reported that distracted driving was associated with fatal accidents five times as often as texting or using a phone. Galéra et al. (2012) found that the individuals who reported being engaged in task-unrelated thoughts at the time of an accident were more likely to be responsible for causing the accident. These studies provide crucial real-world support for the hypothesis that mind wandering may be dangerous, but some care should be taken in interpreting them. First, mind wandering could not be collected during driving due to the potential risk of the distractions (auditory probes). Instead both studies relied upon a post-accident self-report of the individuals thought content at the time of the accident; in Erie Insurance (2012) this was reported to an officer, and in Galéra et al. (2012) this was reported to an experimenter at a hospital. The accuracy of such a report is reliant upon the memory of the individual, attribution bias as they wish to be seen in a positive light, and honesty, as individuals may to hesitant to tell officers they weren't paying attention to the road at the time of the accident. For these reasons we would expect the reported proportion of mind wandering to be an underestimate. Furthermore, as mind wandering will be compared to a mixture of mind wandering and on-task thoughts, the effect size of the cost would be an underestimate as well.

Comparing to external distraction, mind wandering shows unique costs on driving performance through the role of compensatory behaviors. External distraction is often associated with a number of operational compensatory behaviors (Young, Regan, & Hammer, 2007); most notably decreased speed (Rakauskas, Gugerty, & Ward, 2004; Haigney et al., 2000) and increased headway distance (James, Westerman, Hockey, & Carsten, 2004; Strayer & Drews, 2004; Strayer, Drews, & Johnston, 2003). Compensatory behaviors increase the safety margin during distraction, though not enough for the distraction to be safe (Klauer, Guo, Simons-Morton, Ouimet, Lee, & Dingus, 2014) and this change is likely not conscious. Yanko & Spalek (2014) not only found that these operational compensatory behaviors were not present, mind wandering actually increased speed and decreased headway distance, effectively shrinking the safety margin.

Table 2

Complexity of Simulated Driving Scenarios Used in Mind Wandering Studies

	He et al., 2011	Yanko & Spalek, 2014	Dündar, 2015
Incoming Traffic	No	No	No
Lanes	2	4	2
Intersections	No	No	No
Pedestrians	No	Yes	No
Rural	Yes	Yes	Yes
Peripheral Objects	Yes	No	No

Environmental Variables in Driving Safety

Driving safety is an incredibly complex topic with a large number of influential environmental variables including road curvature (Haynes, Lake, Kingham, Sabel, Pearce, & Barnett, 2008), regional complexity (Zwerling, Peek-Asa, Whitten, Choi, Sprince, & Jones, 2005), road lighting (Wanvik, 2008), lane width (Zegeer & Deacon, 1987), rumble strips (Persaud, Retting, & Lyon, 2004), weather (Qiu & Nixon, 2008), traffic volume (Zhou & Sisiopiku, 1997), speed limits (Ossiander & Cummings, 2002), external distractions (Stutts et al., 2005), and driving duration (Otmani, Pebayle, Roge, & Muzet, 2005), to name just a few. These environmental factors can also interact with cognitive factors in complex ways that are still currently being explored. Due to the large number of relevant environmental factors present, this study had to restrict its scope to two factors; perceptual load and driving duration. Perceptual load and driving duration were selected as the environmental variables of interest for three primary reasons; their ubiquitous presence during driving, previously established relationships with mind wandering, and their easy detectability/measurement, with the eventual goal of interactive systems in mind.

Perceptual Load

Given the limited body of work on perceptual load within the driving domain, some critical insights on the influence of perceptual load on selective attention can be inferred from research within the attentional domain. The manipulation of perceptual load is not as straightforward as it may seem, as perceptual load is an ill-defined concept composed of a number of characteristics, such as number of stimuli (Do-Joon, Woodman, Widders, Marois, & Chun, 2004; Lavie & Fox, 2000) or spatial uncertainty (Marciano & Yeshurun, 2011), can influence the relationship of perceptual load and selective attention. The predominant theory of how perceptual load impacts performance and attention has been perceptual load theory (Lavie, 1995), which claims that as perceptual load increases, the processing of task-irrelevant stimuli decreases due to a reduction in available cognitive resources. While many studies have found support for perceptual load theory (Beck & Lavie, 2005; Lavie & Cox, 1997; Maylor & Lavie, 1998), there is increasing criticism as a number of studies have found contradictory results (Chen & Chan, 2007; Handy & Mangun, 2000; Theeuwes, Kramer, & Belopolsky, 2004) . An alternative theory that has been gaining support is called dilution theory (Tsal & Benoni, 2010), which is based on the claim that the previous studies did not control for the dilution phenomenon. The dilution phenomenon is the reduction in task-irrelevant processing as the volume of task-irrelevant distractors increases (Kahneman & Chajczyk, 1983, Yee & Hunt, 1991; Brown, & Roos-Gilbert, & Carr, 1995). When controlling for stimulus dilution different results are found; either perceptual load no longer changes distractor interference (Benoni & Tsal, 2010; Tsal & Benoni, 2010) or increased perceptual load actually increases interference (Wilson et al., 2011; Benoni & Tsal, 2012). Another impact of perceptual load is an increase in inattentional blindness/deafness (Cartwright-Finch & Lavie, 2006; Macdonald & Lavie, 2011).

Within the driving domain, there is some support for the detrimental impact of visually complex scenes on driving performance (Wallace, 2003; Young, Mahfoud, Stanton, Salmon, Jenkins, & Walker, 2009; Harms, 1986), such as an excess of billboards. Edquist, Rudin-Brown, & Lenné (2012) found increased perceptual load was associated with a slower reaction time and driving speed. Increased visual complexity on the road has also been associated with visual tunneling and longer fixations (Chapman & Underwood, 1998). There is evidence that perceptual load may moderate external distraction costs to response time in higher perceptual load scenarios (Strayer, Drews, & Johnston, 2003; Strayer & Johnston, 2001), however this result was not found in Brookhuis, de Vries, & de Waard (1991) or Lee, Caven, Haake, & Brown (2001). All four studies used cell phones as the perceptual load, however given the small sample size of some of the studies and the limited number of studies conducted it is hard to assess why the different results were found. An interaction between perceptual load and external distraction has also been detected for driving speed in Törnros & Bolling (2006), where driving speed during a handsfree cellphone conversation was reduced in a rural environment with a speed limit of 90km/h and a urban environment. Participants reduced their speed in all perceptual load conditions during the handheld cellphone condition.

Driving Duration

Time can influence driving in a number of ways depending on the scale being investigated; repeated exposure across a long period can result in practice effects as expertise grows, while along a shorter time scale vigilance decrements emerge from elongated sustained attention due to either fatigue or boredom. Repeating exposure to driving over a large number of instances improves the driver's expertise, and results in some "practice effects", which are the changes in performance due to the exposure, such as improving vehicular control, decreasing perceived driving difficulty (Charlton & Starkey, 2011), and insulating the driver from deleterious dual task effects (Shinar, Tractinsky, & Compton, 2005). Practice effects typically follow an exponential curve (Heathcote, Brown, & Mewhort, 2000) or power curve (Newell & Rosenbloom, 1981), depending on if task trials are averaged, and approach a performance asymptote after a certain amount of practice. Another time related factor is the driver's familiarity with their driving route, which according to Yanko & Spalek (2013) is associated with a decrease in hazard perception, a longer reaction time, and a shortened headway distance. These detriments were explained in terms of an increase in driver inattention as the route required less attention to navigate. Support for this claim was found in the third experiment where all detriments disappeared when drivers were forced to attend to the task.

On a shorter time scale, vigilance decrements for a sustained task typically occur due to a mixture of boredom and/or fatigue. Fatigue slows down response time (Ting, Hwang, Doong, & Jeng, 2008; Dorrian, Roach, Fletcher, & Dawson, 2007), increases lane drifting (Riemersma, Sanders, Wildervanck, & Gaillard, 1977), and reduces the driver's useful field of vision (Rogé, Pébayle, Lambilliotte, Spitzenstetter, Giselbrecht, & Muzet, 2004). Fatigue can also be problematic due to the comorbidity with sleepiness (Shen, Barbara, & Shapiro, 2006), as both are prominent on the road and correlated with an increase in crash risk (Desmond & Matthews, 2009; Knipling & Wang, 1994; Philip et al., 2005). Elongated task duration is associated with a decrease in performance, even if the task difficulty is low, as maintaining sustained attention for a prolonged period is resource intensive (Grier et al., 2003) and can encourage boredom. Boredom is associated with increased moving violations on the road (Kass, Beede, & Vodanovich, 2010;), speeding (Heslop, Harvey, Thorpe, & Mulley, 2010; Steinberger, Moeller, & Schroeter, 2016) and unsafe driving (Dahlen, Martin, Ragan, & Kuhlman, 2005; Schwebel, Severson, Ball, & Rizzo, 2006). Boredom occurs often on familiar driving route and long-distance drives (Schroeter, Oxtoby, Johnson, & Steinberger, 2015), conditions in which we would expect high proportions of mind wandering as well.

Vigilance decrements are hard for an individual to control and/or prevent as the current vigilance state is often misjudged (Schmidt, Schrauf, Simon, Fritzsche, Buchner, & Kincses, 2009) as their cognitive resources are sapped from the elongated sustained attention, leaving less available to engage in meta-awareness. Vigilance costs increase as the time on task increases (Verster & Roth, 2013), with more difficult tasks causing earlier vigilance decrements (Helton, Warm, Tripp, Matthews, Parasuraman, & Hancock, 2010) with some paradigms measuring vigilance decrements in tasks as short as 10 minutes (Loh, Lamond, Dorrian, Roach, & Dawson, 2004).

Statistical Methods

Analyzing mind wandering data can be technically challenging. A brief mention has been made of the difficulty in acquiring sufficient power in mind wandering research due to the limited proportion of data that can be used, and the typical binary response variables of task accuracy and reported thought state (mind wandering or on-task). In order to analyze the binary data, researchers often aggregate responses for mind wandering and on-task episodes per an individual, and then compare them using either a paired samples t-test (He, Becic, Lee, & McCarley, 2011) or a repeated measures ANOVA (McVay & Kane, 2009). An assumption for the use of these aggregates is that the trials that compose them are independent of each other, an untenable claim considering the shown effect of practice and time on mind wandering (Risko, Anderson, Sarwal, Engelhardt, & Kingstone, 2012; Mason, Norton, Horn, Wegner, Grafton, & Macrae, 2007), as well as the presence of correlated errors. The violation of independence, whether it is within groups, sequences, or space, can substantially bias the results of an ANOVA or t-test (Kenny & Judd, 1986). Additionally, the use of an ANOVA on proportional data can be problematic as proportional data is usually heteroscedastic (Ahrens, Cox, & Budhwar, 1990; Sileshi, 2007), conditions under which an ANOVA is not robust. This violation costs a significant portion of power (Warton & Hui, 2011) and can have a significant impact on mean inferences, particularly in the case of unequal sample sizes (Brown & Forsythe, 1974).

