# Perception-Response Time to Emergency Roadway Hazards and the Effect of Cognitive Distraction

by

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## Abstract

A critical part of traffic safety is a driver's ability to detect and respond to emergency roadway hazards. This thesis uses eye movements and motor responses to divide driver perception-response time in three stages: perception, inspection, and movement time. The effects of cognitive distraction and repeated exposure on each stage were investigated for three distinct hazards (left-turning vehicle, pedestrian, right-incursion vehicle).

In general, there were varying effects of cognitive distraction observed depending on the hazard being responded to. Cognitive distraction resulted in a significant increase in perception times for the pedestrian and right-incursion vehicle hazards, whereas cognitive distraction resulted in significantly longer inspection times for the left-turning vehicle hazard.

When considering the effect of repeated scenario exposure, perception times were the most greatly affected. Perception times were significantly shorter during the second exposure to the left-turning vehicle hazard in the baseline condition, and for all hazards in the distraction condition.

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# CHAPTER 1

## 1.0 INTRODUCTION

Driver error is a commonly reported cause of motor vehicle collisions. Therefore, a driver's ability to detect hazards on the roadway and respond accordingly plays a vital role in traffic safety. The main focus of the research described herein was to examine the effects of cognitive distraction and repeated scenario exposure on driver perception-response times to a variety of emergency roadway hazards. The primary objectives were to explore the use of eye movement recordings to further sub-divide driver perception response time into a number of stages and to evaluate the effects of cognitive distraction and repeated scenario exposure at each stage. It was hypothesized that evaluating the effects at each stage would lead to a better understanding of how information is processed in the driving environment in the context of emergency hazard perception, identification and response.

This thesis made use of eye movement recordings and motor responses in a simulated driving environment to divide driver perception-response time into three separate stages, including (a) perception time, (b) inspection time, and (c) movement time. Driver response times to three different emergency roadway hazards were measured. The hazards presented to the drivers were designed such that they warranted emergency avoidance maneuvers. They included a left-turning vehicle cut-off at an intersection, a pedestrian stepping onto the roadway from in front of a parked vehicle, and a vehicle accelerating perpendicularly into a driver's path from the right. Subjects participated in two simulated drives, one while executing a secondary cognitive distraction task (the delayed digit recall 1-back task) and the other without distraction. The effects of cognitive distraction and repeated scenario exposure on the individual response time stages were evaluated.

The first chapter of this thesis will provide an introduction and background on some of the relevant literature. Details of the experimental design and methodology are provided in Chapter 2. Chapter 3 presents the data analyses completed and results. Chapter 4 and 5 provide a summary and discussion of the results, contributions to the field, as well as recommendations for future work.

## 1.1 Introduction

Driving in its simplest form can be described as a form of locomotion, with the primary function being to safely move from one location to another (Gibson & Crooks, 1938; Shinar, 2007). However, driving is not simply a motor activity, it involves cognitive procedures (Parkes, 1991). Driving demands the execution of many complex abilities, and failures in these abilities can lead to devastating results (Hancock & Scallen, 1999). Although crash rates are declining (Transport Canada, 2009, U.S. Department of Transportation, 2009), motor vehicle collisions are still a leading cause of death and injury. About 1.3 million people are killed due to motor vehicle collisions globally each year and an additional 20 to 50 million sustain non-fatal injuries (World Health Organization, 2009). Road traffic injuries are the leading cause of death among people aged 15 to 29 (World Health Organization, 2009).

Motor vehicle collisions are typically the result of several contributing factors, which can include driver behavior, environmental factors, such as road design and surface conditions, and vehicle deficiencies. Based on an in-depth study of causation factors in over 2500 motor vehicle accidents (Treat et al., 1979), human factors were cited as probable causes in over 90% of collisions, which were much more frequent than environmental and vehicle factors. The primary human factors causes were recognition and decision errors, which included improper lookout, excessive speed, inattention, improper evasive action, and internal distraction. An investigation of 723 crashes by Hendricks et al. (1999) found very similar results, with driver behavioural error either causing or contributing to 99% of crashes. An examination of over 1,000 crashes also reported recognition and decision errors to be the primary causes in 44% and 23% of accidents, respectively (Najm, Mironer, Koziol, Wang, & Knipling, 1995). Driver error, such as inattention, inadequate information processing, and missed or delayed hazard perception, is a commonly reported major cause of traffic collisions (Horswill & McKenna, 2004; Smiley & Brookhuis, 1987; JS Wang, Knipling, & Goodman, 1996). A more recent study, the 100-car naturalistic driving study (Dingus et al., 2006) found that inattention or improper visual orientation is a large contributing factor of accidents, with about 80 percent of all crashes and 65 percent of near-crashes involving a driver who was looking away from the forward roadway just before conflict onset. It is important to note that driver inattention in this study encompassed many different forms and was found to occur very frequently (Klauer, Dingus, Neale, Sudweeks, & Ramsey, 2006). This may have led to an overstatement in the involvement of inattention in crash and near-crash events.

Although the exact numbers vary between studies, which may be partially due to inconsistencies in terminology, especially with respect to inattention and distraction (Gordon, 2008), what is consistent is that recognition and decision errors made by the driver are a leading contributing factor to many motor vehicle collisions. Recognition errors usually mean that a critical event was either not recognized at all before a crash or that recognition was delayed so that by the time the driver responded it was too late (Shinar, 2007). Therefore, a driver’s ability to detect potential hazards and respond accordingly is crucial for traffic safety (Shahar, Alberti, Clarke, & Crundall, 2010). Hazard perception with respect to driving has been described as the ability to identify or anticipate dangerous traffic situations (Horswill et al., 2009; Velichkovsky, Rothert, Kopf, Dornhöfer, & Joos, 2002).

In driving research, the time that it takes for a driver to perceive and respond to a hazard is commonly referred to as perception-response time, and has been defined as the time interval that starts when an obstacle first becomes visible to a driver and ends when the driver has initiated a response, such as touching the brake pedal (Olson & Sivak, 1986; Olson, 1989). Others have defined this interval as the brake-reaction time (Muttart, 2004; Shinar, 2007) and have retained the term perception-response time to also include the latency of the vehicle’s braking system. There are a variety of different terms used in the literature that refer to driver response times, and although sometimes used interchangeably, there are usually subtle differences between when the time interval starts and ends, which can lead to confusion when comparing results (Muttart, 2004). For the purpose of this discussion, driver response and perception-response time will be used in a general sense, with details regarding the specific intervals provided when necessary.

Driver perception-response time is of particular importance in road design for providing adequate sight distance to allow drivers the opportunity to perceive potential obstacles and bring their vehicle safely to a stop (Olson, Cleveland, Fancher, & Schneider, 1984; Shinar, 2007). There is also considerable interest in driver response times by accident investigators who are frequently required to assess a driver’s actions leading up to a collision for litigation purposes. There have been numerous studies conducted measuring driver response times to different stimuli under a variety of driving conditions, as well as investigations into factors that affect driver response times (Green, 2000; Muttart, 2001, 2004; Olson & Farber, 2003; Summala, 2000).

A common limitation of perception-response time studies is that an assumption is inherently made as to when an object or event first becomes identifiable as a hazard, or when perception occurs. This is the point when the response time interval is started. Some studies, especially those conducted for the purpose of road design, start the clock when an object first becomes visible to a driver (Olson et al., 1984). Others have chosen such starting points as when a vehicle first starts to accelerate into a driver's path (Lechner & Malaterre, 1991; Mazzae, Barickman, Forkenbrock, & Baldwin, 2003; McGehee et al., 1999) or when a pedestrian first steps onto the roadway (Broen & Chiang, 1996). These starting points seem to correspond with the first opportunity the driver likely had to identify the object as a hazard; however they are somewhat arbitrary and do not provide any information about when a driver actually first detected the hazard. There are also some situations where a logical starting point is not obvious, such as in reduced visibility conditions (Muttart, 2004; Olson & Farber, 2003), or when there is ambiguity as to when an object or event transitions from being a non-hazard to a hazard. More recently there has been research conducted into the use of driver eye movements to provide a better estimate as to when an object is first perceived (Huestegge, Skottke, Anders, Muesseler, & Debus, 2010; Kledus, Bradac, & Semela, 2010; Velichkovsky et al., 2002).

A driver's ability to perceive and respond to a hazard is limited by his information processing capabilities, which are limited both in the amount of information that can be attended to at one time and the rate at which information can be processed (Wickens & Hollands, 2000). Humans have limited cognitive resources; therefore if task demands exceed the capacity at any given time it can lead to degraded performance, or with respect to driving, it can result in an accident (Hole, 2007; Hurts, Angell, & Perez, 2011; Shinar, 2007). While operating a motor vehicle there are many sources that compete for mental resources, including those related to the primary driving task and a variety of secondary activities (Hurts et al., 2011). These secondary activities can be further sub-divided into those related to driving (e.g., checking the speedometer) and those which are completely unrelated to driving (e.g., looking at a billboard or talking on the phone). These secondary tasks are commonly referred to as driver distractions, which has been defined by Lee et al. (2008, p.34) as "a diversion of attention away from activities critical for safe driving toward a competing activity". Distractions can be introduced in the driving environment in various forms, including visual, auditory, biomechanical, and cognitive (Ranney, Mazzae, Garrott, & Goodman, 2000). However, these different forms do not occur in pure isolation from one another. All distractions can be said to have a cognitive component. With the increasing use of hands-free devices while driving, there has been an increased amount of interest and research conducted on the effects of cognitive distraction on driving performance. For these reasons, the focus of this discussion will be on the effects of cognitive distraction (anything that takes the mind off the road) on the ability to perceive and respond to hazardous roadway events.

## 1.2 Human Information Processing and Perception-Response Time Stages

Humans are essentially limited capacity processors of information (Shinar, 1978; Wickens & Hollands, 2000). A model of human information processing proposed by Wickens (2000) represents the process in a series of stages, which include sensory processing, perception, cognition and memory, response selection, and response executive. Attentional resources are a separate block of the model, which reign over the entire process and can be allocated to different stages. The model also has a feedback loop which represents that human information processing is a continuous closed-loop system where any response actions made by the human operator will in turn create new sensations to be perceived. Wickens' model is a generic representation of information processing, which can be used in any domain. Shinar (1978) proposed a similar model, specifically focused on the information processing functions of a driver. Both models can be directly related to the stages commonly associated with a driver's perception-response time to an external stimulus (Olson, 1989; Pignataro, 1973). Olson (1989) classified these stages as detection, identification, decision, and response. Figure 1 illustrates an adaptation of Wickens' (2000) model of information processing with respect to the stages of driver perception-response time.

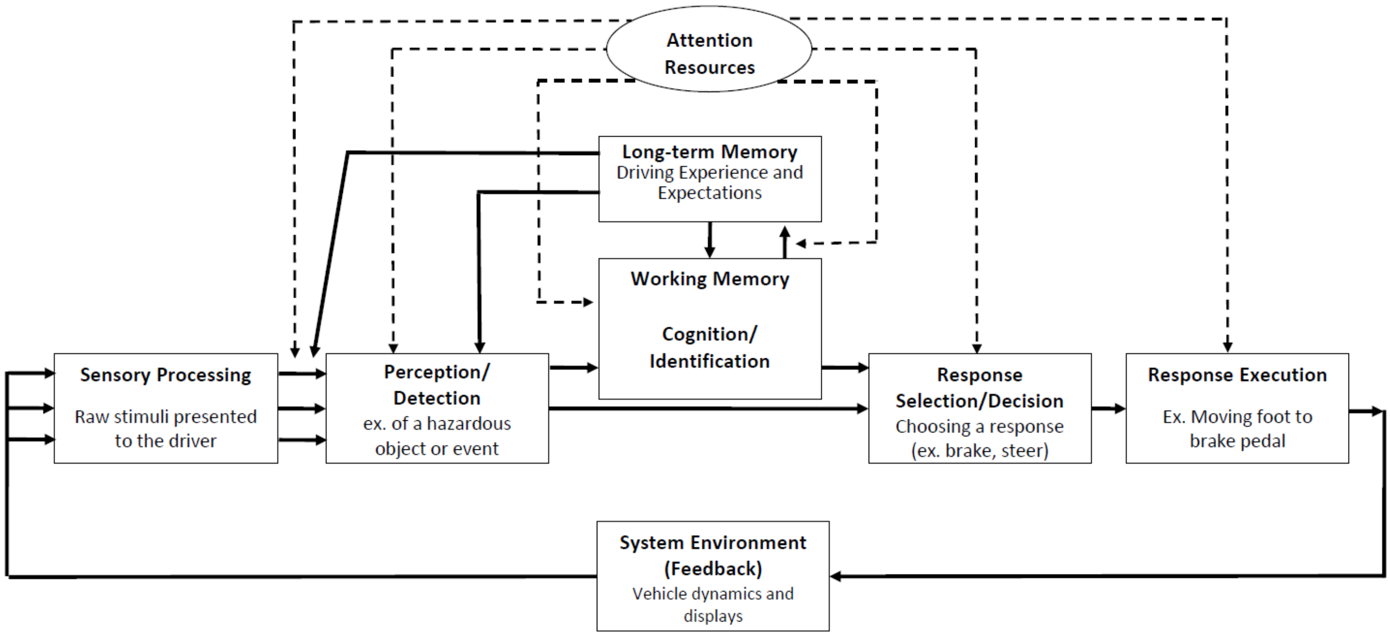


**Figure 1**: Adaptation of Wickens' (2000) model of information processing with respect to the stages of driver perception-response time.

Green (2008) describes sensation as the detection of energy from the environment. Sensory processing consists of the raw stimuli from the environment gaining access to the brain through the senses (Wickens & Hollands, 2000). Our sense organs are bombarded with about 1 million bits per second of new information, however we are consciously aware of only about 16 bits per second (McCormick, 1970). Senses can exist; however if attention is not allocated to those senses they will not be perceived. Green (2008) refers to this as the "attentional filter", which acts as a gatekeeper allowing only some information through to perceptual processing. It has been estimated in the literature that driving makes use of sensory input that is 90 percent visual (Hills, 1980), and although there are no hard data to support this precise number, information input to the driver is predominantly visual (Byrnes, 1962; Sivak, 1996).

Perception is the process of interpreting and providing meaning to raw sensory data. Perception is dictated not only by the sensation itself, through bottom-up processing, but also from stored knowledge, such as expectancies and past experiences from long-term memory, through top-down processing (Hole, 2007; Wickens & Hollands, 2000). The perception process is fairly automatic and quick, with little attention required. The perception stage of Wickens' (2000) model is comparable to the detection stage of the driver perception-response time interval, which starts when a hazard enters a driver's field of view and ends when the driver develops a conscious awareness that something is present (Olson & Farber, 2003).

The cognition stage requires greater time and mental effort than the perception stage, and draws on memory to assign meaning to the sensation that was just perceived (Wickens & Hollands, 2000). In driver perception-response research, this stage is referred to as identification. During the perception stage the diver becomes aware that something is present; however during the identification stage the driver must acquire information regarding what that something is, and if the object is moving, the driver must make judgments with respect to its speed and trajectory (Olson & Farber, 2003).

The next stage is response selection or decision. This is the stage where the driver uses the information acquired during the identification stage to determine if a response is warranted and to choose which response to make, such as braking or steering. The final stage is response execution, the process of the brain sending commands to the appropriate muscles to carry out the chosen response action (Olson & Farber, 2003).

Attention is the final component of the model, which represents a supply of mental resources at each stage of the process (Wickens & Hollands, 2000). Humans have a limited supply of mental resources and the allocation of these resources is driven by both top-down cognitive factors, such as knowledge, expectations, and goals, as well as stimulus-driven bottom-up factors, such as sudden movements (Corbetta & Shulman, 2002; Egeth & Yantis, 1997; Victor, 2005). Humans are not only limited in their supply of attentional resources, they are also limited in the ability to divide attention between two concurrent tasks (James, 1890). Driving is a multitasking skill that requires the division of attention between a variety of tasks, including operational control (e.g., lane keeping), tactical control (e.g., gap acceptance), and strategic control (e.g. navigation) (Hurts et al., 2011; Michon, 1985). The amount of attention devoted to each driving task will vary with the demands of the driving environment (Shinar, 1978). Most of the time we have enough attentional capacity to be able to successfully time-share between not only the driving tasks, but also non-driving tasks without incident (Shinar, 2007). However, sometimes the demands of the driving environment, combined with non-driving related tasks, increase suddenly and maximum capacity is reached, leading to dangerous driving errors and accidents (Hurts et al., 2011; Shinar, 2007). Late detection or failures to respond to unexpected hazards on the roadway is largely attributed to failures of attention (Wickens & Horrey, 2009).