The currently used statistical methods often fail to account for individual level variation, and how it may impact the estimated differences between conditions. Working memory capacity has been linked to both mind wandering and performance (McVay & Kane, 2012a; McVay & Kane, 2012b; Mrazek, Franklin, Phillips, Baird, & Schooler, 2013; Unsworth & McMillan, 2013), but often is unmeasured when comparing the impact of mind wandering and on-task performance. A final critique is that all of these models assume that the response variable will be linear in respect to the continuous predictors (Tabachnick & Fidell, 2001; Warner, 2008). This has already been shown to not be the case, as mind wandering would be expected to increase over time before reaching an asymptote due to rising fatigue and boredom, and then after a certain period of time we would predict a general decrease in performance. While no study has directly paired fatigue and mind wandering, a correlational study has been conducted pairing increased sleepiness with increased rate of mind wandering (Carciofo, Du, Song, & Zhang, 2014). A violation of linearity reduces the power of an ANOVA or t-test (Tabachnick & Fidell, 2001; Warner, 2008).

In order to address some of these concerns, a few studies have begun to employ the use of mixed effect models (Feng, D'Mello, Graesser, 2013; Ruby, Smallwood, Engen, & Singer, 2013; Foulsham, Farley, & Kingstone, 2013; Farley, Risko, & Kingstone, 2013). Mixed effect model allow the specification of fixed and random effects, and can account for nested and crossed designs. They are highly flexible, allowing for the specification of varying covariance matrices to account for time dependence and in combination with generalized linear models can account for binary response variables. Random intercepts and random slopes allow for the separation of individual specific effects, and for inferences to be made on the individual level. These models allow for greater flexibility, but they come at the cost of increased complexity and significantly more computational power. Misspecification of random effect distributions in longitudinal data can result in biased covariance matrices (Verbeke & Lesaffre, 1997), particularly when using conditional variance (Heagerty & Kurland, 2001), however mixed models are typically robust to misspecification of the mixture distribution (Neuhaus & Hauck, 1992).

The nonlinear change in mind wandering over time can be accounted for as well through the employment of generalized additive models (GAM; Hastie & Tibshirani, 1986), a form of nonparametric regression which can approximate nonlinear relationships. This method can be used in conjunction with mixed effects models (mixed effect additive models) to address all of the concerns above. There are a number of different methods to smooth the effect of interest, one of the simplest is cubic regression splines in which a series of cubic regressions are connected at a number of knots. This method requires care in the choice in number of knots in order to avoid overfitting the data and an appropriate choice in the placement of the knots. In this proposal penalized thin plate regression splines are used instead, as they are computationally efficient, stable, and generally effective at avoiding overfitting (Wood, 2003). The cost of the additional flexibility of using GAMs is a loss of interpretability and increased complexity. A nice feature of linear models is their high interpretability, some of which is lost in GAMs while interpreting a nonlinear effect as one cannot look at a single coefficient to understand the relationship. For this reason, plotting is particularly important when using GAMs. The other primary drawback of GAMs is their increased complexity, resulting in fewer degrees of freedom than a linear model and making sample size estimation more challenging. There is currently no analytical method for conducting a power analysis on a GAM, instead requiring the use of computationally intensive simulations. Specifying a predicted effect size for a nonlinear relationship is also more difficult than it is for a linear relationship, as it is more challenging to identify a function than a single coefficient.

Gaps in the Literature

Perceptual load can impact selective attention through attenuating processing of distractors (Lavie, 1995) and increasing inattention blindness (Cartwright-Finch & Lavie, 2007), however there is limited research within the driving domain. Increased perceptual load is associated with decreased speed, slower reaction time (Edquist, Rudin-Brown, & Lenné, 2012), visual tunneling, and longer fixations (Chapman & Underwood, 1998). Forster & Lavie (2009) found that increased perceptual load decreases the rate of mind wandering, however there is currently no research on how perceptual load impacts the rate or cost of mind wandering within a driving context. As both perceptual load and mind wandering reduce visual scanning, it is possible that the combination would be particularly dangerous for unexpected peripheral events, and given the interaction of perceptual load and external distraction, it is hard to say how they may interact for vehicular control.

Vigilance costs can be seen within intervals as short as 10 minutes (Loh, Lamond, Dorrian, Roach, & Dawson, 2004), and given the average time on the road a day is 47.1 minutes (Triplett, Santos, Rosenbloom, & Tefft, 2016), driving duration is likely an important factor in driver safety (Ting, Hwang, Doong, & Jeng, 2008; Dorrian, Roach, Fletcher, & Dawson, 2007). A few studies have found that the rate of mind wandering increases over time (Smallwood, Obonsawin, & Reid, 2002; Smallwood et al., 2004), however these studies aggregated non-independent trials together and treated time as a linear function, which may not be an appropriate assumption based on some evidence in the practice (Heathcote, Brown, & Mewhort, 2000), fatigue, and boredom literature. The change in rate of mind wandering over time likely increases still, however the shape of this relationship and the relative maximum are unknown.

Additionally, mind wandering has been found to increase response time variability (Bastian & Sackur, 2013; Seli, Cheyne, & Smilek, 2013), but these results are also based on methods aggregating non-independent data together. This is both statistically questionable and prevents the delineation of this variability differences from being within a particular interval or over time.

Overview of Experiments

Experiment 1 explored the influence of perceptual load and task duration on mind wandering and mind wandering performance decrements in two abbreviated driving scenarios. Experiment II extended the duration of experiment I in a single perceptual load condition (the low perceptual load scenario used in experiment I) in order to look at the effect of elongated task duration on the same vehicular control measures. Experiment III increased the difference between perceptual load conditions in experiment I and measured the impact of mind wandering using headway distance and cued/un-cued braking events. See figure 1 for a general overview.

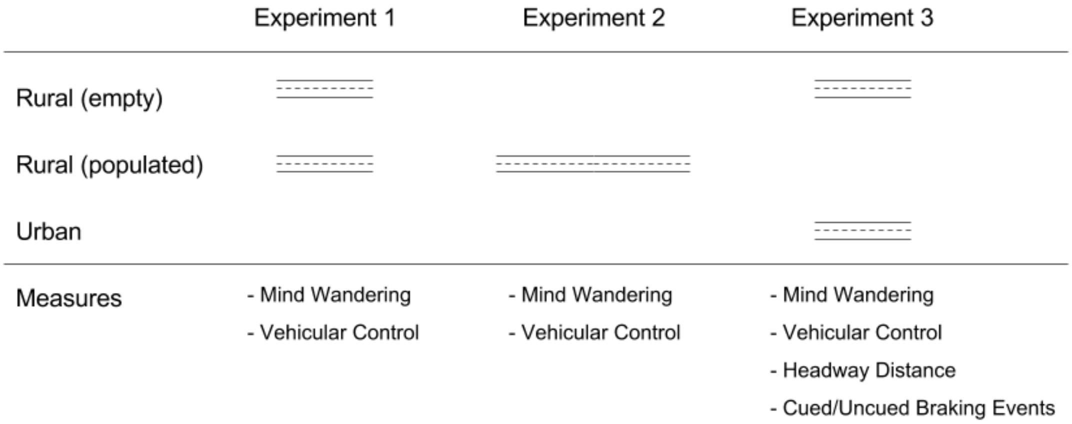

Figure 1: Method overview for experiments.

EXPERIMENT I

Introduction

The purpose of experiment I was to test the transfer of task duration and perceptual load effects on mind wandering within a simulated driving context, as well as to explore their influence on mind wandering costs. Findings from this experiment have been published (Geden, Staicu, & Feng, in press) and thus the description of methods and results appear similar to that in the journal manuscript. As shown in Table 2, research on mind wandering during driving has typically employed simplified driving scenarios in order to maximize the rate of mind wandering and maintain sufficient statistical power. As the degree to which perceptual load affects the rate of mind wandering is unknown, this first experiment will use moderate manipulations of perceptual load using task-unrelated stimuli such as trees, houses, non-interactive intersections, and incoming traffic. There are two hypotheses about how perceptual load will influence mind wandering. First, a replication of the results in Forster & Lavie (2009) in which the rate of mind wandering decreases with increased perceptual load. Second, the impact of mind wandering on vehicular control measures will be exacerbated in higher perceptual load conditions. This hypothesis is based on some interactions that have been found between external distraction and perceptual load previously (Strayer, Drews, & Johnston, 2003; Strayer & Johnston, 2001), though these differences have been primarily changes in response time to unexpected events.

The primary focus of task duration for this experiment was on the potential effect of fatigue and boredom by limiting each monotonous driving scenario (low/high perceptual load) to approximately 20 minutes. Within this duration both fatigue and boredom are expected to become relevant, with some support found in Yanko & Spalek (2014) in which drivers were asked to repeatedly drive the same route in a simulator, with driving performance decreasing over time as familiarity grew. There are two hypotheses about the relationship of driving duration and mind wandering in this experiment. First, mind wandering will increase at the beginning of the experiment until reaching an individual-specific asymptote. Second, mind wandering will be associated with increased variability in vehicular control over time. This hypothesis is based on a number of studies that have found mind wandering is associated with increased response variability (Bastian & Sackur, 2013; Seli, Cheyne, & Smilek, 2013), however they did not control for time, making it unclear if the increased variability is point specific (within a small interval) or increased oscillations over time.

Methods

Participants

Sample size estimation was not possible given the computational power required for GAMMs with autocorrelated residuals and the lack of any theoretical justification for the choice of a specific nonlinear relationship between the variables of interest given the exploratory nature of the analysis. The sample sizes of Yanko & Spalek (2013) and He et. al (2011) were respectively 18 and 17. A sample size of 40 participants was decided upon in order to be conservative about avoiding being underpowered. A total of 43 undergraduates (17 women, 26 men) participated in this study as three participants (2 women, 1 man) were removed from analysis due to language barriers, falling asleep, and excessive speeding during the simulated driving task (mean speed > 100 mph). All participants will be required to have normal to corrected-to-normal vision and a valid driver’s license. As a result, the final sample included in analysis consisted of 15 women (mean age: 19.40 years, age range: 18-21 years) and 25 men (mean age: 18.96 years, age range: 18-21 years). Participants were recruited from an introductory

Psychology course from North Carolina State University and were compensated for their time with class research credits.

Driving Simulator

Driving simulations were run using a low-fidelity STISIM Drive 3 console simulator (Figure 2). The use of STISIM was deemed appropriate for the study given the established relative validity for lateral position (Törnros, 1998) and speed (Bella, 2008; Godley, Triggs, Fildes, 2002). Participants were seated in a full-size fixed base driver seat equipped with a full-size steering wheel, gas/brake pedals, and a button panel for reporting their mind state (i.e., on task, or mind wandering). The driving scenarios were displayed on three 42" monitors covering a field of 135° of visual angle horizontally and 24° vertically. Vehicular control data, including lateral lane position, lateral velocity and acceleration, longitudinal velocity and acceleration, was sampled every 0.1 second. During analyses, these vehicular control data was truncated to only one data point per second. This was deemed sufficient for analyses based on the small amount of variance in driving measures on the millisecond scale. All measures were recorded using feet.

Figure 2: The STISIM Drive 3 Console simulator used in this experiment.

Driving Scenarios

All simulated driving occurred on a two-lane rural highway through a series of hills and curves. Participants were instructed to follow a lead vehicle which maintained a constant distance from the driver. Perceptual complexity was manipulated into two separate conditions through the control of task-irrelevant environmental stimuli such as trees, houses, oncoming vehicles, etc. The lower perceptual load condition had no other traffic on the road, minimal objects in the visual field (Figure 3). In contrast, in the higher perceptual load condition participants encountered incoming traffic (on average two per minute), houses, trees, and intersections. None of these objects required any action by the participant and other components of the drives were identical in the lower and higher perceptual load conditions, in order to keep interactivity of the environment constant across the conditions. In both conditions, the speed limit was 45 mph and was posted every 1.2 miles. Full length drives were 40.4 miles, and training drives were 3.7 miles.

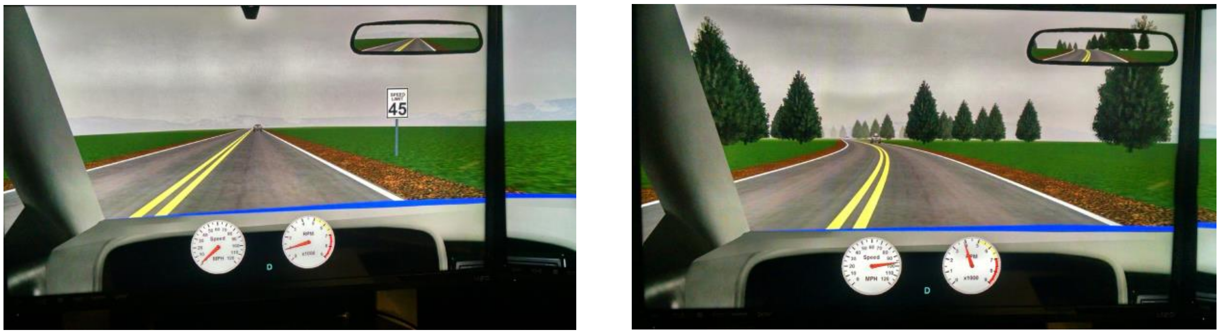

Figure 3: Examples of the lower perceptual load condition (left) and the higher perceptual load condition (right).

Mind Wandering Probes

Throughout the driving scenarios participants were probed by a pure tone (400Hz, 1 second duration), and they had to report whether their thoughts had been task-related or task-unrelated by pressing the corresponding marked buttons to the right of the steering wheel. Take-related thoughts were described as any thoughts related to the current task, while task-unrelated thoughts were described as thoughts unrelated to the current task (such as thinking about eating during an exam). Mind wandering probes occurred at a random interval between 30-90 seconds, with a total of 15 per full-length drive. This probing method is similar to the one used in Yanko & Spalek (2014) and is one of the typical methods in the cognitive psychology literature on mind wandering (e.g., Smallwood, McSpadden, & Schooler, 2008). Compare to other methods (e.g., self-caught method, He et al., 2011), this probing method is able to capture mind wandering with and without awareness. Vehicular control data from the 0-15 seconds interval prior to the mind wandering probe was used in the subsequent analyses, an interval used previously in Smallwood, Beach, Schooler, & Handy (2008).

Procedure

Participants first consented to their participation in the experiment and filled out a brief questionnaire comprised of demographic questions about their age, sight, driving history, and gender. Afterwards participants were informed about the general task procedure, simulated driving and the mind wandering probes (asking whether the thoughts immediately before the probe was task-related or task-unrelated). Examples of task-related thoughts (e.g. thinking about incoming traffic) and task-unrelated thoughts (e.g. thinking about eating during a test) were provided. Additional examples were given when participants needed elaboration. After a brief practice drive, each participant drove on two driving scenarios with different levels of perceptual complexity in a randomly chosen order (low-high or high-low). In between the two drives, participants were given a brief two-minute break before starting the next drive.

Results

Generalized additive mixed effect models (GAMMs) employing penalized thin plate regression splines were used to examine the impact of perceptual load and driving duration on the rate of mind wandering and its cost on vehicular control performance. GAMMs were run using the mgcv package (Wood, 2004) in the R environment and estimated using a Laplacian approximation. All models included a random intercept for participant, and a random slope for driving duration. Driving duration (i.e., time since the start of a drive) was measured using the simulator, with the two-minute break included between the two drives. A smooth effect for driving duration is considered during both mind wandering and on-task thoughts; the other covariates appeared to have a linear effect based on visual evidence. Both smooth effects of driving duration are modeled using thin plate regression splines; the smoothing parameters are estimated using restricted maximum likelihood estimates (REML), as generalized cross-validation (GCV) tends to overfit (Wood, 2011) and can experience problems with correlated covariates (such as reported mind wandering and driving condition in this study) in repeated measures designs (Wood, 2006). Gender was included in all models based on the results of Qu et al. (2015), in which a significant interaction was found between gender and dangerous driving behaviors for high mind wandering individuals. In addition to gender, age and order of presentation for perceptual load conditions (high - low, low - high) were added as covariates.

The constrained nature of the samples used in this and the following studies (undergraduate students at a large land grant university with ages between 18-22) limited inferences to being made about the overall population of similar students rather than the more heterogeneous population of drivers in general.

Rate of Mind Wandering

A binomial family logistic additive mixed model was used to analyze the rate of reported mind wandering. No significant autocorrelation was present in the residuals. Variables included in the model were age, gender, order of presentation of the scenarios, perceptual load condition, and a smoothing effect for driving duration. There were significantly lower rates of mind wandering in the higher perceptual load condition (M = 41.17, SD = .49) compared to the lower perceptual load condition (M = 49.66, SD = .50) ($b = -.41$, $z = -2.69$, $p = .007$).

The smooth effect for driving duration was statistically significant (X^2 (3.18, 1158) = 12.15, p =.017), with a rise in the rate of mind wandering for approximately the first 12 minutes (Figure 4). The y-axis in the left figure in figure 4 represents the coefficient for time on the rate of mind wandering. For linear effects we would expect to see a straight line, and for non-significant effects we would expect a straight line around 0 (the mean).

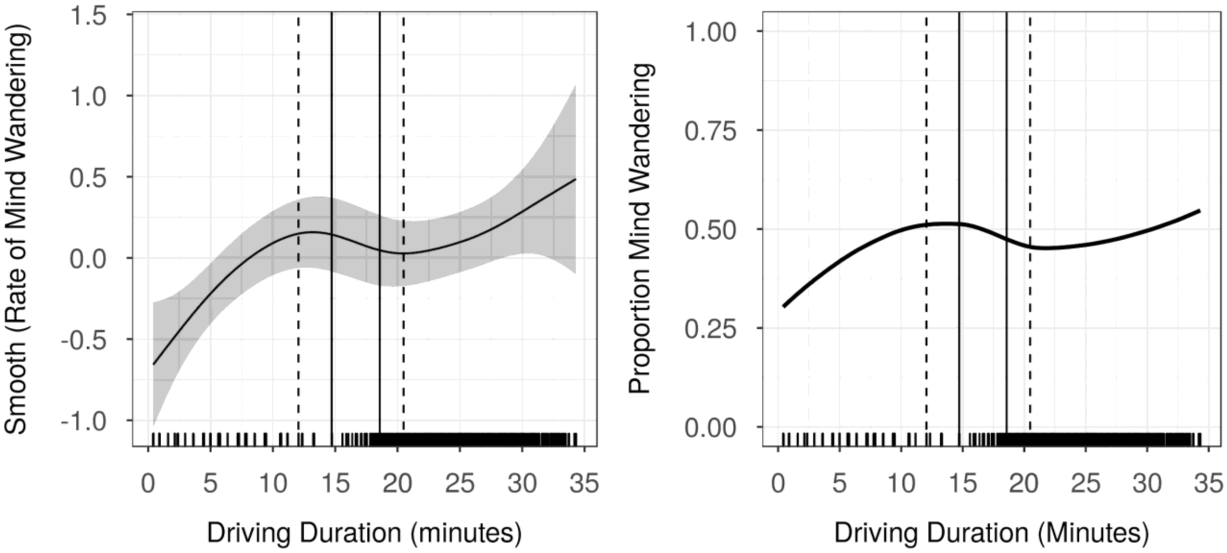

Figure 4: Left: The smoothing function coefficient for the rate of mind wandering over driving duration (minutes) with the grey region representing the 95% confidence interval. The vertical lines represent the transition region between the two experiments, with the dotted lines covering all participants and the whole lines 50% of the participants. The rug plot shows the distribution of mind wandering reports over time with an equal number in the first and second half. Right: Loess smooth of the rate of mind wandering over time by driving duration (minutes).

Vehicular Control

GAMMs on driving control measures all displayed significant autocorrelation of residuals, even with the random effect structure taken into account. This is likely due to the fact that while the random effect structure accounted for dependence within individuals and across probes, it did not account for the dependence within probes. We would expect that driving speed at time T seconds would be correlated to driving speed at T + 1 seconds. A nested autoregressive lag 1 (AR[1]) autocorrelation structure was specified within each mind wandering probe, starting at the point 15 seconds before the probe to the time 1 second before the probe. Rho was initially set based on the lag 1 autocorrelation value, and then visually inspected and adjusted, with a final value of .94. An AR(1) appeared to be sufficient to account for the residual autocorrelation. Variables included in the models were age, gender, response to mind wandering probes, perceptual load, order of presentation of the driving scenarios (i.e., lower or higher perceptual load condition), a smooth effect for driving duration while mind wandering, and a smooth effect for driving duration while on-task (Table 2). Analyses were run on 5 vehicular control measures; lateral velocity/acceleration, longitudinal velocity/acceleration, and lane position. No main effects were found for model predictors for driver acceleration, lane deviation, and lateral acceleration. The interaction of mind wandering and perceptual load was significant for driver speed (see Table 3), however the effect size of these differences was small.