## 1.3 Perception-Response Time Studies

The simplest form of a reaction time study is in a laboratory setting where a subject is provided with only one possible response action and told to respond as quickly as possible when a known stimulus occurs (such as when a light turns on). This is referred to as simple reaction time (Teichner, 1954; Wickens & Hollands, 2000). Essentially, the information processing in this task jumps directly from perception to response execution, without the need for identifying the stimulus or deciding on a response. In contrast, choice reaction time refers to a more lengthy and complex process where there could be uncertainty in the stimulus and/or the response, as is predominantly the case for the driver of a motor vehicle (Card, Moran, & Newell, 1986; Wickens & Hollands, 2000). The notion that choice reaction time is longer than simple reaction time and that reaction time occurs in successive stages was demonstrated through the development of the subtractive method by Donders (1869). Through experimental manipulation, Donders successively removed different stages of the perception-response process, such as eliminating response choice by having only one predefined response option and removing stimulus uncertainty by providing only one known stimulus. This allowed him to compare choice reaction time to simple reaction time, as well as determine the time required to complete the intermediate stages of response selection and stimulus identification.

Several authors have provided extensive summaries of many of the driver perception-response time studies conducted (Green, 2000; Olson & Farber, 2003; Sens, Cheng, Wiechel, & Guenther, 1989). When evaluated on the whole, there is substantial variation in the response time values reported in these studies. However, it is important to note that the experimental methodology, as well as the stimuli being responded to, differ between studies. Some studies have been conducted using a driving simulator (Barrett, Kobayashi, & Fox, 1968; Lechner & Malaterre, 1991; McGehee et al., 1999), while others were performed on the roadway (Fambro, Koppa, Picha, & Fitzpatrick, 1998; Johansson & Rumar, 1971; Lerner, 1993; Olson et al., 1984; Triggs & Harris, 1982). Some subjects were alerted to the purpose and nature of the study prior to participating (Korteling, 1990) while others were given false impressions, in order to obtain a more realistic surprise response (Fambro et al., 1998; Lerner, 1993; Mazzae et al., 2003; Olson et al., 1984). The types of stimuli being responded to also differed from auditory (Johansson & Rumar, 1971) to a variety of visual stimuli, including changes of traffic signals (Wortman & Matthias, 1983), brake lights of a lead vehicle (Sivak, Post, Olson, & Donohue, 1980), pedestrian encroachments (Barrett et al., 1968; Broen & Chiang, 1996), moving crash barrels

(Fambro et al., 1998; Lerner, 1993), stationary objects on the roadway (Olson et al., 1984), and intruding vehicles at an intersection (Lechner & Malaterre, 1991; Mazzae et al., 2003; McGehee et al., 1999).

Many authors have commented on the factors that may have an effect on driver response times, such as age, urgency of response, expectancy, eccentricity, response complexity, speed, etc. (Green, 2000; Muttart, 2001, 2004; Olson & Farber, 2003; Summala, 2000), with some conflicting views as to which factors have the greatest effect.

Research by Muttart (2003, 2004) has shown that many of the differences in the results of the published research can be accounted for if the methodology and stimulus used in the study are considered. Muttart (2003) conducted a meta-analysis of the published research and used multiple stepwise linear regression to determine which potential factors had a significant influence on response time, such as eccentricity, speed, road type, headway, time-to-contact, etc. The factors were used to develop a series of mathematical equations for estimating driver response times for a variety of situations.

There are also inconsistencies in the terminology used between studies, which can lead to confusion when comparing results. Despite being reported by identical names, the measured response times may represent different intervals, such as time to first foot motion versus time to brake pedal application. Lastly, there are also inconsistencies in how data are reported across studies. Some studies reported 50$^{th}$ percentile response time values, while others report means. Since there is a limit to how fast someone can respond but no limit to how slowly they can respond, the distribution of response time data is generally positively skewed, meaning that the mean value can sometimes be much greater than the 50$^{th}$ percentile value (Olson & Farber, 2003).

Driver response time to emergency hazards is the primary focus of this thesis; therefore the results that will be described here will be confined to studies that measured perception-response times of drivers to visual roadway hazards that warranted an emergency avoidance response. The majority of the studies described consist of surprise, unexpected roadway hazards, meaning that subjects were unaware of the true purpose of the study and were faced with an unexpected object or event that required an immediate response. Each subject in these studies can participate in only one trial in which they were truly surprised. Following the initial surprised trial, some studies had subjects perform subsequent trials where they were now aware of the type of hazard and at least partially aware of where or when the hazard would appear. The results of these subsequent trials are also described for comparison.

An on-road study was conducted by Olson et al. (1984) in order to determine perception-response times for stopping sight distance applications in road design. Subjects drove a winding route for several miles under the impression that they were familiarizing themselves with the test vehicle. The subjects eventually crested a hill in a rural area and were confronted with an object (a piece of yellow foam rubber, 15 cm high and 91 cm long) in the left wheel track. The time-to-collision, which is the time it would take the vehicle to reach the object if it continued at a constant speed, was between about 3 and 4 seconds (Olson & Sivak, 1986). Response times were measured from when the object was first visible to the subject (i.e., the first moment there was a direct line of sight) until the accelerator was released, as well as the time from accelerator release to brake pedal contact. The total perception-response time was the summation of the two measures. Two age groups were tested, including 49 young subjects (aged 18 to 40 years) and 16 older subjects (aged 60 to 84 years). The 50$^{th}$ percentile total perception-response time for the younger subjects was about 1.1 seconds, with a 95$^{th}$ percentile of about 1.6 seconds. The 50$^{th}$ and 95$^{th}$ percentile time to accelerator release was about 0.5 and 1.0 seconds respectively. It was found that the total perception-response time for the younger and older subjects were very similar. After completing the first unexpected trial, subjects were told the true nature of the study and asked to crest the hill an additional five times to collect response time data for what they described as an ‘alerted’ scenario. The position of the obstacle was changed on each of the alerted trials. Total perception-response times for the alerted trials were about 0.4 seconds shorter than the initial surprise trials.

A recent study by Fitch et al. (2010) measured both surprise and alerted response times to a barricade that inflated out of the road. Subjects drove a test vehicle around a close course at 45 mph (72 km/h) for about 25 minutes before they were confronted with the surprise barricade which popped up at a time-to-collision of 2.5 seconds. In order to eliminate the option to swerve, the barricade spanned the entire width of the road. The mean perception time, which was defined as from the launch of the barricade until the foot was lifted off of the accelerator pedal, was 0.73 seconds. The mean movement time from the accelerator to first application of the brake pedal was 0.33 seconds, resulting in an average brake response time of 1.06 seconds. After the surprise trial was completed, subjects encountered the barricade a second time, this time aware that the barricade would launch, but unaware of when it would launch. The mean perception time and movement time for the expected trials were reduced to 0.56 and

0.22 seconds respectively. Therefore, the average expected brake response time (from launch to brake pedal application) was 0.78 seconds, which is about 0.3 seconds less than the unexpected trials.

Fambro et al. (1998) performed three separate studies where driver response times to an unexpected object was measured for younger (less than 25 years) and older (more than 55 years) subjects. The first two studies involved drivers travelling at 90 km/h in a closed course who were confronted with an unexpected barricade that deployed 65 meters ahead of them. The only difference between these two studies was whether the subjects were driving a test vehicle or their own personal vehicle. The third study was conducted on a rural, low-volume, open road, where unsuspecting subjects were confronted with a large barrel that rolled off a truck at the side of the road. The mean perception-brake response time (defined as the time from hazard onset to the driver touching the brake pedal) for the younger subjects in each of these studies was 0.82, 0.93, and 1.14 seconds, respectively.

Barrett et al. (1968) measured driver response times to sudden pedestrian hazards in a driving simulator where subjects were able to drive freely around a terrain model. The study involved 11 male subjects who drove an identical course 10 times while participating in a speed estimation study. On the 11$^{th}$ run when the vehicle was approaching a shed on the right side of the road (which they had passed without incident in 10 previous runs), a pedestrian dummy was released. The mean time between when the dummy was released to the first brake response was 1.14 seconds.

Lerner (1993) conducted a study where subjects drove their own vehicles on actual roadways, under the impression that they were taking part in a road quality assessment study. The subjects were confronted with a large crash barrel that had been released from behind a bush and began rolling towards the roadway. The subjects were about 200 feet away and travelling at 40 mph (64 km/h) at the time that the barrel was released, resulting in a time-to-collision of about 3.4 seconds. Out of 56 subjects who responded by braking, the mean perception-response time (measured from the emergence of the barrel until either the brake lights turned on or when a tape switch attached to the brake pedal was activated) was 1.5 seconds and the 85$^{th}$ percentile response time was 1.9 seconds.

A simulator study conducted by Broen and Chiang (1996) was designed to measure the effect of different pedal configurations (different locations of the accelerator and brake pedals) on driver response time to an unexpected pedestrian stepping into the traffic lane. Based on the available information, it is unclear if the pedestrian in this study was visible to drivers on approach. Brake response time was defined as the sum of reaction time (the time from the pedestrian stepping into the roadway until the driver initiated a foot movement) and movement time (from initiation of foot movement until illumination of the brake pedal event light). Pedal configuration was not found to have a significant effect and the overall mean reaction time, movement time, and brake response times were 1.16, 0.17, and 1.33 seconds respectively. The overall full range of brake response times was between 0.81 and 2.44 seconds.

A more recent study funded by the Insurance Bureau of Canada (Smiley & Caird, 2007) used a high-fidelity driving simulator to analyze the effects of cellphone and CD use on novice and experienced driver performance. One of the hazards encountered in the study was a pedestrian walking into the subject's path from behind a parked car on the right. When the subject's vehicle was 46 meters from the pedestrian, the pedestrian walked into the road, accelerating at a rate of 0.9 $m/s^2$ until it reached 6 km/h. Participants were travelling in a 60 km/h zone, which would correspond to a time-to-collision at hazard onset of about 2.8 seconds. Perception-response time was defined as the time between when the pedestrian became visible until brake application. Six simulated drives were completed by participants, 4 experimental drives, as well as a pre- and post-test drive, with the pedestrian incursion encountered during each drive at different locations. Half of the experimental encounters with the pedestrian occurred while subjects were interacting or conversing on a cell phone, with the other half occurring without a distractor (baseline conditions). The mean perception-response time to the pedestrian hazard in the baseline conditions for experienced and novice drivers were 1.51 seconds and 1.87 seconds, respectively. Note that these values are aggregated from the results of multiple experimental drives, likely with varying levels of expectancy or hazard anticipation.

Several studies have evaluated perception-response times to intersection vehicle path intrusion scenarios. For example, Lechner and Malaterre (1991) used a driving simulator to measure the emergency response behaviour of 49 subjects to an unexpected intersection incursion. Travelling approximately 90 to 100 km/h, subjects approached an intersection where a vehicle on the perpendicular road suddenly accelerated from a stop into their path and subsequently braked to a stop in the middle of the intersection. The incursion vehicle started to accelerate at one of three different times-to-collision (2.0, 2.4, or 2.8 seconds). The mean time from start of acceleration of the incursion vehicle to the driver's first response was 0.8 seconds for those who released the accelerator first and 0.82 seconds for those who steered first. The mean time to first brake response was 1 second, which corresponds to an average movement time from accelerator to brake pedal of 0.2 seconds. The authors also indicated that some subjects approached the intersection with their foot already off the accelerator. This may have resulted in lower brake response times. Time-to-collision was not found to have a significant effect on first response times (such as accelerator release); however there was a significant effect of time-to-collision on time to brake application. Following the initial unexpected trial, all subjects performed two additional trials, this time aware of the emergency they were going to encounter. The mean first response times were about 0.2 seconds lower during the expected trials.

McGehee et al. (1999) conducted a similar study using the Iowa Driving Simulator. Subjects drove a route for a period of time, unaware of the true nature of the study. The subjects approached an intersection with two vehicles stopped on either side of the intersection on the perpendicular road. There was a lead vehicle present about 6 seconds ahead of the subjects in order to encourage them that it was safe to travel through the intersection without slowing or stopping. When the time-to-collision was either 2.5 or 3.0 seconds, the stopped vehicle on the right accelerated into the intersection at 13.8 ft/sec$^2$ (4.2 m/s$^2$) and then decelerated to a stop with its front bumper 6 feet into the subjects' lane. The mean time from start of motion until release of the accelerator pedal was 0.97 seconds and the mean time until brake pedal application was 1.14 seconds. This resulted in a mean transition time from the accelerator to the brake pedal of 0.17 seconds.

In an attempt to validate the results of the simulator study (McGehee et al., 1999), a second study with a very similar surprise intersection incursion scenario was completed on a test track (Mazzae et al., 2003). Subjects completed several laps on the track and passed an intersection where two vehicles were stopped on either side facing the driver's path. Similar to the McGehee (1999) study, a lead vehicle was used to guide the subjects around the test track and to encourage them to travel through the intersection without slowing or stopping. Between the third and fourth laps, the stopped vehicles were replaced with foam replicas. On the subject's fourth lap, the vehicle on the driver's right was towed rapidly into their path. The mean time from the onset of motion of the intruding vehicle until the first application of the brake pedal for subjects on dry pavement was 1.5 seconds (SD = 0.30). The mean time to throttle release was 1.19 seconds (SD = 0.29), with a mean transition time from throttle release to brake input of 0.31 seconds (SD = 0.18).

Although there were differences in the accelerator and brake response times between the simulator and test track studies, a comparison of the two studies (McGehee, Mazzae, &

Baldwin, 2000) showed that there were no significant differences between the total time to maximum brake pedal depression and time to initial steering input. The authors also suggest some reasons for the longer response times from the test track study. The drivers in the test track study passed the incident intersection three times before the incursion; therefore the subjects may have responded later, after having already experienced passing and the vehicle's remaining stationary. The subjects in the test track study were also concurrently monitoring a visual display to maintain a certain headway, which may have resulted in an increase in response time when compared to the simulator study where no secondary task was performed.

A common limitation of perception-response time studies is that a choice needs to be made as to when to start the clock and begin the response time interval. Studies conducted for the purpose of stopping sight distance research for road design (Olson et al., 1984) have understandably chosen when the object first enters a driver's field of view. Other studies have chosen when an object first starts to move towards the drivers path (Lechner & Malaterre, 1991; Mazzae et al., 2003; McGehee et al., 1999) or when a pedestrian first steps onto the roadway (Broen & Chiang, 1996). Although many of these chosen starting points seem logical, an assumption is inherently made as to when an object or event first presents itself as an immediate hazard, or when perception occurs. When applying these research results for accident investigation purposes, this limitation is typically overcome by using an analogous starting point. However, this limitation presents a greater concern in situations where there is no clearly defined entry point of the hazard into the driver's field of view, usually due to visibility restrictions such as night, rain, fog, etc. (Muttart, 2004; Olson & Farber, 2003). There is also concern when trying to apply this research to situations where there is ambiguity in when an event is presented as an obvious hazard, such as a vehicle blowing through a red traffic signal. For a driver on the intersecting roadway, that vehicle would be in their field of view for some time but it would transition from a non-hazard to a hazard at some unknown point.

## 1.4 Vision and Eye Movements

As mentioned previously, driving is a highly visual task and therefore driver eye movements can provide important insight as to where attention is being allocated and which objects are likely to be detected (Olson, Battle, & Aoki, 1989; Shinar, 2007; Victor, Engstrom, & Harbluk, 2008). However, looking at an object does not guarantee that it is being attended to and that it will be detected, a phenomenon known as inattentional blindness (Beanland & Pammer, 2010; Huestegge et al., 2010; Mack, 2003).

Eye movements serve a number of functions, with one of them being to bring new or relevant information to the fovea (Unema, 1995). The fovea is the area of the eye with the highest resolution vision and has a diameter of about 1 to 2 degrees and surrounds the centre of fixation (Cohen, 1978; Green et al., 2008; Yarbus, 1967). The central 30 degree area around the fovea represents focal vision and is used for such things as object recognition, whereas the area in the periphery, outside of focal vision is referred to as ambient vision and is used for spatial orientation, such as lane keeping (Green et al., 2008; Schieber, Schlorholtz, & McCall, 2008).

Due to the limited size of the fovea area, a large amount of information is likely sensed through peripheral vision (Miura, 1990; Mourant & Rockwell, 1970). Eye movements are necessary in order to view larger areas and to project objects that were sensed in the periphery onto the fovea (Hole, 2007; Shinar, 2007). Olson et al. (2003) described typical eye movements as fixations, saccades, transitions, and glances. A fixation was defined as when a gaze is directed at a particular location and remains there for some time. A saccade is an abrupt, rapid eye movement from one location to another within a given region. This is similar to a transition; however transitions move between different regions. A glance was defined as a combination of all consecutive fixations and saccades in a given region, as well as the preceding transition to that region. Saccades are generally very quick, about 10 to 50 ms, whereas fixations typically last about 100 to 500 ms (Shinar, 2007). A phenomenon known as saccadic suppression indicates that little new information is gained during saccades and that in fact this suppression effect actually precedes the saccade (Zuber & Stark, 1966).