Table 3

Generalized additive mixed model (GAMM) with autoregressive lag 1 (AR[1]) for driver speed.

Parametric Coefficients	Estimates	Standard Error	*t*-value	*p*-value
(Intercept)	53.88	16.26	3.31	< .001*
Age	.81	.82	.98	.325
Gender (male)	-3.08	1.75	-1.76	.079
Order (PL-high first)	3.88	1.73	8.95	< .001*
Mind Wandering	-.51	.18	-2.76	.006*
PL (high)	-.97	.26	-3.71	< .001*
MW x PL (high)	.79	.26	3.06	.002*
Smooth Terms		Estimated *df*	*F*-value	*p*-value
s(duration) x MW		8.63	13.76	< .001*
s(duration) x OT		7.12	17.96	< .001*
Random Effects				
re(ID)		35.40	2977.97	< .001*
re(duration, ID)		34.93	2733.24	< .001*

Note: Reference variables for the estimate were on-task thought, females, low perceptual load, and low perceptual load first for the order of presentation. For the smooth terms, s( ) represented a thin plate spline, and re( ) a random effects for ID and random slope for duration/ID.

There was a significant interaction between mind wandering and perceptual load condition, however the effect size was small and did not match the direction of the hypothesis (see Table 3). Mind wandering in the load condition was associated with a lower speed compared to on-task thoughts, while mind wandering in the high load condition was associated with a faster speed compared to on-task thoughts. These results did not support hypothesis 4, in which mind wandering costs were expected to be exacerbated in the higher perceptual load condition.

A smooth effect was fit for time for both mind wandering and on-task thoughts with speed as the dependent variable. These terms were significant and showed a large difference between conditions (see Table 3 and Figure 5). Differences do not appear to be present within individual times, as the confidence intervals are approximately equivalent, however a larger variation over time in speed can be seen for mind wandering compared to on-task.

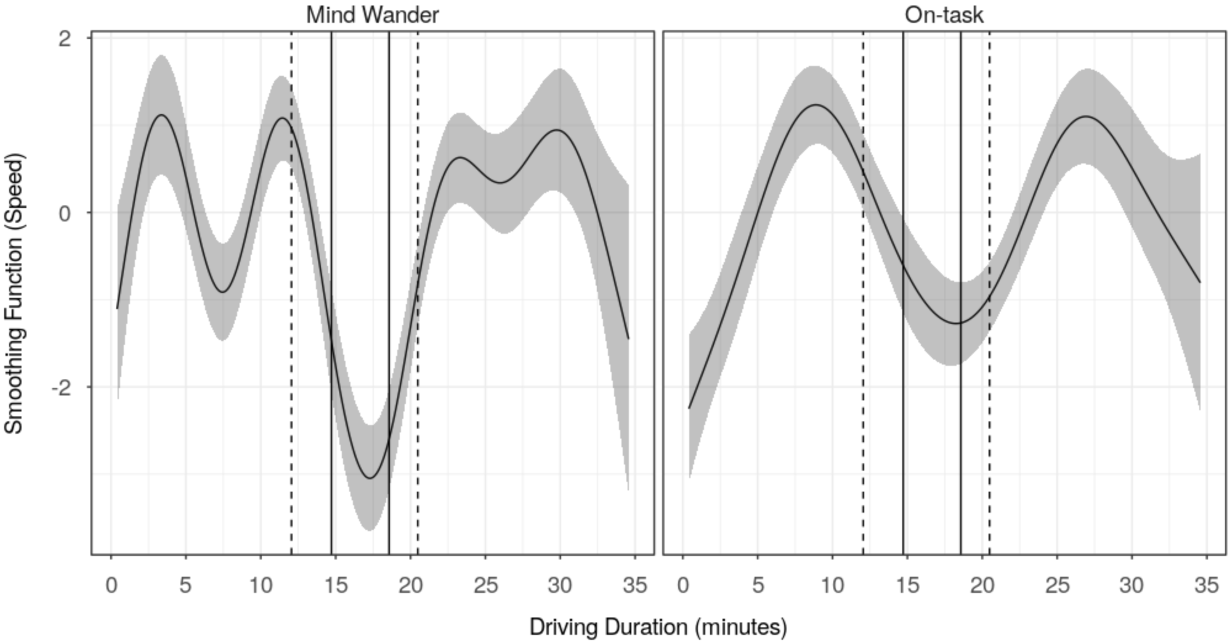

Figure 5: Smoothing function for longitudinal velocity over time (seconds) for mind wandering (on the right) and on-task thoughts (on the left), with the grey regions representing 95% confidence interval. Differences in the variability over time can be seen between the two thought types, with more oscillations in speed over time during mind wandering compared to on-task.

Discussion

The primary objective of experiment I was to explore the influence of driving duration and perceptual load on the rate of mind wandering and its influence on vehicular control measures. In the study, participants completed simulated driving while being intermittently probed about their mind states. Responses to these probes were recorded together with vehicular control performance measures. Participants reported lower rates of mind wandering while driving in a more visually complex environment which included oncoming traffic, peripheral objects, and intersections. This finding is consistent with Forster & Lavie (2009) in which participants reported lower rates of mind wandering during lower perceptual load conditions during a visual search task. Even with the decreased rate of mind wandering in the higher perceptual load driving condition, the rate of mind wandering was high enough (41%) to preserve sufficient statistical power. Given this result, future research can investigate the impact of mind wandering in other driving situations; an important finding considering single vehicle crashes make up just 33% of accidents, and only 50% of accidents occurred when the driver was going straight (NHTSA, 2008). Additionally, considering the ubiquitous nature of mind wandering and the fact that it does not always impact performance (Smallwood, Obonsawin, & Heim, 2003), it would be more beneficial to research its impact during high-risk situations, rather than only a limited set of generic driving scenarios.

There was a significant interaction between the influence of mind wandering and perceptual load on driver speed. For both mind wandering and on-task, driving speed was lower during the lower perceptual load scenario. Engström, Johansson, & Östlund (2005) found similar results, as visual distraction led to decreased driving speed. The same slowing down effect is found during distracted driving in general (Alm & Nilsson, 195; Burns, Parkes, Burton, Smith, & Burch, 2002; Haigney, Taylor, & Westerman, 2000; Rakauskas, Gugerty, & Ward, 2004), though the speed change is likely not a conscious choice (Charlton, 2004; Lewis-Evans, De Waard, & Brookhuis, 2011). The lower speed during distractions has been thought to be a form of compensatory behavior (Young, Regan, & Hammer, 2007) as individuals self-regulate to compensate for the decreased attentional resources available for driving. During the lower perceptual load condition, people drove faster while engaged in on-task thoughts compared to mind wandering, however the opposite was found in the higher perceptual load condition, as people drove faster while mind wandering than when engaged in on-task thoughts. These results may be explained when considering that mind wandering likely requires executive resources to maintain a train of thought (Smallwood & Schooler, 2006; Smallwood, 2010), and is associated with increased activation in executive systems in addition to the recruitment of the default mode network (Christoff, Gordon, Smallwood, Smith, & Schooler, 2009). The use of executive resources while mind wandering would likely leave less resources available to engage in self-regulation and monitoring, potentially limiting the occurrence of compensatory behaviors such as speed changes in more distracting environments such as the higher perceptual load condition. Some support for this has been found in Yanko & Spalek (2014), where they observed that mind wandering was associated with decreased headway distance compared to an external distraction.

Nonlinear effects were found for the rate of mind wandering over driving duration, and on driving speed, meaning that both the rate of mind wandering and the cost on driving speed fluctuated over driving duration. An important consideration when interpreting our results on the effect of driving duration is that unlike typical longitudinal data where data at time point N and N + 1 are the same, each time point was composed of different groups of individuals as they reported either mind wandering or on-task for that time. Note that this effect of driving duration was determined with the effect of perceptual load controlled for in the mixed models, with no differences found in the smoothing function for driving duration between the lower perceptual load and higher perceptual load conditions. The rate of mind wandering gradually rose for approximately the first 12 minutes, and then plateaued until near the end of the experiment (~27 min), where a nonsignificant positive trend started. The initial rise in the rate of mind wandering was expected as boredom and/or fatigue grew as participant's expectations aligned with the monotonous task. Once cognitive resource allocation to the external task (i.e., driving) and internal thought processes (i.e., mind wandering) stabilizes, rate of mind wandering is expected to remain consistent until fatigue effects start to play a significant role. The nonsignificant upward trend seen at the end of the experiment indicates that if the experiment were longer, fatigue effects may have started to develop, however it is likely that the change in driving conditions caused a rise in arousal, as perceptual variation can alleviate vigilance effects (Thomson, Smiley, & Besner, 2015).

Different nonlinear effects for the relationship of driving duration and driver speed were found during mind wandering versus on-task states, as mind wandering showed a greater amount of fluctuation over driving duration compared to on-task states. Speed variations can negatively impact both driver safety and overall traffic flow (Stavrinos et al., 2013). Given how commonly mind wandering occurs on the road (~11% of accidents according to NHTSA, 2008) and in general (~ 50% of total wake time according to Killingsworth & Gilbert, 2010), and mitigation strategies such as removing the source of external distraction would not apply to this internal distraction, the potential impact on overall traffic flows on the road due to mind wandering could be profound. In addition, with the increasing levels of automation in vehicles, drivers may no longer need to execute sub-driving-tasks such as speed control and lane maintenance (e.g., Merat, Jamson, Lai, Daly, & Carsten, 2014), and subsequently experience more mind wandering due to the boredom rising from a "task-deprived" state. Understanding how mind wandering could change over driving duration and potentially impact performance is critical to road safety with high levels of vehicle automation, particularly when take-over events occur. Given the nonlinear relationship of driving duration and mind wandering, it is important to consider the use of nonlinear models for future mind wandering studies, as using linear models for nonlinear effects can inflate Type I error.

EXPERIMENT II

Introduction

The driving scenarios that were used in experiment I took approximately 20 minutes, which given the ease of the task, its short length, and the positive impact of secondary tasks on vigilance (Atchley & Chan, 2010; Ariga & Lleras, 2011) such as responding to mind wandering probes, there were likely negligible fatigue-induced vigilance decrements. Building upon the paradigm in experiment I, experiment II aimed to expand on the driving duration to see how vigilance decrements occur in a more prolonged drive. This experiment used a single longer drive, taking approximately 45 minutes, with the perceptual complexity of the higher perceptual load condition in experiment I. The higher perceptual load condition was chosen as it had higher external validity, as most real world driving scenarios include other vehicles and visual objects. The As in experiment I, an initial increase in the rate of mind wandering was expected as a result of the combination of fatigue and boredom, however, with the extended duration resource depletion was expected to become more pronounced resulting in greater fatigue-induced performance decrements, increased rate of mind wandering, and potentially exacerbated mind wandering costs on vehicular control over time.

Methods

Participants

A total of 48 participants (15 women, 33 men) participated in the study. All participants had normal to corrected-to-normal vision and a valid driver's license. Data from three participants was excluded from analysis due to technical problems or a participant's failure to follow directions (e.g., passing the lead vehicle). The final sample consisted of 13 women (mean age: 19, age range: 18-21) and 32 men (mean age: 19.25, age range: 18-23). Participants were recruited from an introductory Psychology course from North Carolina State University and were compensated for their time with class research credits.

Driving Scenario

The driving scenario was the same as the high perceptual load scenario used in experiment I except the duration was extended to approximately 48.5 miles with a speed limit of 65 miles per hour in order for the experiment to take approximately 45 minutes.

Mind Wandering Probes

The mind wandering probes were attached to specific locations within the drive, rather than based on the individual's driving duration. With the extended duration of the drive, small differences in speed would cause large variations in the places where time-based probes would occur, so the location-based mind wandering probes were designed to control for impacts from differences in speed across participants. There was a total of 44 mind wandering probes, at approximately once per a minute depending on an individual's driving speed.

Results

Data were analyzed using the same methods employed in experiment I. The rate of mind wandering and vehicular control measures were analyzed using generalized additive mixed effect models (GAMMs) with a smoothing effect for driving duration and a random intercept for participant.

Rate of Mind Wandering

The rate of mind wandering was modeled using a binomial family logistic mixed effect regression. No significant autocorrelation was present in the residuals. The variables included in the model were age, gender, and a smoothing effect for driving duration. There was a significant smooth effect for time (X^2 (4.81, 1962) = 68.14, p < .001) which presented similar behavior as to that found in experiment I (see Figure 6).

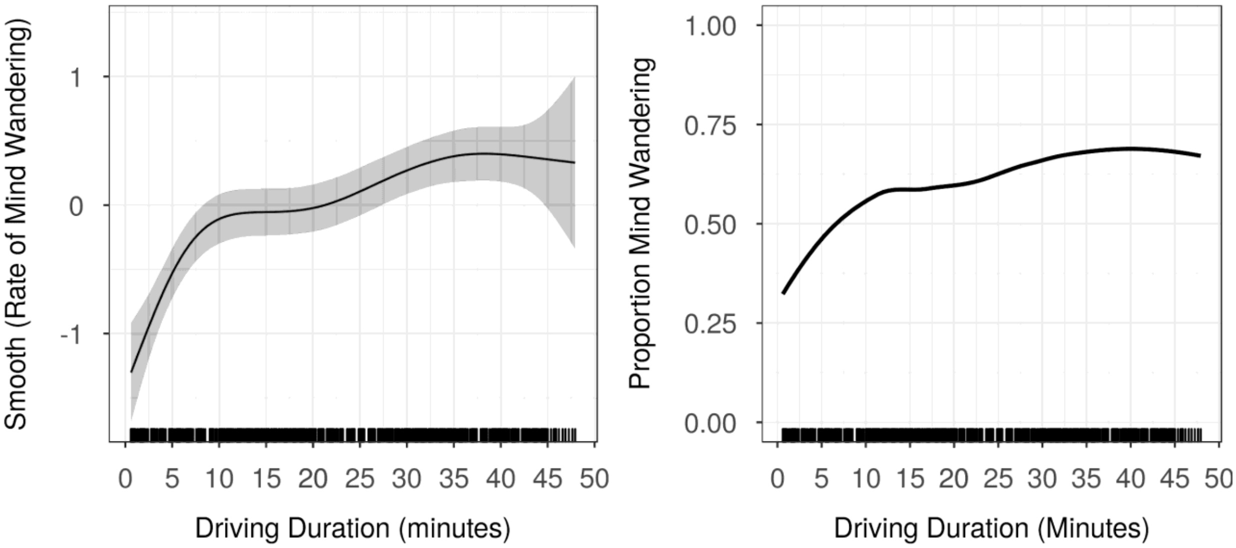

Figure 6: Rate of mind wandering over time. Left: The smoothing function coefficient for the rate of mind wandering over driving duration with the grey region representing the 95% confidence interval. The rug plot shows the distribution of mind wandering reports over time with an equal number in the first and second half. Right: Loess smooth of the rate of mind wandering over time by driving duration.

Vehicular Control

Serial autocorrelation in all vehicular control measures elicited the use of nested AR(1) models, with rho calculated based on a null models residual autocorrelation at lag 1. ACF and

PACF plots indicated no further terms were needed. The influence of mind wandering on vehicular control was tested using 5 dependent variables; absolute lane deviations (absolute deviation from the center of a lane disregarding the direction), longitudinal (parallel to the road) speed, longitudinal acceleration, lateral (orthogonal to the road) velocity, and lateral acceleration. Mind wandering was associated with decreased driver speed compared when on-task (b = -.64, *t* = -6.61, *p* < .001). There was no significant difference between mind wandering and on-task thoughts for longitudinal acceleration, lateral velocity, absolute lane deviations, or lateral acceleration. There was a significant smooth effect for mind wandering (F(8.88, 31259.05) = 24.83, *p* < .001) and on-task thoughts (F(8.12, 31259.05) = 48.81, *p* < .001) over time (see Figure 7) on longitudinal speed. The relationship overtime with increased variation for driver speed over time during mind wandering compared to on-task was similar to the results found in experiment I.

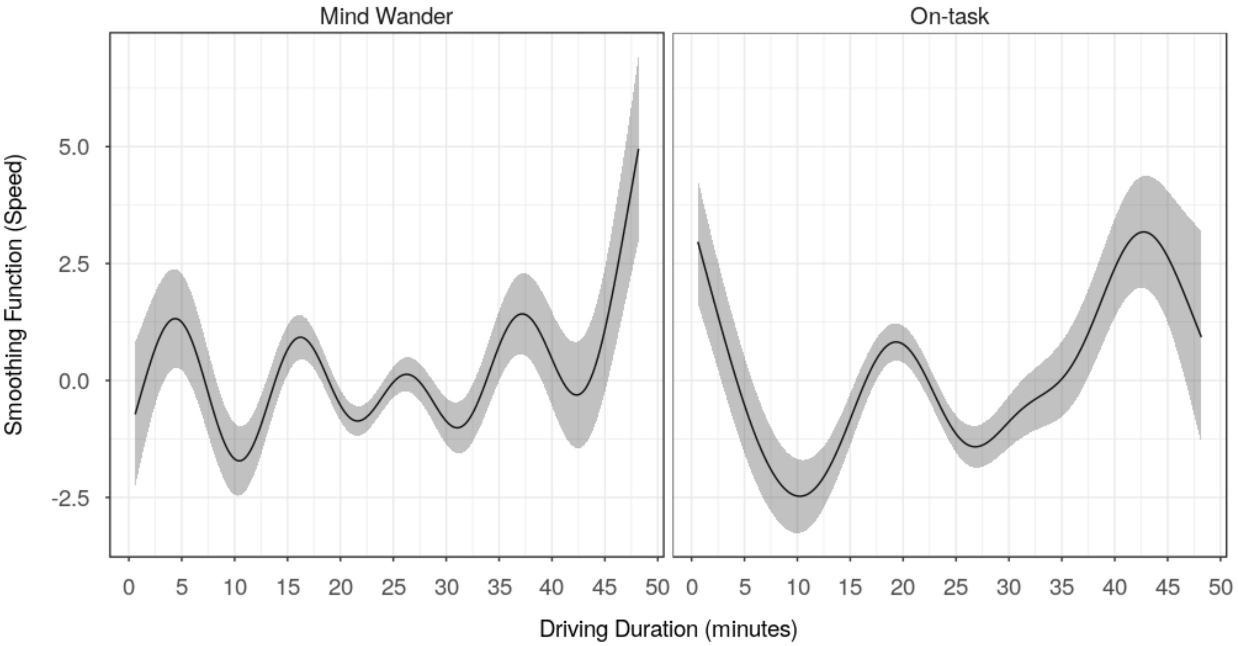

Figure 7: Smoothing function for longitudinal velocity over time (seconds) for mind wandering (on the right) and on-task thoughts (on the left), with the grey regions representing 95% confidence interval. Differences in the variability over time can be seen between the two thought types, with more oscillations in speed over time during mind wandering compared to on-task.

Discussion

The primary objective of experiment II was to investigate the influence of an extended driving duration on the rate and cost of mind wandering, and to examine if plateau in the rate of mind wandering reached in experiment I would continue or rise with an increased task duration. Increased variation in driver speed over time during mind wandering compared to on-task was replicated, with no significant effect of mind state on any other longitudinal or lateral vehicular control measures. The asymptotic rise in the rate of mind wandering over time for the first 20 minutes was approximately the same as in experiment I, successfully replicating the findings in the earlier experiment. There was inconclusive evidence of a secondary rise in the rate of mind wandering over time. This result is likely a conservative estimate of the impact of an extended driving duration on the rate and cost of mind wandering as participants may have been alerted by the mind wandering probes during the experiment. In more naturalistic driving without mind wandering probes, drivers' vigilance decrements could be worse.

The goal of this experiment was to see how the rate of mind wandering changes over time in order to assess the viability of the use of a periodic alert system for future experiments, wherein a limited number of reminders could be used with maximal impact by targeting times at which the rate of mind wandering reaches an asymptote. The relatively stable plateau reached after approximately 20 minutes indicates that an alert provided around this time may be effective. The primary challenge of integrating an attentional alert system to mitigate mind wandering in safety critical environments will be the amount of data required to assess whether the binary variable has reached an asymptote. The application of the external reminders will also require the ability to detect mind wandering in real time, a feat which has had limited success so far. These technical details are beyond the scope of this study, which focused on identifying whether or not this tactic would be potentially useful.