Visual search patterns are guided by both bottom-up (endogenous) and top-down (exogenous) factors (Green et al., 2008; Hole, 2007). The bottom-up factors have been described as automatic and involuntary attraction to external stimuli (such as sudden movements or loud noises), whereas top-down factors are described as goal-driven and dependant on the task being performed (Egeth & Yantis, 1997; Green et al., 2008; Shinar, 2007). The notion that scanning patterns are goal-driven was demonstrated by Yarbus (1967). The eye movements of subjects while scanning a stationary picture were recorded and the areas of fixations changed substantially depending on the instructions provided to the subject prior to each trial (such as to determine the ages of the people or to remember the clothes worn). Mourant and Rockwell (1970) demonstrated how visual scanning patterns while driving are also affected by the task being performed. Driver eye movements were recorded during both open road and car-following situations. Three identical routes were completed for each condition where drivers were asked to vary which signage they attended to. In the first trial, they were asked to read all signs on the route; in the second, only signs necessary to successfully complete the route; and lastly, not to read any signs. It was found that the scanning patterns narrowed across successive trials, with less time spent looking at the right side of the road (where traffic signage would be located). Also in the car-following condition, the scanning patterns were narrowed even further, with more time spent fixating on the rear of the lead vehicle (Mourant & Rockwell, 1970).

Many studies have been conducted to examine where drivers look for a variety of driving environments, as well as what factors affect eye movements. For example, on straight road sections drivers tend to scan the road fairly uniformly and spend most time focusing near the centre of the road (Olson et al., 1989), whereas when navigating around curves drivers spend less time looking at the road ahead and the majority of time is spent looking along the tangent of the curve (Kandil, Rotter, & Lappe, 2010; Land & Lee, 1994; Olson et al., 1989). There is a large amount of research with respect to driver eye movements in naturalistic settings and the effect of the task and driver state, such as experience, fatigue, alcohol, etc. (Cohen, 1978; Crundall, Shenton, & Underwood, 2004; Mourant & Rockwell, 1972; Underwood, Chapman, Bowden, & Crundall, 2002).

There is only limited research in terms of driver eye movements specifically related to hazard perception in emergency situations. Measurements of driver eye movements when faced with an emergency situation have the potential to provide valuable insights as to when and how hazards are detected (Dow, Brown, & Marshall, 2008). Velichkovsky et al. (2002) conducted a simulator study where the eye movements of 12 drivers were measured while driving an urban route at about 50 km/h. Subjects were presented with a variety of potential and immediate hazards along the route. A potential hazard was defined as a situation that demanded monitoring of objects that could turn into immediate hazards, such as a green traffic signal or a pedestrian standing facing the roadway. An immediate hazard was one that required immediate action in order to avoid a collision and always evolved from a potential hazard. The fixations surrounding the emergence of the immediate hazards were analyzed and it was found that there was a sudden increase in fixation duration at the presentation of the hazard. However, the authors caution that an increase in fixation duration alone cannot predict how a subject responds to a hazard because a similar fixation trend was found for the presentation of potential hazards that were subsequently dismissed without any evasive action.

A driving simulator study by Garay et al. (2004) evaluated visual scanning patterns of novice and experienced drivers to determine their ability to predict and scan for potential risks under three different non-emergency situations (noticing pedestrians at a crosswalk, advanced warning signs, and conflicting traffic). It was found that foreshadowing, or advance warning cues, such as a pedestrian visible in the crosswalk prior to drivers reaching the crosswalk, increased visual scanning of potential risk locations. However, these effects were more prominent for experienced drivers.

A more recent simulator study made use of eye movement recordings to investigate the effect of driving experience on hazard perception abilities for different types of hazard scenarios (Crundall et al., 2012). Hazards were divided into three main categories: (1) *behavioural prediction hazards*, involving precursors that are the same stimuli as the hazard and allowing for easier projection of future behaviour or anticipation (e.g., a child visible at the side of the road between parked cars, the precursor, which then steps into the road, the hazard), (2) *environmental prediction hazards*, where the precursors are not directly related to the hazard, therefore leading to more 'surprise' type events (e.g., a near side parked ice cream van, the precursor, from which a child steps out from behind into the driver's path, the hazard), and (3) *dividing and focussing attention hazards*, requiring dividing of attention across multiple potential hazards (e.g., a near side parked bus and a pedestrian on a centre median, the precursors, then the pedestrian steps into the driver's path, the hazard). First fixation and dwell times were reported in terms of a percentage of the time available in the precursor and hazard windows. The precursor window started when the precursor was first visible and ended when the hazard was triggered. The hazard window started when the hazard was triggered and ended when the participant either passed the hazard or crashed into it. It was found that learner drivers fixated on fewer critical stimuli and took longer to first fixate on all hazard types than more experienced drivers.

In terms of first fixation to precursors, experience led to shorter times to first fixation only for the behavioural prediction precursors. The longest first fixation times were observed for the environmental prediction precursors, with no significant difference found across experience levels. Overall, there were longer dwell times found for the hazards than the precursor stimuli. It was also found that experienced drivers spent a longer amount of time looking at all stimuli than both learner drivers and instructors. The results of this study show that there are differences in drivers' first fixation and dwell times to different types of hazards and these eye glance measures are also affected by experience level. Although the authors did not measure reaction times in this study, they suggested that the lower reaction times of learner drivers found in previous research for video-based hazard perception tests are likely in large part due to slower hazard fixation times. This study highlights the importance of studying driver eye movements in the context of hazard perception, as it can lead to a further understanding of why reaction times to certain types of hazards or of certain types of drivers are different.

Huestegge et al. (2010) studied eye movements of experienced and inexperienced drivers to the presentation of potentially dangerous static traffic scenes. The objective of this study was to use eye movements to divide overall response time into two sub-categories; time until first fixation on a potentially dangerous object and the subsequent time until final response. The authors discuss how previous research has reported shorter hazard response times of experienced versus inexperienced drivers. However, response times were commonly reported from hazard onset until response, providing little insight into the factors that may contribute to these differences. The study conducted by Huestegge et al. (2010) consisted of presenting sequences of traffic scene pictures at 2 seconds intervals. The images were separated by a black screen for 1 second, followed by a white fixation cross in the upper left corner. A variety of traffic scenes were presented with different potential hazards (pedestrians, brake lights on a lead vehicle, etc.). Subjects were asked to respond as quickly as possible by pressing a button when they would have initiated braking. Consistent with previous research, it was found that the overall response times were shorter for experienced drivers. Upon further examination of the sub-categories, there was no significant difference found based on expertise for the time from hazard onset until first fixation, but there was a significant expertise effect for the subsequent time from first fixation until response. This study showed the potential benefits of using eye movement recording in combination with typical response measures to gain further insight into driver hazard perception and response capabilities.

A similar concept was used by Kledus et al. (2010) where driver eye movements were used to try and determine the moment an object is perceived under nighttime conditions. As mentioned previously, hazard perception under nighttime conditions presents a difficult situation, because there is no clearly defined point when the hazard enters the driver's field of view (Muttart, 2004; Olson & Farber, 2003). Typically nighttime visibility measures are used to determine the point when the hazard would have likely first been visible to a driver (Olson & Farber, 2003). Kledus et al. (2010) conducted an on-road study under nighttime conditions, where the eye movements of 8 drivers to the presence of pedestrians were recorded. The subjects were not told the true purpose of the study prior to participating. In general, the drivers spent the majority of the time watching the road ahead of them. The first moment that the drivers changed their direction of vision towards the pedestrian was identified and any subsequent responses were recorded. The change in gaze direction could often be directly linked to a subsequent avoidance response. This study presents promising results of using a driver's change in gaze direction to obtain a better estimate of when a potential hazard is detected.

The use of eye movement recordings has the potential to provide better estimates as to when a hazard is first detected. It may also allow for the perception-response time stages to be analyzed in greater detail, providing further insight into how information is processed and how certain factors affect each individual stage. However, any such analysis must be done with caution, as a foveal fixation itself does not guarantee that something is being attended to and will be detected (Beanland & Pammer, 2010; Huestegge et al., 2010; Mack, 2003; Olson et al., 1989). Conversely, the lack of a fixation on an object does not guarantee that it was not detected. First fixation also does not necessarily represent when an object is first perceived. Due to the small size of the foveal area, cues and information are typically acquired through peripheral vision, resulting in a shift of direction of vision towards the object, meaning that first perception can occur before first fixation (Crundall, Underwood, & Chapman, 1999; Miura, 1990; Olson et al., 1989).

## 1.5 Effects of Cognitive Distraction on Detection and Response to Hazardous Events

As described earlier, humans have a limited amount of attentional resources for which to distribute among a variety of driving and non-driving related tasks while operating a motor vehicle. De Waard (1996) described a simplistic definition of mental workload as the demands placed upon humans. When these demands exceed the available resources, performance degrades and errors or accidents can occur (Gopher & Donchin, 1986; Hole, 2007; Hurts et al., 2011).

There are many things within the driving environment that compete for attentional resources, including driving and non-driving related tasks. The discussion to follow will be focused on the effects of devoting attentional resources away from the primary driving task by engaging in non-driving related tasks. These non-driving related tasks are usually described as distractions. Lee et al. (2008) has provided a summary of many of the published definitions of distractions and emphasized the need to develop a common, generally accepted definition in order to alleviate confusion when interpreting crash data and when comparing research results. The following definition was proposed "driver distraction is a diversion of attention away from activities critical for safe driving toward a competing activity" (Lee et al., 2008, p.34). Since driving is a multitask activity, this definition allows for the possibility that even some driving related tasks can be considered distractions if at any given moment these tasks are diverting attention away from safety critical driving tasks (Lee et al., 2008). However, this discussion will be limited to those distractions that are not related to driving.

There are a variety of sources of non-driving related distractions. Ranney et al. (2000, p.1) suggests dividing them into four categories, including "visual distraction (e.g., looking away from the roadway), auditory distraction (e.g., responding to a ringing cell phone), biomechanical distraction (e.g., manually adjusting the radio volume), and cognitive distraction (e.g., being lost in thought)." The focus here will be on non-driving related cognitive distractions, or anything that takes the mind off the road. There is discrepancy in how cognitive distraction is defined in the driving literature, leading to differences in which secondary tasks are included (R. Young, 2012). An extensive summary of many of these definitions is provided by Young (2012), with a large discrepancy being whether cell phone conversation is included. For the purpose of this discussion, cognitive distraction will refer to any non-driving related activity that has the potential to compete for cognitive attentional resources and it will include hands-free cell phone conversations.

There is a large body of research on the topic of distraction and how it affects driving performance, especially with respect to use of hand-held and hands-free cell phones. Although the act of actually dialing the phone or sending a text message represents a visual and/or biomechanical distraction, a conversation on a hands-free cell phone is a form of cognitive distraction. Other common forms of cognitive distraction investigated in the literature include passenger conversations (Consiglio, Driscoll, Witte, & Berg, 2003; Laberge, Scialfa, White, & Caird, 2004), and the execution of secondary tasks designed to induce cognitive load, such as mental arithmetic (Harbluk, Noy, Trbovich, & Eizenman, 2007), spatial-imagery tasks (Hammel, Fisher, & Pradhan, 2002; Recarte & Nunes, 2000), and memory tasks (Victor, 2005).

Many different measures have been used to assess the effects of distraction on driving performance, including longitudinal control (speed and headway), lateral control (lane keeping and steering wheel metrics), event detection, reaction time, gap acceptance, and subjective measures (K. Young, Regan, & Lee, 2008). When considering how distraction affects a driver's ability to detect and respond to hazardous events, the metrics of most importance are visual scanning patterns and reaction time.

### 1.5.1 Effects on Visual Behaviour

Mackworth (1965) has demonstrated that when presented with an increasing amount of visual information, humans respond by contracting their useful field of view in order to prevent being over-loaded, which he refers to as tunnel vision. A number of driving-related studies investigating cognitive distraction have reported results that support the notion of tunnel vision for increasing cognitive demands.

An on-road study conducted by Recarte and Nunes (2000) measured driver eye movements while performing a variety of secondary cognitive tasks, which included verbal tasks (such as reciting words starting with a certain letter) and spatial-imagery tasks (such as indicating whether a letter was open, closed, or if it would change when rotated). When subjects were engaged in a secondary task there was a noticeable reduction in their visual inspection window in both the horizontal and vertical directions, with a more pronounced reduction for the spatial-imagery tasks. There was also an increase in mean fixation durations when performing the spatial-imagery tasks, which the authors refer to as “eye freezing” and suggest will result in impairments of perception.

The Recarte and Nunes (2000) study was replicated in a simulator environment with very similar results (Hammel et al., 2002). There was a reduction in the variability of horizontal and vertical fixations away from the central forward view, as well as an increase in mean fixation durations for the spatial-imagery tasks.

The effects of cognitive distraction on driver visual behaviour was investigated by Harbluck et al. (2007) during an on-road study where subjects performed both simple, single-digit arithmetic tasks and difficult, double-digit arithmetic tasks. Visual behaviour during the arithmetic tasks was compared with the control (no secondary task) condition and it was found that with increasing task difficulty subjects tended to have fewer saccades, and they spent more time looking centrally, less time at the periphery, and less time looking at the instruments and mirrors.

A number of experiments conducted to examine the effects of a variety of secondary tasks on driver eye movements have been summarized by Victor (2005). Of the secondary tasks investigated, the following can be considered examples of cognitive distractions: listening to email over car speakers, answering questions from a passenger or a hands-free phone, counting backwards by 7 from 568, and an auditory working memory task in which subjects were required to remember a varying number of target sounds and determine how many times these sounds appeared in a playback series. While performing all of the above mentioned tasks, there was an increase in the amount of time spent looking at the road centre, as well as a reduction in gaze variability.

Very similar findings were reported in an on-road study measuring driver eye movements while performing increasingly complex auditory cognitive tasks (Reimer, 2009). There was a significant reduction in gaze variability between the easiest and most difficult task level.

Based on this research, an increase in driver mental workload from non-driving related cognitive distractions leads to a narrowing of a driver's field of view with larger amounts of time spent looking at the central forward roadway. This narrowing has the potential to result in degraded peripheral vision and detection of hazardous events that emerge outside of the forward field of view.

### 1.5.2 Effects on Reaction Time

There is a large, growing body of research on the topic of the effect of cell phone use on driving performance. Two meta-analyses of such studies have been conducted (Caird, Willness, Steel, & Scialfa, 2008; Horrey & Wickens, 2006). One of the main findings of both studies is that the largest effect on driving performance due to cell phone use is the increase in reaction time to stimuli and road hazards. Although the focus of the meta-analysis by Caird et al. (2008) was on the effects of cell phone use, many of the studies in this area have also investigated other types of secondary tasks, such as passenger conversation, cognitive tasks to approximate a cell phone conversation, and listening to the radio. These variables were also included in the reaction time analysis by Caird et al. (2008) and it was found that when averaged across all tasks and conditions, the overall mean increase in reaction time when performing a secondary distracting activity was 0.25 seconds. The different types of distracting tasks and the different stimuli being responded to were also evaluated individually. Table 1 is a subset of the reaction time results reported by Caird et al. (2008, p.1287).

**Table 1**: Mean reaction time increases (i.e., drive with distraction - baseline drive), standard deviation of difference means, number of studies, and number of participants

| Condition | Mean increase in reaction time (s) | Standard deviation | Number of studies | Number of participants |
|---|---|---|---|---|
| All distracting tasks | 0.25 | 0.28 | 26 | 1170 |
| Hands-free phone | 0.18 | 0.29 | 16 | 518 |
| Cognitive task | 0.33 | 0.39 | 10 | 292 |
| Converse with passenger | 0.20 | 0.13 | 3 | 84 |
| BRT, lead vehicle brakes | 0.36 | 0.42 | 7 | 630 |
| BRT, light change at intersection | 0.18 | 0.19 | 5 | 504 |
| BRT, pedestrian | 0.19 | 0.09 | 3 | 472 |
| RT, peripheral detection | 0.20 | 0.15 | 3 | 124 |

**Subset of data adapted from Caird et al. (2008, p.1287).*

These results show that cognitive distraction while driving leads to a delay in responding to a variety of events and stimuli. However, what is not clear from these results is the cause of these delayed responses. Since the majority of these studies measured reaction times from the onset of the event or stimuli until some measurable motor response was executed, it is unknown at which stage (or stages) of the information processing model the delay occurred. Attentional resources are required to successfully complete each stage of the process. Therefore, it is possible that the detection, decision making, and response execution phases are all affected by cognitive distraction. It is also possible that certain stages experience greater effects than others.

A study by Bellinger et al. (2009) looked at the effect of cell-phone use and listening to music on brake response time and two individual sub-components of reaction and movement time. The study was performed in a laboratory setting using a station consisting of a seat, steering wheel, accelerator pedal, and brake pedal. Participants were instructed to release the accelerator and apply the brakes as quickly as possible following the activation of a simulated brake lamp. Reaction time was defined as the time from brake light activation to the initial movement of the foot from the accelerator. Movement time was the time between initial movement of the foot from the accelerator up to initial brake pedal application. It was found that cell phone use resulted in significantly longer brake response times (mean increase of 42 ms). When the sub-components were analyzed separately there was a significant increase in reaction time due to cell-phone use (mean increase of 60 ms), but a significant decrease in movement time (mean decrease of 18 ms). This study demonstrates the value of considering the sub-components of perception-response time when assessing the effects of distraction.

Recarte and Nunes (2003) made use of eye movements to further sub-divide perception-response time. An on-road study was conducted where subjects were required to divide their attention between the naturalistic driving task, performing mental tasks, and visual target discrimination. The mental arithmetic task included mentally converting various amounts of euros to pesetas and vice versa. Subjects completed this task either through communication over a hands-free device or with an in-car experimenter. Two-minute intervals of mental tasks were alternated with two-minute control intervals without any mental tasks. A visual-detection and discrimination test was also being simultaneously performed which involved manual responses. Ten different light stimulus targets were used whose locations ranged in eccentricity from 8 to 35.4 degrees. Eye movement recordings were combined with motor response measurements in order to divide the total reaction time into three stages: (a) Perception time – the time from stimulus target activation until the beginning of a saccade towards the target, (b) Inspection time – the total time that the target was being looked at, and (c) Decision time – the time between when the eye leaves the target until the manual response is executed. Overall, there was no significant difference between total reaction time with or without the secondary mental task. However once the individual stages were analyzed, it was found that while performing the mental tasks, there was an increase in perception time, a decrease in inspection time, and virtually no change in the decision time. Therefore, the null effects were due to the mental tasks having opposite effects on the perception and inspection stages.

Similar to the hazard perception eye movement studies described previously (Crundall et al., 2012; Huestegge et al., 2010; Kledus et al., 2010; Velichkovsky et al., 2002), the study conducted by Recarte and Nunes (2003) has demonstrated the potential benefits of using eye movements and response measures to gain insight into how information is processed and how each individual stage is affected by different factors.

## 1.6 Summary and Research Gaps

Based on the literature review conducted, one of the major limitations identified in the available driver perception response time research is that, although theoretically driver response time is described to occur in a number of stages very closely relating to the stages of human information processing, other than the research by Recarte and Nunes (2003), currently in practice it is typically measured in at most two stages, perception and movement time.

Based on some of the more recent uses of eye movement recordings in the driving environment and in the context of hazard perception, it has been shown that eye movements can allow for response times to be further sub-divided. However, the literature review did not reveal any research using eye movement recordings that specifically focused on analyzing individual driver response time stages to emergency roadway hazards.

Another major limitation of driver perception response time studies is that a choice needs to be made as to when to start measuring the response time. In some scenarios there is a logical starting point, such as when an object first becomes visible or first starts to move. These starting points are valid and can be applied in the field or compared across studies if analogous starting points are also chosen. However, they do not provide any information as to when a hazard is actually detected by a driver. Research on hazard perception has revealed that the use of eye movements has the potential to provide an approximation as to when a hazard is first detected, or at the very least when it is first looked at, cautioning that looking or not looking at something does not necessarily mean it was or was not detected.

There is a large body of research investigating the effects of cognitive distraction on driver behaviour, with one of the major findings being a delay in driver response times while distracted. The majority of these studies examined effects on overall response times, from the onset of the event or stimuli until some measurable motor response was executed; therefore, it is unknown at which stage (or stages) of the information processing model the delay occurred. The study conducted by Recarte and Nunes (2003) has demonstrated the potential benefits of using eye movements and motor response measures to gain insight into how individual response time stages are affected by cognitive distraction. However, subjects in this study were responding to light stimuli and not realistic emergency roadway hazards. The literature review did not reveal any research using eye movements and motor responses to investigate the effects of cognitive distraction on individual stages of driver response times to emergency roadway hazards.

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# CHAPTER 2

## 2.0 RESEARCH OBJECTIVES AND SIMULATOR EXPERIMENT METHODOLOGY

Based on the limitations and research gaps identified through the literature review, one of the objectives of this research was to further investigate the use of eye movement recordings in the driving environment, specifically relating to driver response times to emergency roadway hazards. Eye movement recordings were used to further sub-divide driver perception-response time into three stages (perception, inspection, and movement time) for responses to three distinct emergency roadway hazards (a left-turning vehicle, a pedestrian, and a right incursion vehicle).

The second objective was to investigate the effects of cognitive distraction and repeated scenario exposure on each response time stage. In order to achieve this, the experiment was divided into two main stages with two simulated drives. The first stage analyzed only the data collected from the first simulated drive to investigate the effect of cognitive distraction on driver perception-response times to surprised, unexpected roadway hazards. The second stage compared data collected from the first drive to the second drive, to investigate the effect of repeated scenario exposure on response time stages with and without cognitive distraction.

An additional objective of the study was to investigate any relationships between self-reported susceptibility to distraction and engagement in other unsafe driving behaviours to performance on the cognitive distraction task and a variety of response time measures. Information about participants' susceptibility to distraction and engagement in other unsafe driving behaviours was gathered through a post-experiment questionnaire

The experiment was conducted in a driving simulator at the Human Factors and Applied Statistics (HFASt) Laboratory at the University of Toronto. This experiment was approved by the University of Toronto Research Ethics Board.

### 2.1 Participants

Twenty-four participants (11 male and 13 female) aged 25 to 40 years old (M = 31, SD = 5) participated in the experiment. No significant age differences were found between male and female participants ($F(2,10)=1.42$, $p=.58$). Participants were recruited through the University of Toronto and online advertising. A screening questionnaire was completed (attached as

Appendix A), in order to assess eligibility in terms of driving experience and to ensure that participants were not prone to simulator sickness. All participants possessed a valid driver's license, had at least 2 years of driving experience (range 2-20 years, M = 12, SD = 5.5), drove at least one day per week (range 1-7 days/week, M = 5.3, SD = 2.0), and had normal or corrected-to-normal vision. Participants were compensated for their participation in the experiment at a rate of $15/hour.

## 2.2 Apparatus

This research was conducted using a PC-based, quarter-cab MiniSim™ driving simulator developed by the University of Iowa's National Advanced Driving Simulator (NADS). The simulator uses three 42-inch 1024x768 plasma widescreen displays to create one display spanning a 130 degree horizontal and 24 degree vertical field of view at a 48-inch viewing distance. An additional 19-inch screen is integrated into the dash and acts as a virtual instrument cluster. The simulator uses an authentic steering wheel, column gear selector, pedals and driver seat. Stereo sound of the vehicle and its surroundings are portrayed through two speakers in the front. Roadway vibrations are simulated through a third speaker mounted below the driver seat. The simulator collects a large number of driver input measures, as well as measures of the dynamic objects (other traffic) around the driver for analysis. The data acquisition system logs all variables at 60 Hz. The simulator is equipped with a four-channel analog video capture system.

A faceLAB™ 5 eye-tracking system, developed by Seeing Machines, was integrated into the simulator. The faceLAB™ 5 eye-tracking system uses a pair of cameras mounted on the dash of the simulator as a passive measuring device. Images from the cameras are analyzed to generate data on eye movements, head position and orientation, eyelid aperture, pupil size, etc. Images are processed by faceLAB at 60 Hz. The gaze tracking has a range of ±45° around the y-axis (horizontal range) and ±22° around the x-axis (vertical range). The typical static accuracy of gaze direction measurements is 0.5° to 1°. EyeWorks software, developed by EyeTracking Inc., was incorporated into the faceLAB system, which synchronizes the gaze data with the simulator centre screen video display and provides a video output with the participant's gaze location overlaid on the centre simulator display at 30 Hz. Figure 2 is a photograph of the simulator set-up used for the experiment.

**Figure 2**: Photograph of the NADS MiniSim simulator used in the experiment. The faceLAB cameras are mounted on the dashboard on either side of the instrument panel.

## 2.3 Experimental Design

Each participant completed two drives (Drive A and Drive B). In each of these drives, participants experienced three distinct emergency events (left-turn, pedestrian, and right incursion). In one of these drives, participants experienced these emergency events while performing a cognitive secondary task. The assignment of task condition (i.e., baseline or distraction) to drive (A or B) was counterbalanced. That is, half of the participants had the baseline condition in Drive A and the other half had it in Drive B. This design enabled the following analyses to be conducted to address the research objectives.

The analyses were conducted in two stages. The first stage aimed to investigate the effect of cognitive distraction on driver response times to unexpected roadway hazards. Only one set of surprised, unexpected responses could be collected for each participant. Therefore, this stage was restricted to the data collected from each participant for the first experimental drive (Drive A). This was a 2 x 3 repeated measures design with task (two levels; baseline and distraction) as a between-subjects factor and event type (three levels; left-turn, pedestrian, right incursion) as a within-subjects factor with repeated measures.

The second stage aimed to investigate the effect of repeated hazard exposure (i.e., differences between Drive A and Drive B, once the subjects were primed to the types of hazards they may encounter) on driver perception-response for both task conditions. The data collected from Drive A and Drive B were used in this analysis. The data were first split into two subsets by task condition (baseline and distraction) and separate analyses were conducted on these subsets. Each data subset was a 2 x 3 repeated measures design with drive (two levels; Drive A and Drive B) as a between-subject factor and event type (three levels; left-turn, pedestrian, right incursion) as a within-subjects factor with repeated measures.

## 2.4 Cognitive Distraction Task

The secondary cognitive distraction task used was a delayed digit recall (n-back) task. Participants were required to listen to several pre-recorded series of single-digit numbers and respond verbally with the digit that was presented one position previously or one back from the current number. For example, if the first number in the series was 2, the participant would not say anything, and then if the next number was 5, the participant would say 2, and so on. Each series consisted of 10 different numbers, between 0 and 9, presented in random order with a spacing of 2.25 seconds. There was a brief pause between each series of numbers. The n-back task procedure followed was based on the research and protocol developed by MIT AgeLab (Mehler, Reimer, Coughlin, & Dusek, 2009; Reimer, 2009). Performance on the secondary distraction task was recorded. An n = 1 was chosen as it was believed that this would place sufficient demands on the subjects' attention and working memory, while ensuring that the task was not overly difficult for any one subject to complete. The 1-back task has also been shown to have significant effects on driver visual attention and a variety of driving performance measures (Reimer, Mehler, Wang, & Coughlin, 2012).

## 2.5 Procedure

Upon arrival, participants were first required to review and sign an approved informed consent (Appendix B). A brief overview of the experiment and equipment was given. Participants were asked to sit in the driver seat of the simulator and adjust the seat and steering wheel to a comfortable position. Next, the standard procedure for calibrating and setting up the eye-tracking system was followed. Each participant was then provided with instructions on the 1-back task (Appendix C) and was given time to practice.

Participants completed a total of three simulated drives. The roadway environment for all drives was an urban route with several parked vehicles and buildings lining the streets. The first drive was a practice drive, where participants were able to familiarize themselves with the operation of the simulator in the absence of any surrounding traffic. The practice drive lasted a minimum of 5 minutes, but participants were free to continue driving until they felt comfortable. Partway through the practice drive, participants also practiced performing the secondary cognitive distraction task while driving. The instruction script read to each participant prior to the practice drive is attached in Appendix D.

Following the practice drive, participants were given a short break during which they were monitored for any signs of simulator sickness. Participants then completed two experimental drives (Drive A and Drive B), each of approximately 15 minute duration, separated by a short break. The scripts read to participants prior to each experimental drive are attached in Appendix D. During each drive participants were instructed to drive as close as possible to the posted speed limit of 70 km/h, remain in the left lane (the lane closest to the centerline), and avoid turning at any intersection. Prior to the first drive, participants were told that their driving behaviour and eye movements would be continuously recorded, as well as their responses to typical roadway events, such as traffic lights changing states. In an attempt to obtain as close as possible to true surprise, unexpected responses participants were not told that the true intention of this first experimental drive was to measure their response times to emergency roadway hazards.

During the first experimental drive, Drive A, participants were presented with three unexpected roadway hazards that warranted an emergency avoidance response in the following order: (1) Left-turning vehicle cut-off at intersection, (2) Pedestrian stepping onto the roadway mid-block from in front of a parked vehicle on the right, (3), Vehicle accelerating into the driver's path from the right at an intersection. For the purpose of this research, the response time data collected for each emergency hazard in Drive A will be referred to as the unexpected response times. However, it is important to note that after the presentation of the first emergency hazard in Drive A, participants' expectations of any subsequent hazards may have been increased. Although unaware of where, when, or what type of hazard may appear next, they were at least aware of the possibility of another emergency hazard.

During the second experimental drive, Drive B, participants were presented with nearly identical hazards in a different order and slightly different surrounding traffic. The pedestrian hazard was presented at a different location along the route in Drive B than Drive A. The left-turning vehicle and right incursion vehicle hazards occurred at identical intersections in both drives, with varying vehicle colours and surrounding traffic. The starting location within the urban route was different for each drive, resulting in a different order of hazard presentation. Table 2 lists the order of hazard presentation in each experimental drive. Further details about each of these hazards are described later.

**Table 2**: Order of Hazard Presentation in each Experimental Drive.

| Drive A | Drive B |
|---|---|
| Left-Turning Vehicle | Right-Incursion Vehicle |
| Pedestrian | Pedestrian |
| Right-Incursion Vehicle | Left-Turning Vehicle |

Participants were also presented with a variety of other familiar roadway events throughout each drive, such as lead vehicle braking events and vehicles changing lanes ahead of the subject's vehicle.

Each participant completed a baseline drive with no distraction task and a drive while performing the cognitive distraction task. Half of the participants performed the 1-back cognitive distraction task continuously during Drive A, while the other half performed the task during Drive B. Restricted randomization, blocked based on gender, was employed to assign participants to each order group.

After completing both experimental drives, each subject filled out a post-experiment questionnaire, consisting of some general questions about memory and driving record, as well as questions from two pre-established questionnaires. The Susceptibility to Driver Distraction Questionnaire (SDDQ) was used, which consists of 39 items rated on a 5-point Likert scale divided into three subsections, including engagement in distraction while driving, potential causes of voluntary distraction, and susceptibility to involuntary distraction (Feng, Marulanda, & Donmez, 2014). A subset of questions from the Manchester Driver Behaviour Questionnaire (DBQ) (Reason, Manstead, Stradling, Baxter, & Campbell, 1990) was also used to assess other unsafe driving behaviours apart from distraction. The DBQ consists of 50 items (24 of which were used) rated on a 6-point Likert scale and divided into four categories, including aggressive violations, ordinary violations, errors, and lapses as suggested by Roca et al. (2013) and Lajuen et al. (2004). Appendix E contains a copy of the post-experiment questionnaire administered.

## 2.6 Description of Roadway Hazards

### 2.6.1 Left-Turn Vehicle Hazard

The left-turning vehicle hazard occurred at a traffic-signal controlled intersection with two through lanes in either direction on the road travelled by the subject's vehicle, as well as a dedicated left-turn lane in either direction. On approach to the intersection, participants were following a vehicle that was programmed to maintain a time gap of 3.5 seconds in front of the subject's vehicle. The oncoming left-turning vehicle was stopped within the intersection, past the white stop line, with its left-turn signal activated. The traffic signal facing the participant was green the entire time. At a time-to-arrival (TTA) of 3.5 seconds, the left-turn vehicle started to accelerate from a stop at a constant rate of 2.0 $m/s^2$, which is within the range of left-turn acceleration rates found by Happer et al. (2009), and execute a left-turn across the path of the subject's vehicle. The TTA was calculated based on the time it would take the front of the subject's vehicle to reach the projected collision point (where its path and the left-turning vehicle's path would intersect) if it continued at a constant speed. The intersection, relative vehicle locations, and vehicle dynamics described above were identical for the left-turning vehicle hazard in Drive A and Drive B. The only differences were the colour of the hazard vehicle and surrounding vehicle traffic. Figure 3 and Figure 4 are example screenshots of the centre screen display of the simulator for one participant on approach to the intersection with the left-turn vehicle hazard in Drive A and Drive B, respectively. Note that the green dot is an overlay of the participant's gaze location, with the green line representing a 500 ms gaze trail leading up to the gaze location.


**Figure 3**: Centre screen simulator display on approach to the intersection with the left-turn vehicle hazard in Drive A for one participant. The green dot and green line represent the participant's gaze location and gaze trail, respectively.


**Figure 4**: Centre screen simulator display on approach to the intersection with the left-turn vehicle hazard in Drive B for one participant. The green dot and green line represent the participant's gaze location and gaze trail, respectively.