EXPERIMENT III

Introduction

Experiment I was expected to display decreased reported rates of mind wandering during the increased perceptual load condition due to the addition of peripheral (trees, houses) and foveal objects (incoming traffic, non-active intersections). This manipulation was moderate in nature due to the uncertainty of the degree of influence that perceptual load would have on the rate of mind wandering. One limitation of experiment I is that both perceptual load conditions occur on simple rural highways, providing limited generalizability to more complex urban environments that are common during driving. A second limitation of experiment I and II was the limited measure of driving performance measures, with vehicular control during standard driving being the primary driving measures. Experiment III addressed this limitation by strengthening the perceptual load manipulation by comparing a rural highway (similar to the higher perceptual load condition in experiment I) to an urban environment. A second change from experiment I was the behavior of the lead vehicle. In experiment I, the lead vehicle maintained a static headway distance to the driver in order to allow for the free choice of speed at the cost of measuring headway distance. Both speed and headway distance are measures of operational compensatory behaviors which (inadequately) increase the safety margin during secondary tasks (Rakauskas, Gugerty, & Ward, 2004), and are thought to be dampened during mind wandering (Yanko & Spalek, 2014). Experiment III instead set the lead vehicle to oscillate within a certain speed range in order to allow the measurement of headway distance at the cost of sensitive speed measurements. There have been mixed results about the significance of mind wandering in regards to vehicle following distance, with He et al. (2011) showing no difference, and experiment II in Yanko & Spalek (2013) displaying a significant difference of approximately 6 meters. The second goal of experiment III is to test whether the headway distance during mind wandering is shorter than while on task, and if there is an interaction with perceptual load and mind wandering on headway distance.

The third primary goal of experiment III was to investigate a situation in which mind wandering may be particularly detrimental; rear-end crashes were selected since they are one of the most common type of accident, making up approximately 29% of all crashes with 87% of rear end accidents associated with some form of distraction (Lee, Llaneras, Klauer, & Sudweeks, 2007). Evidence was found in Yanko & Spalek (2013) that mind wandering is associated with a delayed response to sudden lead vehicle brakes, though there are some criticisms with this study. Yanko & Spalek (2013) measured the relative cost of mind wandering using sudden braking events in which the lead vehicle drastically slowed down until the participant tapped the brake. While response time during mind wandering (1182ms; Yanko & Spalek, 2013, pp. 4) was slower than while on-task (1062ms; Yanko & Spalek, 2013, pp. 4), the analysis did not control for headway distance at the time of onset of the lead vehicle's braking. Given the longer response times to braking events, it is reasonable to speculate that participants' responses may be altered by the safety margin available, in addition to the onset of a stimulus (i.e., braking lights). That is, participants may have taken longer time to respond because of less perceived urgency given a longer headway distance. To test this speculation, this paper analyzed the change in headway distance during breaking events controlling for the starting headway distance instead of response time.

There are two primary cues that capture driver's attention for change in lead vehicle headway distance; looming of the incoming vehicle (Terry, Charlton, & Perrone, 2008; Li, 2006) and the presence of brake lights (McKnight & Shinar, 1992). There is some debate about the relative importance of each factor, with Fisher & Hall (1978) claiming brake lights have no effect, and Xue, Markkula, Yan, & Merat (2018) claiming both looming and brake lights influence brake response, however, the evidence was considered strong enough for further exploration. The abrupt onset of salient stimuli, such as with brake lights and looming, can involuntarily capture attention (Franconeri, Hollingworth, & Simons, 2005; Franconeri & Simons, 2003) in what is known as exogenous orienting. Mind wandering has been associated with decreased exogenous orienting (Hu, He, & Xu, 2012) and increased distractor suppression

(Geden, Staicu, & Feng, 2018), which may make drivers more reliant on the presence of cues. Similar previous evidence has been found with external distraction, with distracted drivers having a slower response to leading vehicles decelerating (Alm & Nilsson, 1995; Hancock, Lesch, & Simmons, 2003). Attentional failures have also been considered a critical contribution to collisions related to failure to detect brake lights (Lee, Wierwille, & Klauer, 2002; Sullivan & Flannagan, 2003). An additional manipulation was added to the braking events with either the lead vehicle brake lights turning on as normal (cued) or not activating (un-cued) in order to test if the absence of an expected cue may be a situation in which mind wandering is particularly detrimental.

Increased perceptual load has also been found to be associated with decreased driver speed and response time (Edquist, Rudin-Brown, & Lenné, 2012). Both interactions, as well as a three-way interaction, were investigated with the goal of finding situations in which mind wandering may be particularly dangerous. Based on the relevant literature summarized above, there are six hypotheses for experiment III, listed as follows;

Methods

Participants

A total of 50 participants (15 women, 35 men) participated in the study. All participants will be required to have normal to corrected-to-normal vision and a valid driver’s license. Four participants were removed from analysis due to technical problems during testing, only reporting one thought type throughout the experiment, or not responding to the thought probes.

The final sample consisted of 13 women (mean age: 19.31 years, age range: 18-21 years) and 33 men (mean age: 19.06 years, age range: 18-22 years). Participants were recruited from an introductory Psychology course from North Carolina State University and were compensated for their time with class research credits.

Driving Scenarios

Perceptual complexity for the driving scenarios was manipulated through the presence/absence of task-irrelevant environmental stimuli such as trees, non-crossing pedestrians, oncoming vehicles, buildings, etc. The lower perceptual load condition was the same as the lower perceptual load condition used in experiment I except the road had four lanes instead of two. This change was made to allow for higher traffic volume in the higher perceptual load condition while maintaining the same road structure across conditions. The higher perceptual load scenario was a drive through a dense urban area with a high density of traffic, pedestrians, intersections, and buildings. None of these scenario components impacted or interacted with the driver in order to maintain the same level of interactivity and task-related stimuli between conditions.

Breaking Events

Unlike in experiment I where events were based on the time driven, thought probes in experiment III were based on driver distance in order to control for environmental effects. Each perceptual load condition had on average one braking event a minute for a total of 20 braking events in each scenario, 10 with braking lights (cue) and 10 without braking lights (no-cue). Braking events began at the same distance regardless of the type (cue/no-cue) and occurred at enough of a distance to make crashing unlikely in order to avoid dramatic changes in a participant’s arousal following a crash. Each braking event occurred approximately 3 seconds before the thought probe in order to allow for data collection on vehicular control measures for the 10 second interval prior to the braking event.

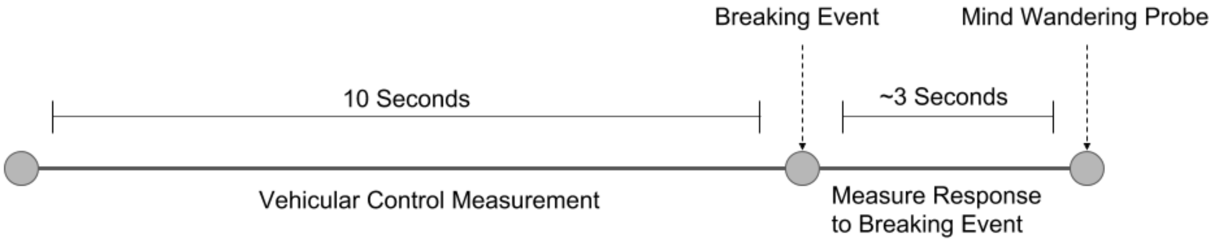

Figure 8: Diagram of measurement timing.

Procedure

Experiment III followed the same procedure as in the previous experiments. Participants were not explicitly informed of the breaking events, but the training drivers for both the low perceptual load condition and high perceptual load condition included 3 breaking events as practice.

Results

Data were analyzed using the same methods employed in experiment I and II. The rate of mind wandering and vehicular control measures were analyzed using generalized additive mixed effect models (GAMMs) with a smoothing effect for driving duration and a random intercept for participant using the mgcv package in R. All other models were analyzed using the lme4 package in R with a random intercept per participant. Covariates initially included in the models were gender, age, and experimental order (higher perceptual load first or second). If these terms were non-significant they were removed from the final model.

Rate of Mind Wandering

Mind wandering was modeled using a binomial family logistic mixed effect regression. No significant autocorrelation was present in the residuals. The variables included in the model were age, gender, perceptual load, and a smoothing effect for driving duration. There was a significant smooth effect for total driving duration (X^2 (4.49, 1840) = 12.71, $p < .031$), however, some differences from experiment I and II were present (see Figure 9). It took a longer duration compared to experiment I to reach a plateau, and a marginal fall in rate of mind wandering appears in the model, though this is quite small as can be seen on the right panel in Figure 8. There was no significant effect of perceptual load on the rate of mind wandering (z = .95, p = .343), unlike in experiment I.

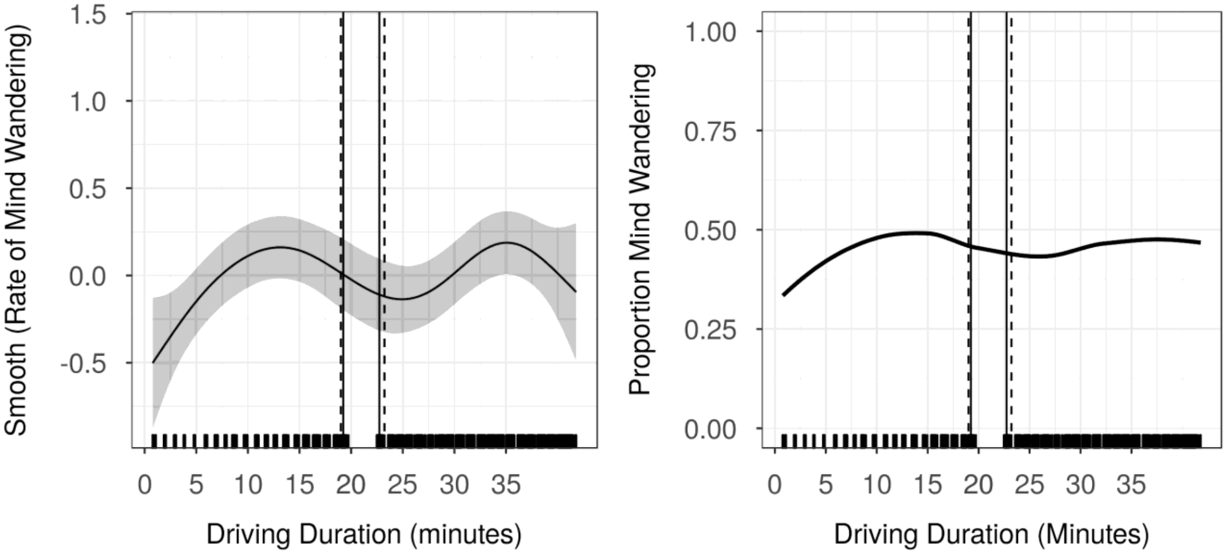

Figure 9: Rate of mind wandering over entire experiment duration. Left**:** The smoothing function coefficient for the rate of mind wandering over duration with the grey region representing the 95% confidence interval. The vertical lines represent the transition region between the two experiments, with the dotted lines covering all participants and the whole lines 50% of the participants. Right: Loess smooth of the rate of mind wandering over time by duration.

Speed

Driver speed was measured as the mean speed within the 5 second pre-braking interval preceding mind wandering probes. The initial model fit tested for significance of non-primary variables with a random intercept by participant; gender with women as the reference (b = .99, t(42.47) = 2.57, *p* = .014), age (b = .07, t(42.36) = .41, *p* = .682), task condition order (b = -.37, t(42.72) = -1.03, *p* = .309), and total driving time (b = .04, t(1780.01) = .36, *p* = .721). Age, order, and time were dropped for the final model, and mind wandering (t(1777.81) = -1.28, *p* = .203) as well as perceptual load (t(1808.55) = .31, *p* = .759) were added; neither of which were significant.

Pre-Braking Headway Distance

This analysis looked to see if there were differences in the headway distance during mind wandering vs. on-task in the interval preceding the braking event. The minimum headway distance within the 5 second interval per probe was used as the dependent variable. The starting model for headway distance was first constructed using non-primary covariates such as age (b = 2.12, t(41.99) = .21, *p* = .337), gender (b = -41.68, t(41.99) = -1.90, *p* = .064), scaled total driving duration (b = 6.71, t(23518) = 13.51, *p* < .001), and order (b = 9.01, t(42.00) = .44, *p* = .664). Non-significant effects were removed (age, gender, and order) and the main effects for mind wandering and perceptual load were added. During the high perceptual load condition, drivers maintained less headway distance than in the low perceptual load condition (b = -9.36, t(1774.12) = -2.33, *p* = .020); however, no difference was found on headway distance during the interval immediately before a mind wandering or on-task response(t(1780.61) = -.52, *p* = .601).

Change in Headway Distance during Braking Events

The differences in headway distance prior to the braking event between mind wandering and on-task thoughts required controlling the starting headway distance in the analysis of the minimum headway distance following the braking event. The modeled variable was then the minimum headway distance following the braking event minus the initial headway distance following the start of the braking event. This variable can be interpreted as the larger the negative magnitude, the more the safety margin decreased, with 0 meaning the driver maintained the same headway distance following the braking event compared to before the braking event. An initial model was run with non-primary covariates testing for the significance of age (t(42.02) = .16, *p* = .874), gender with women as the reference group (b = -8.64, t(42.09) = -2.49, *p* = .017), experiment order (t(42.08) = .56, *p* = .581)), and total experiment time (t(1777.37) = 4.51, *p* < .001).

Non-significant effects were then removed, and a second model was run adding in main effects for perceptual load, mind wandering, and cueing of a braking event. Mind wandering during driving was associated with decreased headway distance compared to on-task driving (b = -1.78, t(1804.28) = -2.27, *p* = .023). The higher perceptual load was associated with decreased headway distance compared to the low perceptual load (b = -4.17, t(1773.43) = -5.57, *p* < .001). The un-cued braking events also had a shorter headway distance compared to the cued condition (b = -1.82, t(1771.67) = -2.44, *p* = .015).

A third model was then fit adding in an interaction between mind wandering and braking cues (F(1,1779.99) = .25, *p* = .615) and an interaction with mind wandering and perceptual load condition (F(1,1779.36) = 4.55, *p* = .033), and a third interaction between perceptual load and braking cues (F(1,1772.61) = 13.08, *p* < .001). While the interaction of mind wandering and perceptual load was significant, there was no significant difference between mind wandering and on-task in the low perceptual load condition, and there was no significant difference between mind wandering and on-task in the high perceptual load condition (see Table 4). Similarly, the interaction of perceptual load and braking cue was significant, however, there was no significant difference between the cued and un-cued braking events in the lower perceptual load condition, and no significant difference between the cued and un-cued braking events in the higher perceptual load condition (see Table 5).

Table 4

Post-hoc Comparisons of Thought Type and Perceptual Load on Headway Distance

Thought Type	Perceptual Load	Mean	95% CI
Mind Wandering	Lower	-3.65	(-6.49, -.80)
Mind Wandering	Higher	-9.58	(-12.45, -6.71)
On Task	Lower	-3.49	(-6.29, -.68)
On Task	Higher	-6.19	(-8.99, -3.39)

Table 5

Post-hoc Comparisons of Perceptual Load and Taillight Cue on Headway Distance

Perceptual Load	Taillight Cue	Mean	95% CI
Lower	Cued (light on)	-4.03	(-6.85, -1.23)
Higher	Cued (light on)	-5.65	(-8.48, -2.82)
Lower	Un-cued (light off)	-3.-9	(-5.92, -.27)
Higher	Un-cued (light off)	-10.13	(-12.95, -7.31)

Discussion

The first goal of Experiment III was to further examine the effect of perceptual load on the rate and cost of mind wandering using strengthened perceptual load manipulation. More specifically, this experiment compared a simple rural environment (lower perceptual load) to a busy metropolis (higher perceptual load). Participants had a 47.23% rate of mind wandering in the lower perceptual load condition compared to 44.91% in the higher perceptual load condition, rates similar to that found in experiment I (lower load: 49.66%, higher load: 41.17%). This difference was significant, however quite modest, particularly when compared to the range of 25-88% found in the search task of Forster and Lavie (2008). One potential explanation for the limited sensitivity of mind wandering to perceptual load in this study was the control of interactivity of the environment. The manipulation of perceptual complexity used in Forster and Lavie (2008) was directly related to the visual search task, requiring participant to process the additional symbols; this is in contrast to the current study, in which participants weren't required to process the additional perceptual load information to perform their task. Although this is unlikely that participants had not processed such irrelevant information at all, it is reasonable to speculate that active processing of this information is dampened given objects in a driving scene are spatially predictable thus maybe more easily inhibited. In order to ensure that differences between conditions were purely a function of the perceptual load manipulation, both environments did not require the driver to make any turns or respond to other vehicles/pedestrians. This prevented interactivity from confounding the effect of perceptual load, however, it would be expected that a more perceptually complex environment in real driving would likely require more and a greater variety of driver responses, which would increase the differences between the situations as the scenario engages the drivers' attention more. A second possible explanation for the difference in manipulation sensitivity between the studies could be the use of abstract stimuli in a simple setting used in Forster & Lavie (2008) compared to the naturalistic driving stimuli used in the current study.

The pattern of change in rate of mind wandering by driving duration was similar to that found in Experiment I and Experiment II when looking within each perceptual load condition, however, there was a difference compared to Experiment I in terms of how the rate changed throughout the entire driving duration. This study showed a temporary drop in the rate of mind wandering when the perceptual load condition changed, unlike in Experiment I. This is likely a function of the increased strength of the manipulation of perceptual load, or differences in the driving behaviors of the scenario (fixed oscillating speed and braking events). No support was found for the influence of mind wandering on headway distance within the interval preceding the braking event. This result was in contrast to experiment II in Yanko and Spalek (2013), which utilized a similar design for periodic braking events, though at a higher volume of breaking events (~2/minute) and with the lead vehicle maintaining speed with the driver compared to the oscillating speed around a fixed point used here and in He et al. (2008). The lead vehicle maintaining speed with the driver allows for measurement of driver speed but not headway distance except during breaking events, while using a fixed or oscillating lead vehicle speed limits the choice in speed but allows for measurement of headway distance. Oscillating rather than fixed speed is commonly used in order to keep the driver engaged. It is perhaps worth noting that the difference in headway distance during mind wandering (M = 42.1m) vs. on-task driving (47.1m) found in Yanko and Spalek (2013) was small. Similar to our finding, He et al., (2008) did not find evidence of a difference.

In terms of the effect of mind wandering on driving performance, this study found that mind wandering was associated with a greater decrease in headway distance during a braking event compared to when drivers were on-task. This result is in line with Yanko and Spalek (2013), which found significant differences between mind wandering and on-task driving for response time to braking events, however, this study instead analyzed changes in headway distance controlling for starting headway distance. This result brings additional support for the claim that mind wandering is associated with a decreased safety margin compared to on-task; however, no support was found for mind wandering being particularly costly during the higher perceptual load condition (a busy metropolis) compared to the lower perceptual load condition (a rural environment) or for the no-cue (no onset of tail lights) braking events compared to the cued (onset of tail lights) braking events. One potential explanation for the lack of support for an exacerbating effect of mind wandering in the other conditions could be the frequent occurrence of braking events (~1 event/minute), which may have helped participants stay engaged in the task. Mind wandering may be more detrimental in naturalistic driving situations when potential crash events are far rarer and there is no secondary task (responding to mind wandering probes) to maintain driver's attention. An alternative explanation may be that while mind wandering could have an exacerbating effect on driving performance, it may be a relatively small effect size, as has been seen in the other mind wandering related costs (Yanko & Spalek 2013; He et al., 2008).

Insufficient evidence was found in support for an exacerbating effect of perceptual load on car following distance during non-cued versus cued braking events. A potential explanation for this finding is that since all of the perceptual load information was task-unrelated in the sense that it did not involve interaction with the driver, it may have had little impact with task critical information such as with braking events. This relationship may differ in situations in which task-related perceptual load or interactivity are added, as the additional information would force the participant to respond to it, likely slowing their response time to unexpected events. Additional research is needed on how task-related perceptual load differs from task-unrelated perceptual load within a driving context, and their interaction with other contextual factors during a driving.