### 2.6.2 Pedestrian Hazard

The presentation of the pedestrian hazard occurred at a mid-block location, and was not at a location of a marked pedestrian crosswalk. The roadway consisted of two lanes in either direction with the outer lanes partially filled with parked vehicles. Leading up to the area of the pedestrian hazard, the subject's vehicle was following a vehicle that was programmed to maintain a time gap of 3.5 seconds. At a time-to-arrival (TTA) of 2.5 seconds, a pedestrian stepped out from in front of a large parked vehicle into the subject vehicle's path. The TTA was calculated based on the time it would take the front of the subject's vehicle to reach the location of the pedestrian, if it continued at a constant speed. The pedestrian was initially concealed by the parked vehicle and was not visible until the moment it stepped out. The pedestrian walked across the subject vehicle's path at a constant speed of 1.6 m/s, which was found to be the average walking speed for adults (those who appeared to be within 20 and 64 years of age) when crossing the street (Montufar, Arango, Porter, & Nakagawa, 2007). At an approach speed of 70 km/h, the angle between the forward line of sight and the pedestrian when it first became visible (eccentricity angle) was about 4 degrees. The pedestrian hazard was presented at a different location along the route in Drive A than Drive B; however the details described above remained constant. Figure 5 and Figure 6 show the simulator centre screen display for one participant shortly after the presentation of the pedestrian hazard in Drive A and Drive B respectively.


**Figure 5**: Simulator centre screen display shortly after the presentation of the pedestrian hazard in Drive A for one participant. The green dot and green line represent the participant's gaze location and gaze trail, respectively.


**Figure 6**: Simulator centre screen display shortly after the presentation of the pedestrian hazard in Drive B for one participant. The green dot and green line represent the participant's gaze location and gaze trail, respectively.

### 2.6.3 Right Incursion Vehicle Hazard

The right incursion vehicle hazard occurred at a traffic-signal controlled intersection. Both intersecting roads consisted of two through lanes in all directions, as well as dedicated left turn lanes. The traffic signal facing the subject was green and remained green the entire time. There was an intermittent stream of oncoming vehicles. The right incursion vehicle was stopped for the red traffic signal on the intersecting road to the subject's right. When the TTA was 3.5 seconds, the right-incursion vehicle violated its traffic signal and started to accelerate perpendicular across the path of the subject's vehicle at a constant rate of 1.5 m/s$^2$, which is within the range of straight acceleration rates reported by Wang et al. (2004). The TTA was calculated based on the time it would take the front of the subject's vehicle to reach the projected collision point (intersection of the two vehicle's paths), if it continued at a constant speed. At an approach speed of 70 km/h, the eccentricity angle to the right-incursion vehicle when it started to accelerate was about 6.5 degrees. The intersection and vehicle dynamics described above were identical for the right incursion vehicle hazard in Drive A and Drive B, with very similar surrounding traffic. Figure 7 and Figure 8 are screen captures of the center display of the simulator for one participant on approach to the right incursion hazard in Drive A and Drive B, respectively.


**Figure 7**: Screen capture of the centre display of the simulator on approach to the right incursion hazard in Drive A for one participant. The green dot and green line represent the participant's gaze location and gaze trail, respectively.


**Figure 8**: Screen capture of the centre display of the simulator on approach to the right incursion hazard in Drive B for one participant. The green dot and green line represent the participant's gaze location and gaze trail, respectively.

## 2.7 Outcome Variables

Several dependent variables were measured during the experiment. The majority of the outcome variables were directly related to driver perception-response time and its sub-components, as illustrated in Figure 9 . These variables included the Perception Time (PT), Inspection Time (IT), Accelerator Release Time (ART), Movement Time (MT), Brake Reaction Time (BRT), and Initial Steer Reaction Time (SRT). Note that SRT is not illustrated on the time scale in Figure 9, as it is not dependent on foot movement and can occur anywhere along the time-scale. Initial steer direction was also measured.

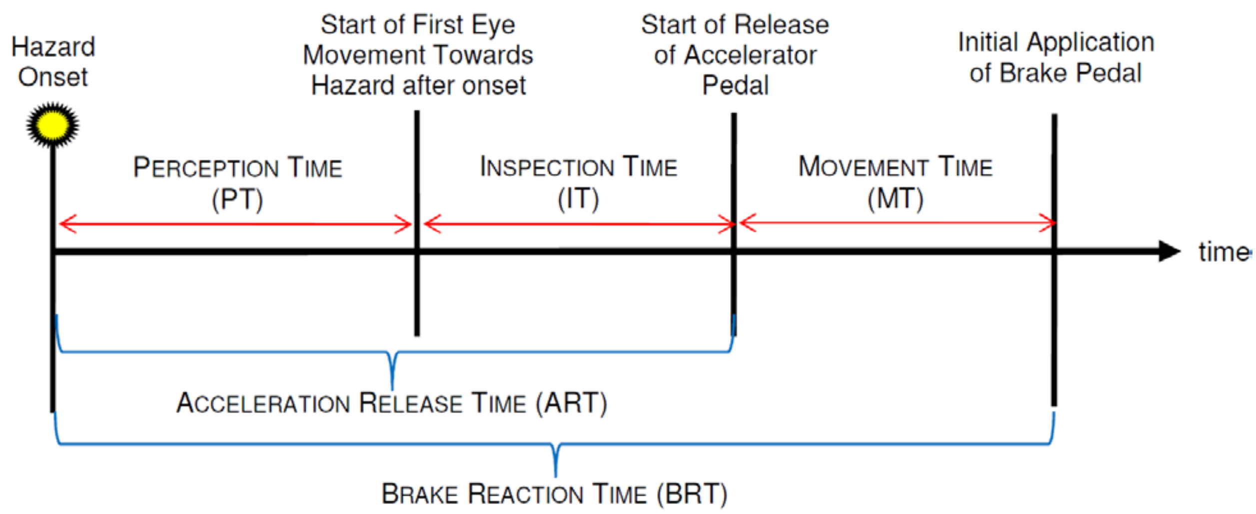


**Figure 9**: Outcome Variables: Subcomponents of Driver Perception-Response Time.

Hazard onset was defined as the start of motion of each of the hazards. Perception time (PT) was defined as the time between hazard onset and the start of the first continuous eye movement towards the hazard after onset, which is also analogous to the end of the previous fixation. A continuous movement was one where movement of the driver's overlaid gaze was observed in every successive frame of the frame-by-frame eye-tracking video analysis. An exception was made in order to account for the possibility of a blink during this continuous movement. If an eye movement towards the hazard was started, but was interrupted with a blink, as long as the eye movement continued towards the hazard following the blink, it was included in the continuous movement. The start time of the continuous eye movement determined from the frame-by-frame video analysis (recorded at 30 Hz) was then compared with raw eye tracking coordinate data (recorded at 60 Hz). Due to the higher sampling frequency, the start of the first continuous eye movement used for analysis was determined from the raw coordinate data. Eye movement recordings were analyzed surrounding the presentation of each hazard. If the first eye movement towards the hazard could not be reliably determined due to poor gaze quality, no perception time was calculated. These instances were entered as missing values for the analysis. If a participant was already looking at the hazard at the onset point, the perception time was set to zero.

Inspection time (IT) was defined as the time between the start of the first continuous eye movement towards the hazard and when the driver first started to release the accelerator pedal. This was determined by an abrupt continuous drop in the accelerator pedal position signal. In some instances, participants reapplied the accelerator pedal for a short period after initial release before braking. In these cases, the start of the second release of the accelerator pedal was used, with the time in between considered as part of the inspection time interval. This occurred only in response to the left-turning vehicle hazard while performing the distraction task (one participant in Drive A and five participants in Drive B).

Accelerator release time (ART) was calculated as the time between hazard onset and when the driver first started to release the accelerator pedal. ART is essentially the addition of the perception time and inspection time; however it was calculated independently from hazard onset to ensure that any missing data from the perception times did not incorrectly result in missing data for ART. If a participant had already released the throttle before hazard onset, both inspection time and accelerator release time were entered as missing values.

Movement time (MT) was defined as the difference in time between when the driver first started to release the accelerator pedal and the first moment contact was made with the brake pedal.

Brake reaction time (BRT) was calculated as the time between hazard onset and the first moment contact was made with the brake pedal. BRT is the addition of perception time, inspection time and movement time; however, similarly to ART, it was calculated independently to ensure that any missing data in either of the segments did not result in missing data in BRT. In some instances, participants did not have their foot on the accelerator pedal at hazard onset, which may have artificially shortened the brake reaction time. Therefore, the brake reaction time (BRT) used for analyses included only data from participants who had their foot on the accelerator pedal at hazard onset.

The initial steer reaction time (SRT) was defined as the time between hazard onset and an abrupt continuous shift in the steering wheel angle following hazard onset, with a minimum steering rate of 15 degrees/second and resulting in an overall change in steering wheel angle of greater than 10 degrees.

# CHAPTER 3

# 3.0 DATA ANALYSIS AND RESULTS

The analysis and results of this study are divided into three main sections. First, the effect of cognitive distraction and hazard type on driver response times to unexpected emergency roadway hazards was analyzed. Next, the effects of repeated hazard exposure on different stages of driver response times were analyzed for both the baseline and the distraction conditions. Finally, the post-experiment questionnaire responses were evaluated to investigate any relationships amongst different sections of the questionnaire, as well as any relationships to performance on the distraction task and a variety of driver response time measures.

## 3.1 Drive A: Unexpected Response Analysis and Results

### 3.1.1 Statistical Model

A 2 x 3 repeated measures design with task (two levels; baseline and distraction) as a between-subjects factor and event type (three levels; left-turn, pedestrian, right incursion) as a within-subjects factor was utilized. Mixed linear models were created for several outcome variables using *PROC MIXED* statements in SAS 9.3, which can facilitate both fixed and random effects. A compound symmetry variance-covariance structure was used for repeated measures. Despite being instructed to drive at 70 km/h, there were variations in participant travel speeds. The time-to-arrival at hazard onset was held constant for the same hazard across participants; however, variations in travel speeds could have resulted in variable distances between the subject’s vehicle and the hazard at onset. Therefore the speed of the subject’s vehicle at hazard onset was included as a covariate in the models. *F*-tests were performed on main and interaction effects. Planned contrasts were then performed using *ESTMATE* statements to compare specific differences between event types, as well as the effect of distraction on the individual hazard types for each outcome variable. Normality and homoscedasticity assumption checks were conducted on the residuals.

### 3.1.2 Descriptive Statistics

Descriptive statistics for each of the three event types, separated by task condition are presented in Table 3. Note that initial steer response times (SRT) are presented only for the left-turning vehicle hazard, as the number of participants who chose to steer in response to the other two hazards was very low. As described earlier, the brake reaction times (BRT) presented are only for subjects who had their foot on the accelerator pedal at hazard onset.

**Table 3**: Descriptive statistics for each of the three event types, separated by task condition in the unexpected response condition (Drive A).

| Event Type | Task Condition | Baseline | | | | | | Distraction | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Outcome Variables | PT | IT | MT | ART | BRT | SRT | PT | IT | MT | ART | BRT | SRT |
| Left-Turning Vehicle Hazard | N | 11 | 10 | 10 | 11 | 10 | 8 | 10 | 10 | 11 | 11 | 11 | 8 |
| | Mean | 0.87 | 0.61 | 0.58 | 1.50 | 2.02 | 1.77 | 0.97 | 0.92 | 0.38 | 1.88 | 2.26 | 1.87 |
| | Median | 0.83 | 0.55 | 0.37 | 1.65 | 2.02 | 1.87 | 0.94 | 0.85 | 0.35 | 1.73 | 2.13 | 1.88 |
| | Min | 0.28 | 0.08 | 0.23 | 0.72 | 1.48 | 1.05 | 0.13 | 0.27 | 0.23 | 1.57 | 1.92 | 1.50 |
| | Max | 1.50 | 1.30 | 1.35 | 2.17 | 2.43 | 2.35 | 1.65 | 1.60 | 0.60 | 3.23 | 3.62 | 2.37 |
| | Std Dev | 0.36 | 0.41 | 0.42 | 0.46 | 0.24 | 0.42 | 0.52 | 0.46 | 0.12 | 0.46 | 0.49 | 0.29 |
| Pedestrian Hazard | N | 11 | 11 | 12 | 12 | 12 | -- | 11 | 9 | 9 | 9 | 9 | -- |
| | Mean | 0.34 | 0.19 | 0.31 | 0.58 | 1.03 | | 0.58 | 0.20 | 0.32 | 0.73 | 1.04 | |
| | Median | 0.37 | 0.13 | 0.27 | 0.55 | 0.88 | | 0.50 | 0.15 | 0.33 | 0.73 | 1.07 | |
| | Min | 0.00 | 0.02 | 0.20 | 0.32 | 0.60 | | 0.13 | 0.00 | 0.22 | 0.53 | 0.80 | |
| | Max | 0.58 | 0.53 | 0.55 | 1.10 | 1.77 | | 1.45 | 0.43 | 0.38 | 0.93 | 1.22 | |
| | Std Dev | 0.17 | 0.15 | 0.12 | 0.22 | 0.54 | | 0.34 | 0.15 | 0.06 | 0.13 | 0.14 | |
| Right Incursion Vehicle Hazard | N | 10 | 8 | 7 | 8 | 7 | -- | 10 | 8 | 8 | 8 | 8 | -- |
| | Mean | 0.74 | 0.26 | 0.28 | 0.99 | 1.32 | | 1.00 | 0.33 | 0.38 | 1.32 | 1.69 | |
| | Median | 0.71 | 0.28 | 0.25 | 0.96 | 1.40 | | 1.04 | 0.31 | 0.30 | 1.24 | 1.62 | |
| | Min | 0.15 | -0.03 | 0.20 | 0.63 | 0.88 | | 0.50 | 0.10 | 0.23 | 0.88 | 1.12 | |
| | Max | 1.35 | 0.52 | 0.47 | 1.48 | 1.82 | | 1.30 | 0.78 | 1.08 | 1.92 | 2.22 | |
| | Std Dev | 0.37 | 0.18 | 0.09 | 0.30 | 0.33 | | 0.23 | 0.21 | 0.29 | 0.31 | 0.38 | |

### 3.1.3 Results

The following is a summary of the results from the analyses performed on the unexpected hazard response times, looking at each individual stage of brake reaction time, as well as overall brake reaction time.

### Perception Time (PT)

The first outcome variable evaluated was perception time (PT), or the time between hazard onset until the start of the first continuous eye movement towards the hazard[1]. There were significant main effects of event type ($F(2,35) = 9.00$, $p=.0007$) and task condition ($F(1,21) = 10.41$, $p=.004$) on perception time, with perception times on average 0.23 seconds longer while executing the secondary distraction task (Figure 10a). There was no significant effect of the covariate of speed at target onset ($F(1,35) = 1.70$, $p=.20$). There was also no significant task x event type interaction ($F(2,35) = 0.31$, $p=.73$).

Three planned contrasts were conducted to investigate differences in perception times across the different hazard types. These contrasts revealed significantly shorter perception times to the pedestrian hazard than to the left-turning vehicle hazard ($t(35) = -3.74$, $p=.0007$) and the right-incursion vehicle hazard ($t(35) = -3.56$, $p=.001$), by an average decrease of 0.44 and 0.41 seconds respectively. There was no significant difference in perception times between the left-turning vehicle and right-incursion vehicle hazards ($t(35) = 0.21$, $p=.84$).

Planned contrasts were also conducted to investigate the effect of task type on perception times to each individual hazard type. There was no significant effect of the distraction task on perception times to the left-turning vehicle hazard ($t(35) = -0.82$, $p=.42$). The effect of distraction on perception times to the pedestrian ($t(35) = -1.87$, $p=.07$) and the right incursion vehicle hazard ($t(35) = -1.85$, $p=.07$) were marginally significant, with longer perception times while performing the distraction task by an average of 0.28 and 0.29 seconds respectively.

### Inspection Time (IT)

There was a significant main effect of event type found on inspection times ($F(2,28) = 19.58$, $p<.0001$)[2]. There were no significant main effects found for task condition or the covariate of speed at hazard onset. There was also no significant task x event type interaction effect (Figure 10b).

The inspection time to the left-turning vehicle hazard was found to be significantly longer than to the pedestrian ($t(28) = 5.92$, $p<.0001$) and right-incursion vehicle ($t(28) = 4.65$, $p<.0001$)

[1] A square root transformation was performed on the perception time data to correct for non-homogeneity of residual variance. There were no changes to the results at the alpha=.05 significance level, therefore the untransformed results are reported.

[2] A log transformation was performed on the inspection time data to correct for non-homogeneity of residual variance. There were no changes to the results at the alpha=.05 significance level, therefore the untransformed results are reported.

hazards by an average of 0.55 and 0.45 seconds respectively. There was no significant difference in inspection times between the pedestrian hazard and the right-incursion vehicle hazard ($t(28) = -1.01$, $p=.32$).

Executing the secondary 1-back task resulted in significantly longer inspection times for the left-turning vehicle hazard ($t(28) = -2.41$, $p=.02$), with an average increase of 0.32 seconds. There was no significant effect of distraction task on the inspection times for the pedestrian or right-incursion vehicle hazards.

**Movement Time (MT)**

There was a significant main effect of event type on foot movement times ($F(2,28) = 3.54$, $p=.04$)[3]. However, there were no significant main effects of task condition or speed at hazard onset, and no significant task x event type interaction effect (Figure 10c).

Planned contrasts looking at the differences between hazards showed that foot movement times for the left-turning vehicle hazard were significantly longer than foot movement times to the pedestrian hazard ($t(28) = 2.42$, $p=.02$) and right-incursion vehicle hazard ($t(28) = 2.08$, $p=.047$), with average increases of 0.17 and 0.15 seconds respectively. There was no significant difference in foot movement times between the pedestrian and right-incursion vehicle hazards.

There was no significant effect of distraction on movement times for the pedestrian or right-incursion vehicle hazards. There was a marginally significant effect of task condition on foot movement times for the left-turning vehicle hazard ($t(28) = 1.99$, $p=.056$), where foot movement times were on average 0.20 seconds lower while performing the secondary distraction task.

**Brake Reaction Time (BRT)**

Brake reaction time (time from hazard onset until brake pedal application) was also analyzed, to investigate if any of the effects observed throughout the individual response stages were also observed over the total brake reaction time (Figure 11)[4]. In general, the results show that there were significant main effects of event type ($F(2,28) = 88.49$, $p<.0001$) and task condition

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[3] A log transformation was performed on the movement time data to correct for non-homogeneity of residual variance and a positively skewed residual distribution. There were no changes to the results at the alpha=.05 significance level, therefore the untransformed results are reported.

[4] There was an outlier observed in the BRT data for the left-turning vehicle hazard in the distraction condition, with a BRT of 3.62 s, compared to the overall average for that subset of data of 2.26 s. A sensitivity analysis was conducted by removing the outlier. There were no changes to the results at the alpha=.05 significance level, therefore the untransformed results are reported.

($F$(1,22) = 5.89, $p$=.02) on brake reaction times, with an average increase in BRT of 0.26 seconds for the cognitive distraction task condition. No significant interaction (task x event type) effect was found ($F$(2,28) = 0.55, $p$=.58). There was also no significant effect of the covariate, subject vehicle's speed at target onset ($F$(1,28) = 0.20, $p$=.66).

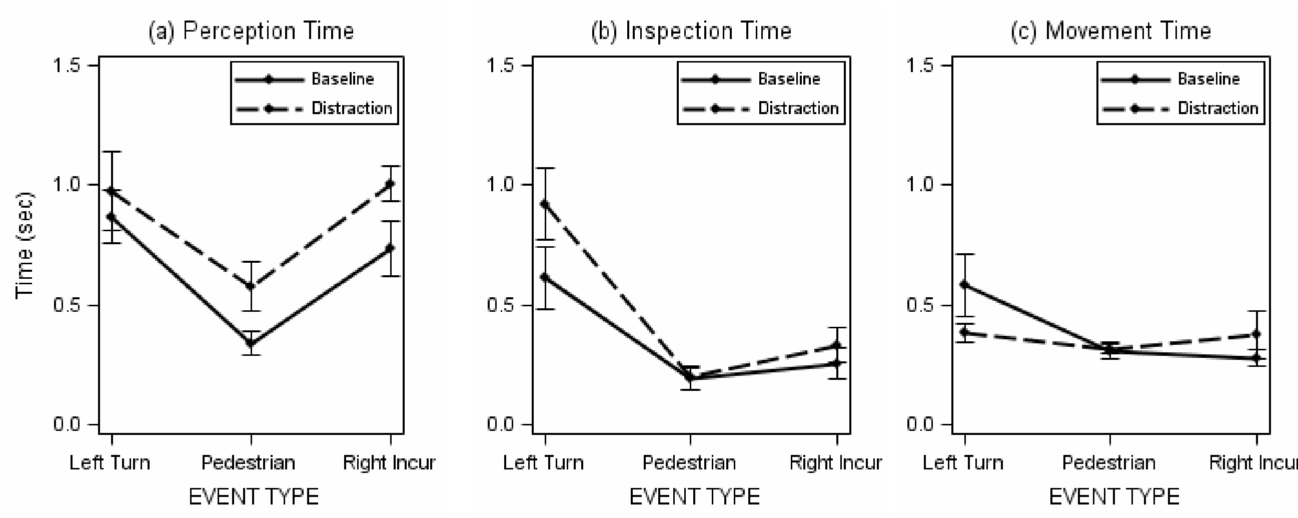


**Figure 10**: Mean perception, inspection, and movement times by event type and task condition (error bars represent standard errors).

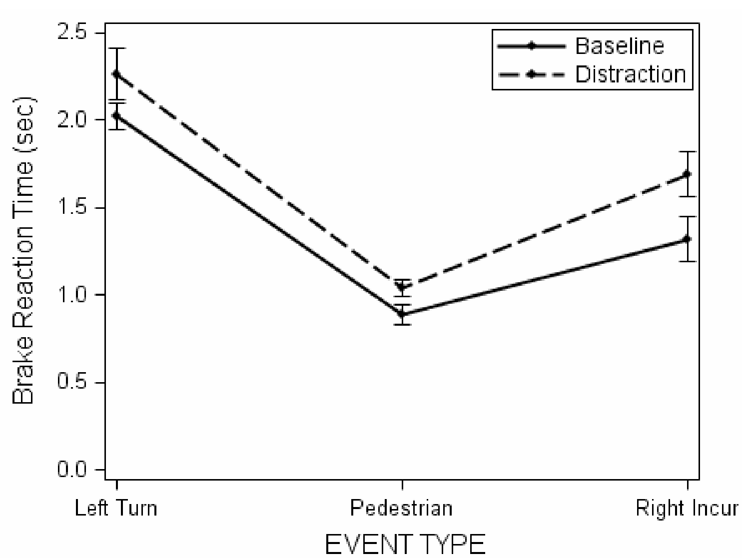


**Figure 11**: Mean brake reaction times (BRT) by event type and task condition (error bars represent standard errors).

BRTs to the pedestrian hazard were significantly lower than BRTs to the left-turning vehicle hazard ($t(28) = -13.28$, $p<.0001$) and the right incursion vehicle hazard ($t(28) = -5.47$, $p<.0001$), by an average of 1.17 and 0.53 seconds respectively. Brake reaction times to the left-turning vehicle were significantly longer than to the right incursion vehicle hazard, with an average increase of 0.64 seconds ($t(28) = 6.67$, $p<.0001$).

Planned contrasts were also conducted to investigate the effect of task condition on brake reaction times to each individual hazard. Brake reaction times to the right incursion vehicle hazard were significantly longer while performing the secondary 1-back task ($t(28) = -2.17$, $p=.04$) by an average of 0.37 seconds. The effect of distraction on BRTs to the left-turning vehicle hazard was marginally significant ($t(28) = -1.74$, $p=.09$), with an average increase of 0.24 seconds. There was no significant effect of task condition on BRTs to the pedestrian hazard ($t(28) = -1.14$, $p=.27$).

**Initial Steer Reaction Time (SRT) and Direction – Left-Turn Hazard**

Due to the low number of steering responses to the pedestrian and right incursion vehicle hazards, an analysis of initial steer reaction times was conducted only for the left-turn vehicle hazard.

An independent *t*-test was conducted to test for differences between initial steer reaction times in the baseline and distraction task conditions (Figure 12). Normality and homogeneity of variance checks were performed. Performing the secondary distraction task was not found to have a significant effect on initial steer reaction times to the left-turning vehicle hazard ($t(14) = -0.52$, $p=.61$).

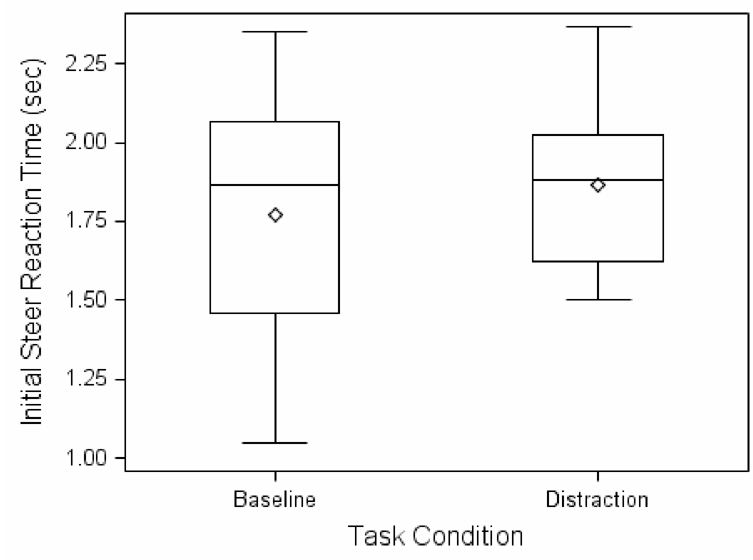


**Figure 12**: Initial Steer Reaction Times in response to the Left-Turning Vehicle Hazard.

The initial steer direction in response to the left-turning vehicle hazard was primarily towards the right, or away from the encroaching left-turning vehicle (Table 4). Of the participants who steered in response to the left-turning vehicle hazard, over 80% chose to steer to the right initially.

**Table 4**: Summary of Initial Steer Directions for the Left-Turning Vehicle Hazard.

| Task Condition | Initial Steer Direction | |
|---|---|---|
| | Right | Left |
| Baseline | 6 | 2 |
| Distraction | 7 | 1 |

## 3.2 <u>Repeated Hazard Exposure (Drive A vs. Drive B)</u>

In order to investigate the effect of repeated hazard exposure on the sub-components of driver response time, analyses were conducted to compare the data collected from Drive A to Drive B. The data was first split by task condition, with the effects of repeated exposure examined for the baseline and distraction conditions separately.

### 3.2.1 Statistical Model

Identical statistical models were built for the baseline and distraction condition data. This was a 2 x 3 repeated measures design with drive (two levels; Drive A and Drive B) as a between-subjects factor and event type (three levels; left-turn, pedestrian, right incursion) as a within-subject factor with repeated measures. Mixed linear models were created for several outcome variables using *PROC MIXED* statements in SAS 9.3, which contains both fixed and random effects. A compound symmetry variance-covariance structure was used for repeated measures. Speed of the subject's vehicle at hazard onset was again included as a covariate in the model. *F* tests were performed on main and interaction effects. Specific contrasts were then performed using *ESTMATE* statements to compare the effect of repeated exposure on each individual type of hazard. Normality and homoscedasticity assumption checks were conducted on the residuals.

### 3.2.2 Baseline Condition Results: Effects of Repeated Hazard Exposure

**Perception Time (PT)**

In the baseline (no distraction) condition, there was a significant main effect of event type ($F(2,35) = 7.38$, $p=.002$) and drive order ($F(1,20) = 5.18$, $p=.03$) on perception time, with an average decrease in perception time of 0.23 seconds between Drive A and Drive B. There was no significant effect of speed at target onset or drive x event type interaction effect (Figure 13a).

Planned contrasts were created to evaluate the effect of repeated exposure on each hazard type. There was a significant decrease in perception time for the left-turning vehicle hazard between Drive A and Drive B ($t(35) = 2.87$, $p=.007$), with perception times an average of 0.47 seconds shorter during Drive B. There was no significant effect of repeated exposure on perception times for the pedestrian or right-incursion vehicle hazards.

**Inspection Time (IT)**

There was a significant main effect of event type on inspection times ($F(2,26) = 22.20$, $p<.0001$). There was also a marginally significant drive order x event type interaction effect ($F(2,26) = 3.35$, $p=.051$)[5].

[5] A square root transformation was performed on the inspection time data to correct for non-homogeneity of residual variance. There were no changes to the results at the alpha=.05 significance level; therefore the untransformed results are reported.

When considering the event types individually, there was a significant effect only of repeated exposure on inspection time for the left-turning vehicle hazard ($t(26) = -2.89$, $p$=.008). The inspection time to the left-tuning vehicle hazard increased by an average of 0.43 seconds during Drive B (Figure 13b).

There was an increase in the number of participants that released the accelerator pedal prior to the onset of the left-turning vehicle hazard during Drive B, which led to an increase in missing data points for inspection time. Therefore, a secondary measure of inspection time was calculated that considered first motor response as the end of the inspection stage (i.e., either accelerator release, brake pedal application, or the start of steer response). In general, the same results were found for this secondary measure of inspection time. Inspection times increased significantly for the left-turning vehicle hazard during Drive B ($t(32) = -3.17$, $p$=.003).

**Movement Time (MT)**

Similar to perception and inspection time, there was a significant main effect of event type on movement time ($F(2,25) = 6.35$, $p$=.006)[6]. There were no significant main effects of drive order, speed at hazard onset, or interaction effect. Planned contrasts of drive order on the individual hazard types found no significant difference in movement times between Drive A and Drive B for any hazard type (Figure 13c).

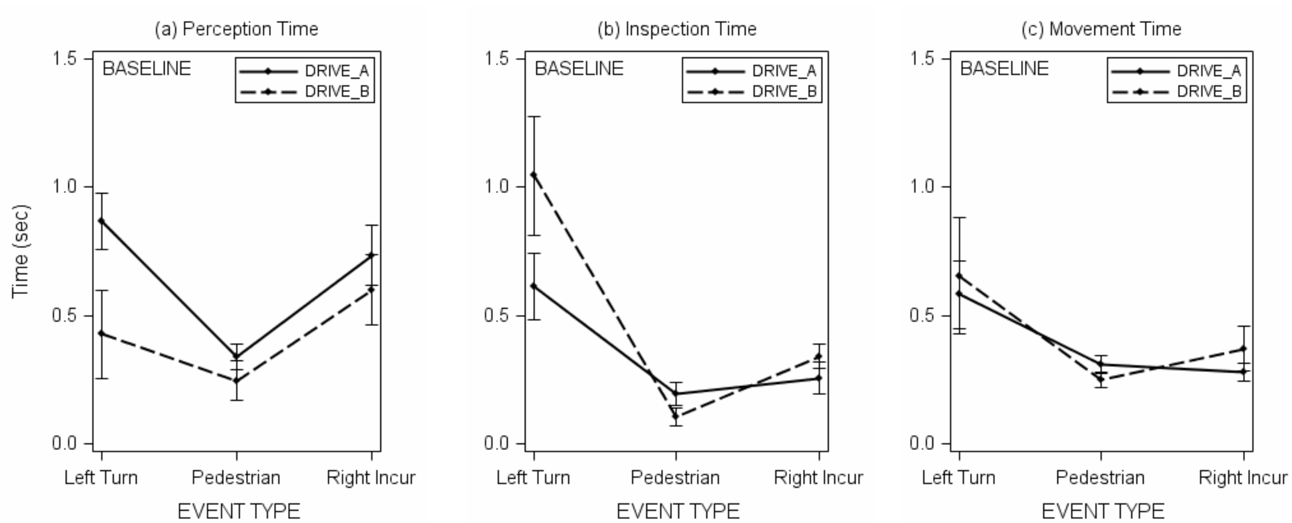


**Figure 13**: Mean perception, inspection, and movement times by event type and drive order for the baseline, no distraction condition (error bars represent the standard errors).

[6] A reciprocal transformation was performed on the movement time data to correct for non-homogeneity of residual variance and non-normal distribution. There were no changes to the results at the alpha=.05 significance level; therefore the untransformed results are reported.

**Brake Reaction Time (BRT)**

When the individual stages are combined, in terms of total brake reaction time, there was a significant decrease in BRT to the pedestrian hazard from Drive A to Drive B ($t(25) = 2.62$, $p$=.01) by an average of 0.29 seconds. There was no significant difference in BRT to the left-turning vehicle hazard or the right-incursion vehicle hazard between drives (Figure 14).

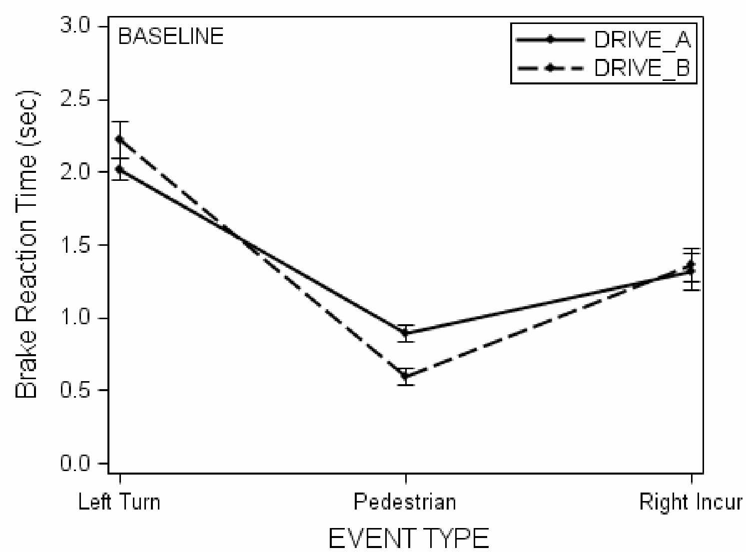


**Figure 14**: Average brake reaction time by event type and drive order for the baseline, no distraction condition (error bars represent standard errors).