GENERAL DISCUSSION

The purpose of this dissertation was to examine some circumstances for which mind wandering may be particularly dangerous or prevalent during driving by investigating environmental and situational factors. There have been a number of previous studies investigating the impact of mind wandering on driving performance, however, these studies all used simple rural roads and took little account of driving duration. The cited reason for the simplified driving scenarios was to maximize the rate of mind wandering (He et al., 2011), presumably in order to have sufficient statistical power. The cost of only using simplified rural driving scenarios is the limiting of the scope of circumstances that can be investigated, potentially overlooking specific circumstances in which mind wandering may be particularly dangerous (e.g., left hand turns in busy intersections, unexpected merging on highways). The current research studies addressed this limitation through exploring driving performance across a number of perceptual load conditions which included traffic and driving unrelated peripheral objects (trees, houses, etc.) which are more representative of the average driving experience. Experiments I and II focused on the impact of perceptual load and driving duration on the rate and cost of mind wandering using conventional vehicular control measures (longitudinal/lateral speed and velocity). Experiment III increased the strength of the perceptual load manipulation from Experiment I and investigated the impact of mind wandering on an additional driving performance measure that was the response to cued and un-cued braking events.

Experiments I and III displayed a lower rate of mind wandering during the higher perceptual load condition compared to the lower perceptual load condition. The effect size of this difference was relatively small, and in all conditions the rate of mind wandering was at least 41%. These results show that there is little need to limit the scope and context of driving scenarios out of concern of eliminating mind wandering in an experimental context and provide additional support to Forster and Lavie’s (2008) finding of the relevance of perceptual load on mind wandering. As the perceptual load increases there are less cognitive resources available to engage in spontaneous task-unrelated thoughts resulting in lower rates of mind wandering. It may be speculated that in higher perceptual load scenarios there are also less available resources for the executive function to engage in mega-cognitive awareness, potentially leading to decreased re-engagement in the task when individuals do engage in mind wandering.

According to perceptual load theory, higher perceptual loads lower the processing of task-irrelevant stimuli and decreases the cognitive resources available for other tasks, as the additional perpetual load consumes cognitive resources. The diminished available resources in higher perceptual load conditions may negatively interact with mind wandering costs, as there would be fewer available resources and a smaller signal-to-noise ratio of task-relevant to task-irrelevant stimuli. This led to the hypothesis that vehicular control detriments during mind wandering may be exacerbated during higher perceptual load conditions. There was little evidence across either study that mind wandering costs were exacerbated during higher perceptual load condition, with only Experiment I having shown a significant interaction for driving speed at a small effect size. This result is not unprecedented, as previous studies have found mixed results on the impact of perceptual load on driving performance (Brookhuis, de Vries, & de Waard,1991; Lee, Caven, Haake, & Brown, 2001), and perceptual load theory in general ((Beck & Lavie, 2005; Lavie & Cox, 1997; Maylor & Lavie, 1998). One explanation for the disparate results may be that many of these studies have not made distinctions about the relevance of the perceptual load to the primary task, a factor that may be relevant, as if few features are shared between the additional perceptual stimuli and task-relevant stimuli then individuals may simply increase their distractor suppression with little impact to primary task performance. This was a key difference between these studies (in which perceptual load was task-irrelevant as it never required a driver response) and Forster and Lavie's (2008) which used task-relevant stimuli. The choice of only manipulating task-irrelevant stimuli was based on the desire to control for differing levels of interactivity of the environment, a key issue in a driving situation. For example, if a metropolis area was directly compared to a rural area without controlling for driving events, then it would be difficult to tell if differences between the conditions were a result of the differing perceptual load or events that they allowed to occur.

The second primary objective of this study was to explore how driving duration relates to mind wandering. All three Experiments showed that the rate of mind wandering approached an asymptotic peak after approximately 20 minutes, with a small rise around 35 minutes in the extended driving duration condition of Experiment II. Given the limited challenge of the driving task, the change in the rate of mind wandering is likely to be a result of increased boredom rather than fatigue. These results have powerful implications on the potential of a sporadic alerting system for drivers once mind wandering detection capability is improved. This study hoped to identify ways in which mind wandering could be managed effectively during driving while controlling for the 'cry wolf' effect, wherein too many alerts would eventually results in the operator ignoring them. By identifying that mind wandering reliably stabilizes over time, it may be an effective strategy for an alerting system to detect when the individual has had a high proportion of mind wandering over a set duration, or a particularly long mind wandering episode, and provide an alert to remind the individual to re-engage their attention. Furthermore, these results contribute to the theoretical understanding of the relationship of the executive function attempting to maintain attention on task and mind wandering and how they reach an equilibrium after a certain duration. This result raises further questions about how task related characteristics, such as difficulty or cognitive load, may influence the amount of time it takes for the rate of mind wandering to stabilize and the maximum at which it arrives.

A few studies have previously found that mind wandering is associated with increased response time variability (Bastian & Sackur, 2013; Seli, Cheyne, & Smilek, 2013), however, these results were based on aggregated trials over time. Using generalized additive mixed effect models, a significant difference was found between the nonlinear function of driving speed over time during mind wandering vs. while on task. Although the exact nature of the function is hard to interpret, it raises the importance of controlling for task duration when considering differences between conditions. These results call into question whether previous differences found between mind wandering and on-task response time variability were really differences in their variability over time, or their variability at any particular point in time. Another important implication of this novel result was the potential impact of mind wandering on driving patterns; increased variability in speed during mind wandering may have detrimental impacts on overall traffic flow.

General measures of vehicular control such as longitudinal/lateral speed, acceleration, and lane keeping performance were analyzed across all three Experiments, with no significant differences except for a small effect in driver speed. Experiment III utilized a lead vehicle which kept an oscillating speed around a fixed point in order to get an accurate measure of headway distance and response to cued and un-cued braking events. No differences were found between the mind wandering and on-task driving for headway distance, a result that was in contrast to that found in Yanko & Spalek (2013) in which drivers when engaged in mind had a marginally smaller safety margin compared to when being on-task.

In Experiment III, drivers engaged in mind wandering had a larger decrease in headway distance during braking events compared to when being on-task, though there was no significant interaction with whether the braking event was cued (brake light, no brake light). The intention of manipulating the cue of the braking event was to determine if individuals had decreased target facilitation during mind wandering and were more reliant on particular features of their environment in order to minimize processing of the primary task. It is possible that due to the presence of alternative distance cues (e.g., increased looming in foveal region) the brake lights were a redundant feature of the environment. Another interpretation is that mind wandering may not significantly decrease sensitivity to task-relevant foveal stimuli but may be more impactful for peripheral stimuli sharing features with task-unrelated stimuli (e.g., pedestrians crossing at an illegal junction). The significantly impacted safety margin during mind wandering for braking events still has implications on when it may be safer to engage in mind wandering; for example on rural roads during the day, where less unexpected stimuli may be present compared to metropolis driving.

Limitations and Future Directions

The current studies contained a number of limitations. First, all experiments were conducted on a fixed-based low-fidelity driving simulator in which the consequences of crashing are unlike real driving and driving behaviors may not exactly match between the simulator and on-the-road scenarios. Validity for driving simulators is often considered in two forms; absolute validity and relative validity. Absolute validity is whether of not driving behaviors are identical between simulated driving and on-the-road driving; there is mixed evidence for the absolute validity of driving simulators (Blaauw, 1982; Mullen, Charlton, Devlin, & Bedard, 2011), likely varying due to the many different driving simulators used as well as the different metrics being compared (speed, lane deviations, signaled intersections, etc.). Relative validity is generally considered good for driving simulators for many vehicular control measures (Blaauw, 1982; Yan et al., 2008). There has been no research directly comparing mind wandering between naturalistic and simulated driving, however, leaving uncertainty for the absolute validity of the findings in simulated studies.

The uncertainty about the power of the three studies is another limitation. The sample sizes were chosen based on the larger side of previous studies due to the low proportion of data that is used in mind wandering studies, however, these studies also involved more complex models. Power calculations were not done due to the challenges in power simulations with additive models, as it is not obvious how to specify the minimum effect size that one is interested in for a nonlinear effect. Given the additional complexity of the models used in these analyses (mixed effect and additive) there is a possibility that some of the analyses were underpowered, particularly those involving the binary data (mind wandering as the dependent variable). The second impact of the limited sample size with these models is that we cannot be confident in the accuracy of the confidence intervals for the logistic additive mixed effects models, as they are based on asymptotic normality assumptions and are point-based rather than simultaneous.

Another challenge in relation to external generalizability was the presence of mind wandering probes, which are required with current methodology to measure the individuals current train of thought but were a constant interruption to the individuals thought pattern. Some support has been found that not all mind wandering is equivalent (Galéra et al., 2012), and that while thinking about certain more challenging topics we are more distracted as the task-unrelated thoughts have a heavier cognitive load. The constant interruptions of the mind wandering probes during laboratory research may be keeping individuals engaged in ‘shallow’ mind wandering, as it is constantly bringing their attention back to the task. A future study comparing the cost of mind wandering across a range of probe rates (e.g., ~1/ minute, 1/5 minutes) could be useful in illuminating how experimental interference is influencing the results being collected, and whether the high rates of self-report are providing a conservative estimate of the dangers of inattention through measuring primarily ‘shallow’ mind wandering.

The cost of the strong internal control of perpetual load conditions across Experiment I and III was the removal of interactivity in the environment when in real driving scenarios the two factors would often occur in conjunction. Future studies should look to control the perceptual load conditions and compare levels of interactivity (lane changing, following a complex route, pedestrian crossing, etc.) in order to see how these influence driving behaviors and attentional oscillation. If mind wandering rates still occur at a high enough rate for sufficient statistical power in higher perceptual load conditions with moderate levels of environmental interactivity, then research can be conducted on specific driving situations in which mind wandering may be more dangerous.

Finally, while the impact of driving duration on mind wandering was explored, neither of the proposed mechanisms (boredom and fatigue) were directly measured. Now that a significant effect of driving duration has been discovered, it would be fruitful for future studies to measure driver boredom and fatigue throughout the experiment to see whether changing mind wandering rates are a function of one, or both at differing durations (boredom at the beginning, fatigue as the duration drags on). Understanding the cause of driving durations impact on mind wandering will inform what strategies can be developed to counteract the high rates found in these studies; if boredom is the primary mechanism then periodic alerts may be effective, while if fatigue is the issue then a recommendation to the driver to take a short break could be more beneficial.

Conclusions

To summarize, environmental variables such as driving duration and perceptual load have a substantial effect on the rate of wandering in simulated driving scenarios, and mind wandering can have a detrimental effect on a number of safety relevant vehicular control variables including headway distance, speed, and change in safety margin during braking events. The ubiquitous nature of mind wandering makes simple prevention strategies such as those used with external distraction (don’t text and drive) impossible, requiring instead a more targeted approach for safety critical situations. These studies help outline situations in which mind wandering may be particularly detrimental to driving performance and prevalent so that targeted alerts could be given to drivers to re-engage their attention in task-related information.

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