### 3.2.3 Distraction Condition Results: Effects of Repeated Hazard Exposure

**Perception Time (PT)**

There was a significant main effect of event type ($F(2,34) = 7.68$, $p$=.002) and drive order ($F(1,21) = 81.52$, $p$<.0001) on perception time while performing the 1-back distraction task[7]. There was a decrease in perception time from Drive A to Drive B by an average of 0.55 seconds. There was also a significant drive order x event type interaction effect ($F(2,34) = 3.43$, $p$=.04). Perception times were significantly longer during Drive A than Drive B for all hazard types (Figure 15a), with an average increase of 0.36 seconds for the pedestrian hazard ($t(34) = 2.76$, $p$=.009), 0.87 seconds for the left-turning vehicle hazard ($t(34) = 6.24$, $p$<.0001), and 0.43 seconds for the right-incursion vehicle hazard ($t(34) = 3.03$, $p$=.005).

[7] A square root transformation was performed on the perception time data to correct for non-homogeneity of residual variance. There were no changes to the results at the alpha=.05 significance level, therefore the untransformed results are reported.

**Inspection Time (IT)**

A square root transformation was performed on inspection times in the distraction condition to correct for non-homogeneity of variances of the residuals. There was a significant main effect of event type on inspection times ($F(2,24) = 26.87$, $p<.0001$). There were no significant differences in inspection times between Drive A and Drive B for any of the hazard types (Figure 15b).

**Movement Time (MT)**

An outlier was observed in the movement time data for the right-incursion vehicle hazard in Drive A, with a studentized residual close to 6. The movement time for this data point was 1.08 seconds, compared to the overall movement time average of 0.33 seconds. A sensitivity analysis was performed by removing this data point and it was found to have an effect on the results. Therefore the reported results are based on the analysis with the outlier removed.

A significant main effect of event type was found on movement times ($F(2,27) = 3.68$, $p=.04$). There was a marginally significant reduction in movement times to the pedestrian hazard from Drive A to Drive B ($t(27) = 2.05$, $p=.0504$), with a mean reduction of 0.08 seconds. There was no significant difference in movement times between Drive A and Drive B for the left-turning vehicle or right-incursion vehicle hazards (Figure 15c).

**Brake Reaction Time (BRT)**

A log transformation was performed on brake reaction times for the distraction condition to correct for unequal variances in the residuals. Since effect estimates cannot be backtransformed in a meaningful way, rather than effect estimates, actual values from the raw data are reported for these analyses. There were significant main effects of event type ($F(2,28) = 70.04$, $p<.0001$) and drive order ($F(1,21) = 15.67$, $p=.0007$) on brake reaction times, with an average decrease of 0.46 seconds from Drive A to Drive B.

Planned contrasts evaluating the drive order effect on each hazard type revealed significantly longer brake reaction times in Drive A than Drive B for the pedestrian ($t(28) = 4.03$, $p=.0004$) and right-incursion vehicle ($t(28) = 2.79$), $p=.01$) hazards while performing the distraction task, with average increases of 0.45 and 0.50 seconds respectively (Figure 16). There was no significant difference in brake reaction times to the left-turning vehicle hazard between Drive A and Drive B.

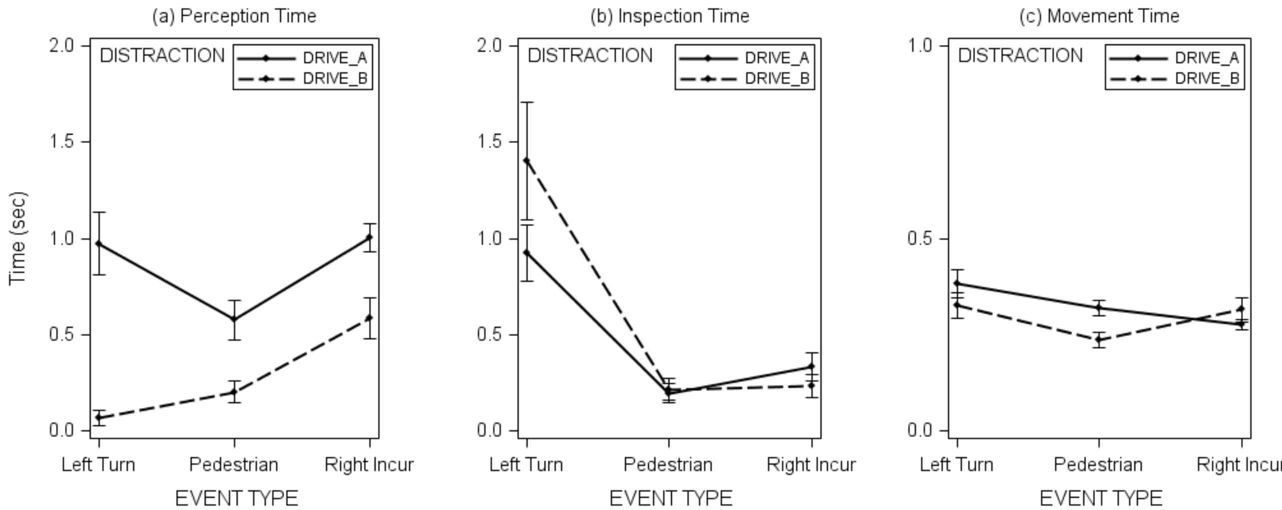


**Figure 15**: Mean perception, inspection, and movement times by event type and drive order for the distraction condition (error bars represent the standard errors).

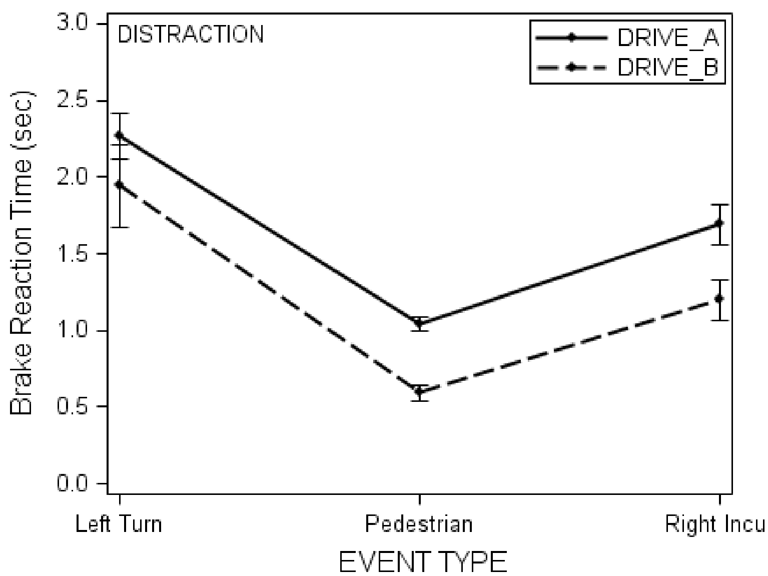


**Figure 16**: Average brake reaction time by event type and drive order for distraction task condition (error bars represent standard errors)

### 3.2.4 N-Back Task Performance: Effects of Repeated Hazard Exposure

Participant performance on the cognitive distraction task was measured throughout the experiment. Performance was expressed in terms of the percentage of correct responses over the entire simulated drive.

Participants were asked to be as accurate as possible while performing the 1-back task; however it is possible that performance on the task was sacrificed during the second drive (Drive B), which may have accounted for some of the drive order effects found throughout the response time stages. Therefore an independent *t*-test was conducted to test for differences in n-back task performance between Drive A and Drive B. Normality and homogeneity of variance checks were performed. There was no significant difference in the percent of correct 1-back responses between the two simulated drives ($t(22) = 0.02$, $p$=.99) (Figure 17).

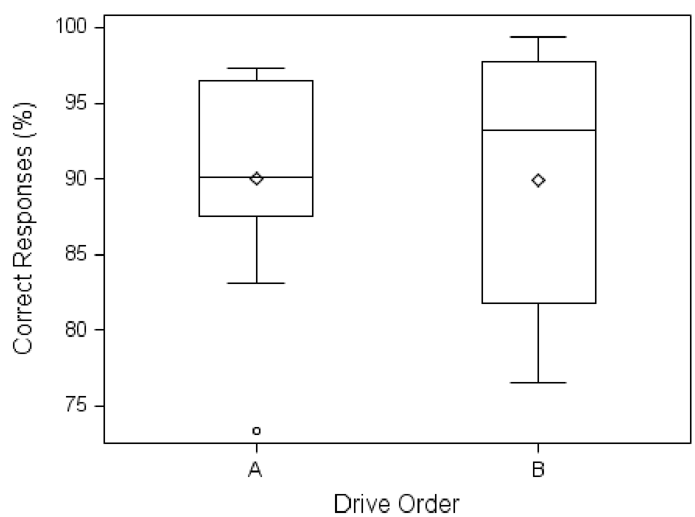


**Figure 17**: Percent of correct responses on the 1-back cognitive distraction task by drive order.

## 3.3 Post-Experiment Questionnaire Evaluation

An average score for each section of the Susceptibility to Driver Distraction Questionnaire (SDDQ) was calculated for each participant. For the distraction engagement section, there were seven items rated on a 5-point Likert scale, with 1 representing “never” and 5 representing “very often”. An average score was calculated by taking the sum and dividing by the number of items. The voluntary and involuntary distraction sections consisted of twenty-four and eight items respectively, each rated on a 5-point Likert scale, with 1 representing “strongly disagree” and 5 representing “strongly agree”. There was an additional option of “never happens” for the involuntary distraction items; however this response was not included in the average score calculations.

Another set of average scores were calculated for each participant based on the subset of 24 items from the Manchester Driver Behaviour Questionnaire (DBQ). There were 24 items divided into four categories, including aggressive violations, ordinary violations, errors, and lapses, with an average score calculated per category. Each item was rated on a 6-point scale with 1 representing “never” and 6 representing “nearly all the time”.

Pearson product-moment correlations were used (*PROC CORR* statement in SAS 9.3) to investigate the relationship between the SDDQ and DBQ measures of the post-experiment questionnaire, as well as participant performance on the 1-back distraction task (measured as percent of correct responses), and self-rating of safe driving behaviour (rated between 1 to 10, with 1 being “very unsafe” and 10 being “very safe”). Normality checks were performed on each variable. The correlation coefficients are shown in Table 5.

**Table 5**: Pearson correlations among all measures of post-experiment questionnaire and n-back results.

| Measure | SDDQ | | | DBQ | | | | 1-Back % Correct | Safe Driver Rating |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| 1) Engagement | -- | | | | | | | | |
| 2) Voluntary | .77* | -- | | | | | | | |
| 3) Involuntary | -.49* | -.59* | -- | | | | | | |
| 4) Aggressive Violations | .42* | .44* | -.48* | -- | | | | | |
| 5) Ordinary Violations | .68* | .68* | -.58* | .83* | -- | | | | |
| 6) Errors | .49* | .43* | -.42* | .56* | .60* | -- | | | |
| 7) Lapses | .45* | .00 | -.07 | .09 | .21 | .34 | -- | | |
| 8) 1-back % correct | -.07 | .08 | .08 | -.03 | -.05 | -.21 | -.27 | -- | |
| 9) Safe Driver Rating | -.08 | .02 | -.01 | .31 | .17 | -.10 | -.22 | .54* | -- |

*represents a significant correlation (α = .05)

In general there were associations found among the individual sub-sections of the SDDQ. Engagement in distracting activities while driving was found to be positively correlated to potential causes of voluntary distraction (r = .77, *p*<.0001). This means that higher self-reported engagement in distracting activities while driving corresponds to more positive opinions about distracted driving, higher levels of perceived control performing secondary tasks while driving, and more favourable perceived social norms towards distracted driving.

Engagement in distracting activities while driving was negatively correlated to susceptibility to involuntary distraction ($r = -.49$, $p<.05$). Drivers who reported engaging in distracted activities more frequently were less likely to find external stimuli distracting. A negative correlation was also found between voluntary and involuntary distraction ($r = -.59$, $p<.01$), meaning that drivers who reported being less susceptible to external distractions while driving had higher ratings on potential causes for voluntary distractions (more position attitudes towards distracted driving, higher perceived levels of control, and greater perceived social norms towards distracted driving).

There were also associations found between three of the four DBQ categories, including aggressive violations, ordinary violations, and errors. People who reported frequent occurrences of aggressive violations while driving, also reported frequent occurrences of ordinary violations ($r = .83$, $p<.0001$) and errors ($r = .56$, $p<.01$). A higher reported number of ordinary violations was also positively correlated to the reported number of errors ($r = .60$, $p<.01$). There were no significant correlations between lapses and the other three categories.

There were several significant correlations between SDDQ and DBQ measures. People who report engaging in distracted activities while driving more often also report more occurrences of all DBQ categories. People with higher average voluntary distraction scores (meaning more positive attitudes towards distraction) also reported higher occurrences of aggressive violations, ordinary violations, and errors. The opposite relationship was true for susceptibility to involuntary distraction, where drivers who were more likely to find external stimuli distracting reported lower incidences of aggressive violations, ordinary violations, and errors. There was no association between self-reported occurrences of lapses and voluntary or involuntary SDDQ measures.

Performance on the 1-back distraction task, measured by percent of correct responses, was not found to be associated with any of the SDDQ or DBQ measures. However, 1-back performance was positively correlated to self-reported safe driver rating ($r = .54$, $p<.01$), meaning that participants who performed better on the 1-back distraction task also rated themselves as safer drivers.

A variety of unexpected response time measures, including mean times for different stages separated by hazard type and task condition for Drive A were investigated. There were no significant correlations found between any of these response time measures and any of the SDDQ or DBQ measures. There were also no significant correlations between these response time measures and performance on the 1-back task.

# CHAPTER 4

## 4.0 DISCUSSION

This study investigated the effect of cognitive distraction on driver perception-response times to a variety of emergency roadway hazards in a simulated environment. Eye movement recordings and motor responses were used to divide perception-response time into three separate stages (perception time, inspection time, and movement time), with the effect of cognitive distraction assessed at each stage, as well as the overall effect on total brake reaction time. The simulator experiment and analyses were divided into two main sections. The first investigated the effect of cognitive distraction to unexpected emergency roadway hazards (data collected from Drive A), and the second assessed any effect of repeated hazard exposure on response times in both task conditions. Lastly, questionnaire data was used to assess if there are any correlations between driver's opinions and susceptibility to distractions and their self-reported engagement in other unsafe driving behaviours, as well as how these measures correlate to performance on the distraction task and different stages of perception-response times.

Overall, this research has shown how eye movement recordings can be used to divide driver perception response time into three stages, consistent with the work of Recarte and Nunes (2003). However, this research has applied the concept specifically to driver perception response times to emergency roadway hazards. Most hazard perception studies involving eye movement recordings analyze first fixation times on a target (Crundall et al., 2012; Huestegge et al., 2010). In order to get a closer approximation to when a hazard is first detected, this study analyzed the start of eye movement towards the hazard as the end of the perception interval rather than first fixation, similar to the study by Recarte and Nunes (2003). The results of this research demonstrate the value of analyzing the effects of different factors, such as cognitive distraction, on each of the response time stages. Varying effects were found across different stages and for different types of hazards, which can provide a better understanding as to how information is processed in the driving environment. In some cases null overall effects were observed, but there were significant effects throughout the individual stages, further emphasizing the value of evaluating each stage individually.

One consistent finding throughout the analysis was that there was a significant main effect of hazard type on total brake reaction times and almost all response time stages for the data collected from both simulated drives and both task conditions. This means that subjects responded differently to the different hazards presented to them. These findings are consistent with a large body of previous research that has shown that perception-response time is dependent on a variety of factors, including the type of stimuli and study methodology (Green, 2000; Muttart, 2005). There is no single value of perception-response time that applies to all situations. These findings reiterate the concept that, when assessing driver perception-response times or comparing across response time studies, particular attention must be paid to the individual circumstances.

## 4.1 Responses to Unexpected Roadway Hazards

The average unexpected brake reaction times from this study for the baseline condition are generally in agreement with the results of previous studies. A simulator study of an unexpected vehicle right-incursion at an intersection (McGehee et al., 1999) found a mean brake reaction time (onset of motion of the intruding vehicle until the first application of the brake pedal) of 1.1 seconds. The McGehee (1999) simulator study was replicated on a test track (Mazzae et al., 2003), with a mean brake reaction time of 1.5 seconds on dry pavement. The mean brake reaction time found in the current study for the right-incursion vehicle hazard was 1.3 seconds for the baseline condition, which is in the middle of the range of the two previous studies. The shorter brake reaction times in the McGehee (1999) simulator study could be due to the fact that the incursion vehicle accelerated into the driver's path much more rapidly than in this study, creating a more immediate hazard. The acceleration rate of the incursion vehicle in the test track study was also more rapid than in this study; however there are other methodological differences that could account for the greater brake reaction times. Such as, the drivers in the test track study had passed the incident intersection three times prior without incident. The subjects in the test track study were also concurrently monitoring a visual headway display, which may have increased the driver's mental workload or eyes off road time, leading to greater brake reaction times.

Three simulator studies measuring driver response times to an unexpected pedestrian moving into the driver's path found mean brake reaction times of 0.8 seconds (Coley, Wesley, Reed, & Parry, 2008), 1.1 seconds (Barrett et al., 1968) and 1.3 seconds (Broen & Chiang, 1996) . The mean BRT to the pedestrian hazard for the baseline condition in this study was 1.0 seconds. There was variation in the driving speed, time-to-collision, and driving environment between the simulator studies referenced above and this study, which may account for the differences in brake reaction times.

A very similar pedestrian hazard scenario was tested in the simulator study by Smiley and Caird (2007). The mean perception-response time (from pedestrian first visible to brake application) of experienced drivers in the baseline (no distraction) condition was 1.5 seconds. This is 0.5 seconds greater than the mean unexpected pedestrian brake reaction time in this current study. Note that the baseline condition reported in the Smiley and Caird (2007) study is aggregated over multiple simulated drives, and therefore is not directly comparable to the unexpected pedestrian hazard responses from this research. The pedestrian hazard in the Smiley and Caird (2007) study was triggered at a slightly greater time-to-collision than in this research, and their subjects were also responsible for monitoring a display for route directions and instructions on intermittent secondary tasks, both of which could account for the larger perception-response times. In the current study, the pedestrian always emerged from in front of a white truck. This truck was highly salient and may have captured subjects' attention even before the pedestrian became visible, which could have led to shorter perception-response times.

There is a lack of literature related to measuring driver perception-response times to left-turning vehicles at an intersection. Therefore, the response times obtained in this study could not be compared to any existing literature. However, the data collected in this study for the left-turning vehicle hazard serves to help fill this gap.

Planned contrasts looking at the differences in response time stages between hazard types revealed that mean perception time to the pedestrian hazard was significantly shorter than mean perception time to the left-turning vehicle and right-incursion vehicle hazards. This difference is consistent with the concept of stimulus-driven, bottom-up capture of attention due to abrupt onsets (Yantis & Jonides, 1984). The pedestrian hazard stepped onto the roadway from in front of a parked vehicle and was not visible to participants on approach. This abrupt appearance likely captured driver's visual attention more readily than the gradual onset of motion of the other two hazards. For reference, in the first half second the right-incursion vehicle would travel less than 20 cm. As mentioned above, it is also possible that the highly salient white truck that the pedestrian emerged from in front of captured subject's attention, even before the pedestrian became visible.

Inspection and movement times in response to the left-turning vehicle hazard were found to be significantly longer than for the pedestrian and right-incursion vehicle hazards. The inspection time measured in this study is closely related to the combination of the cognition and response selection stages of Wickens' model of information processing (Figure 1). During these stages, a driver must use the information available and information drawn from memory to make judgments regarding the projected speed and trajectory of the hazard to determine if a collision is imminent, and then choose how to respond. After the left-turning vehicle started to move, it may not have been immediately obvious that it was going to continue across the driver's path. Therefore, it is logical that the inspection time was lengthened for this type of hazard.

The longer foot movement times to the left-turning vehicle hazard could again be associated with the uncertainty in the intended path of the vehicle. Even once the accelerator was released there may have still been some ambiguity about whether the left-turning vehicle was going to continue across the driver's path. The left-turning vehicle was the first emergency hazard presented to all participants. Therefore, it is also possible that participants' expectancy of potential conflicts increased after the first hazard, therefore leading to a reduction in inspection and movement times to subsequent hazards.

When looking at the effect of executing a secondary cognitive distraction task on the different stages of unexpected perception-response time, the greatest effects were observed for perception times, with an overall average increase of 0.23 seconds. When all stages are combined, the overall average increase in brake reaction times while performing the secondary cognitive task was 0.26 seconds. This average increase is generally consistent with those reported by a meta-analysis conducted by Caird et al. (2008), although there were differences in the stimuli being responded to and the distraction tasks in the studies included in the meta-analysis.

Very similar results were found for the pedestrian and right-incursion vehicle hazard. There was a marginally significant increase in perception times while performing the 1-back task, with average increases of 0.28 and 0.29 seconds respectively. There were no significant increases in inspection or movement times for the pedestrian and right-incursion hazards. This suggests that cognitive distraction leads to delayed detection of these particular hazards, but once detected there is no effect of distraction on decision and response execution. When total brake reaction time is considered, performing the cognitive distraction task led to significantly longer brake reaction times for the right-incursion vehicle hazard (average increase of 0.37 seconds), but there was no significant effect of distraction on total brake reaction times to the pedestrian hazard. At a highway speed of 100 km/h, a delay of 0.37 seconds in brake reaction time corresponds to the vehicle travelling an extra 10 meters before the brakes are applied, which can make a difference between whether a hazard is avoided or whether a collision will ensue.

For the left-turning vehicle hazard, there was no significant increase in perception time while performing the 1-back task. However, there was a significant increase in inspection time, with a mean increase of 0.32 seconds, and a marginally significant decrease in movement time. This suggests that cognitive distraction does not lead to delayed detection of the left-turning vehicle hazard (or when the hazard is first looked at after it starts to move). This may be due to the location of the left-turning vehicle hazard. This hazard was presented nominally directly ahead of the subjects. One of the commonly reported effects of cognitive distraction on visual behaviour is that drivers tend to experience a narrowing of the field of view, meaning they spend more time looking ahead and less at the periphery (Harbluk et al., 2007; Mackworth, 1965; Recarte & Nunes, 2000; Reimer, 2009). Since the left-turning vehicle hazard was visible within the driver's forward field of view, the time taken to first look at the hazard would not be affected by this cognitive visual tunnelling. However, cognitive distraction does increase the time before the driver's foot is lifted off of the accelerator after first looking at the hazard, suggesting a delay in cognitively identifying the vehicle as a hazard requiring an emergency response, as well as choosing the response. Once the response is chosen, it appears that drivers might be trying to compensate for this delay by moving their foot to the brake more quickly.

These results display the potential benefits of analyzing the effect of distraction on different stages of driver perception-response times, as well as on different types of hazards. Cognitive distraction appears to have varying effects on each response time stage depending on the type of stimuli.

## 4.2 Repeated Scenario Exposure

Based on previous research on repeated exposure or different levels of hazard expectancy (Engstrom, 2010; Olson et al., 1984), it is expected that drivers would respond more quickly the second time they are presented with the same hazard. In the baseline condition, the only significant effect due to repeated scenario exposure on total brake reaction time was for the pedestrian hazard, where BRT decreased by a mean of 0.29 seconds in Drive B.

For the left-turning vehicle hazard, repeated exposure resulted in a significant decrease in perception time and a significant increase in inspection time, leading to a null overall effect to the total brake reaction time. In Drive B, drivers were very closely monitoring the left-turning vehicle on approach, therefore leading to lower perception times. However, even though drivers first looked towards the left-turning vehicle earlier in Drive B, it took them longer to subsequently lift their foot off the accelerator. This can mean that there is some threshold or point after the left-turning vehicle started to move when it became obvious to subjects that it was going to turn in front of them. In Drive B, subjects identified the vehicle as a potential hazard and were looking at it earlier, but this threshold point did not necessarily occur any earlier, which could account for the longer inspection times. These findings illustrate how the use of eye movement recordings and analyzing response time stages independently can provide valuable insights that would have been otherwise missed.

When looking at the effect of repeated exposure while executing the cognitive distraction task, the greatest effect was observed for perception times. Perception times were significantly shorter for all hazards, meaning subjects looked at the hazards quicker in Drive B than Drive A. This same result was observed for the left-turning vehicle hazard in the baseline condition, as described above, but not for the pedestrian and right-incursion vehicle hazards. These hazards entered the driver's field of view from the side, whereas the left-turning vehicle was positioned nominally directly ahead. Research has found that increased cognitive load while driving leads to 'cognitive tunnel vision', or more time spent looking centrally and less time at the periphery (Harbluk et al., 2007; Recarte & Nunes, 2000). Therefore, the longer perception times in Drive A to the hazards entering from the side could be the result of subjects spending more time looking at the roadway ahead and not scanning the periphery as often. In Drive B, subjects had a heightened awareness for potential side hazards and may have consciously performed more frequent scans to the periphery and overcome the effects of cognitive tunnel vision. This can be compared to the foreshadowing effects observed by Garay et al. (2004), where it was found that providing cues increased scanning and attention to potential hazard locations, although the cues provided in that study were within the same drive as subjects approached the potential hazard locations. In this study, the initial drive acted as the foreshadowing for the second repetition of nearly an identical drive.

It was hypothesized that participants in Drive B may have sacrificed performance on the 1-back task, placing more emphasis on hazard detection and response. However, there was no significant difference in task performance between Drive A and Drive B to support this.

## 4.3 Questionnaire Response Evaluation

The objective of collecting the questionnaire responses was to investigate any relationships between distraction task performance and response times with drivers' self-reported susceptibility to distraction and other unsafe driving behaviours. Overall, there were no significant correlations between different subsets of driver response times and any of the distraction susceptibility measures from the SDDQ or unsafe driving behaviour measures from the DBQ. There were also no significant relationships observed between performance on the distraction task and any of the SDDQ or DBQ measures. There was a significant relationship between 1-back task performance and self-reported safe driver ratings. Subjects who rated themselves as safer drivers also had better performance on the 1-back task.

There were a variety of significant relationships between and across SDDQ and DBQ measures, many of which are consistent with the findings of Feng et al. (2014). One of the more interesting relationships was that people who report engaging in distracting activities more often while driving also have more positive opinions about distraction, have higher perceived control, and greater perceived social norms towards distracted driving. This relationship suggests that possible countermeasures for reducing driver engagement in distraction is further education and media campaigns to change personal attitudes towards distraction and instill negative perceived social norms towards distracted driving.

## 4.4 Limitations

This study focused specifically on driver response times to daytime roadway hazards presented within about ±10 degrees of the forward roadway. Extrapolation of the results of this study for nighttime conditions or hazards emerging from further out in the periphery (greater eccentricities) should be done with caution.

This research has used eye movements to determine when a hazard is first looked at, which has provided valuable insights into how drivers process information in the driving environment. However, these first look times do not necessarily represent when the hazard is first detected, as eye movements alone cannot predict when something is detected. The use of electroencephalography (EEG) techniques would be required to try and predict hazard detection.

The start of the response times measured in this study was hazard onset, which was defined as the moment each of the hazards began to move. This starting point does not take into account any human perceptual thresholds associated with motion onset. Therefore, the reported perception-response times are all arguably overestimated to some extent.

The first section of this study aimed to collect unexpected driver response times to emergency roadway hazards. Although participants were not informed of the true purpose of the study, simply being involved in a study could have resulted in modified behaviour and heightened overall awareness. Therefore the data collected may not be representative of truly unexpected events.

The study was conducted in a motionless driving simulator. As with all driving simulator studies, there is concern regarding the validity and applicability of the results to real on-road driving situations. The fact that participants did not feel the acceleration, deceleration, and steering inputs in this motionless simulator may have altered the degree of any of these inputs. Also, the consequences of being involved in a collision are not present in the virtual environment of the driving simulator, which may reduce the perceived urgency of the hazards presented and affect the subsequent driver response times. In order to validate the results of this study, ideally the response times measured would be compared to on-road studies with similar emergency circumstances. However, due to a variety of safety reasons there have been few on-road studies conducted with similar hazards. The most comparable is the test track study conducted by Mazzae et al. (2003) with a similar right incursion vehicle hazard, which found a mean brake reaction time of 1.5 seconds. This is generally in agreement with the mean baseline unexpected brake reaction time measured in this study for the right incursion vehicle hazard of 1.3 seconds.

This study was conducted using only one age group and experience level; therefore, caution should be used when applying the findings from this study to other ages and driving experience levels. This study also considered only the effects of one specific cognitive distraction task. Further testing is required to determine if other types of cognitive distraction task with varying workloads produce similar findings.

# CHAPTER 5

## 5.0 CONCLUSIONS AND FUTURE WORK

A commonly reported major cause of traffic collisions is driver error, such as inattention, inadequate information processing and missed or delayed hazard perception (Horswill & McKenna, 2004; Smiley & Brookhuis, 1987; JS Wang et al., 1996). Therefore, a driver's ability to detect and respond to hazards on the roadway in a timely manner is crucial for traffic safety.

This thesis investigated the use of eye movement recordings and foot movement to sub-divide driver perception-response time into multiple stages. In general, it was found that the use of eye movements allowed for driver perception-response time to be divided into three stages, encompassing perception, inspection, and movement time. These stages more closely resemble the stages of information processing as proposed by Wickens (2000) and more specifically to the stages commonly associated with a driver's perception-response time (Olson, 1989), than using foot movement alone.

Eye movements have been used before to investigate hazard perception abilities and to divide response time into different stages. However, the literature review did not reveal any research using this technique specifically relating to driver response times to emergency roadway hazards. This study has investigated driver response times to a variety of emergency roadway hazards and demonstrated the value of analyzing the effects of different factors, such as cognitive distraction, on the individual response time stages. It was also shown that the effects at each stage can vary depending on the type of hazard being responded to. This study also provides driver response time data to a left-turning vehicle hazard at an intersection, for which there is a lack of available research.

Overall, using these stages of driver response times proved to generate valuable insights into driver behaviour under different conditions and an increased understanding about how information is processed within the driving environment, which may have been missed had eye movement recordings not been collected. It was found that cognitive distraction has varying effects on these response time stages depending on the type of hazard being responded to. The largest increase due to distraction in unexpected brake reaction time was observed for the right-incursion vehicle hazard. However, when the individual stages are considered, the most interesting effects of distraction in both the unexpected condition (Drive A) and the repeated exposure condition (Drive B) were observed for the left-turning vehicle hazard. There was a significant increase in the unexpected inspection time while executing the cognitive distraction task. When comparing Drive A to Drive B, there was a significant decrease in perception time to the left-turning vehicle hazard, but no significant difference in inspection times between the drives. This hazard had the most ambiguity associated with it, meaning that it did not create an immediate and obvious hazard as soon as it started moving. Simply looking at the hazard sooner did not necessarily lead to quicker accelerator release. The results suggest that there might be a threshold, either in terms of its relative position or speed, where this left-turning vehicle hazard transitioned from a potential to an immediate hazard requiring an avoidance response.

Although left-turning vehicle crashes at intersections are very common, there is very limited research available regarding driver responses to left-turning vehicles. In the future, it would be interesting to investigate driver response time stages and behaviours for left-turning vehicles under a variety of conditions, including different sized intersections, different acceleration rates and turning paths, as well situations where the left-turning vehicle does not come to a complete stop before executing their turn. Measuring perception-response time from the start of motion for a left-turning vehicle hazard (or any hazard with inherent ambiguity) can result in wide variations depending on the individual conditions. Further research may lead to determining a more logical starting point.

The effect of eccentricity on perception-response times could be investigated through additional analyses of the eye movement recordings from this study. The eccentricity at the moment of hazard onset could be determined for each individual case by calculating the angle between where subjects were looking at hazard onset and the location of the hazard itself. These angles can then be used to analyze the effect of eccentricity on the different response time stages, with and without cognitive distraction.

There was only one distraction task used in the current study, which focused specifically on cognitive distraction. Future research should investigate the effects of different distraction tasks and different distraction modes on these individual response time stages. This study also used only one level of the n-back task, with an n=1, as well as one age group and experience level. Future studies should consider the effects of varying task difficulty levels (i.e., n=0 and n=2), age, and driver experience on driver response time stages. It would also be interesting to investigate any relationships between the SDDQ measures and performance on different distraction tasks.

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# Appendix A: Participant Screening Questionnaire

This study will take place in a driving simulator located in the Human Factors and Applied Statistics Laboratory (HFASt) at the University of Toronto. The simulator uses a driver seat on a stationary platform, with steering wheel, pedals, and three display screens to closely emulate real driving.

This study will examine driver response times to roadway events and the effect of cognitive distraction. The information gathered will be used to answer academic research questions regarding the effect of cognitive distraction on driver behaviour. All data obtained are for research purposes only and will remain confidential. Names will not be associated with the data in any way and no data will be reported to licensing authorities or insurance companies. Throughout the experiment your eye movement patterns will be monitored.

This information will be retained until the completion of the study regardless of your eligibility. For those who participate in the study, this information will be retained for 7 years, which is the standard practice in the discipline. If you wish to continue please answer the series of questions below to verify your eligibility.

1. What is your first name?
2. What is your last name?
3. What is your email address?
4. What is your phone number?
5. Which is your preferred method of contact (email/phone/either)?
6. What is your age?
7. What is your gender (male/female)?
8. Do you have normal or corrected-to-normal vision?
9. Do you wear glasses or contacts when you drive?
10. Do you have an active driver’s license?
11. If so, what type of driver’s license do you have? (G1/G2/G/Other - please specify)
12. How many years of driving experience do you have?
13. How many times per week do you drive?
14. On average, how many kilometers do you drive per year?
15. Is English your first language?
16. Are you right handed?
17. Do you use your right foot to operate the accelerator and brake pedal?

18. If not, do you drive using both feet?
19. Are you color blind?
20. Have you experienced irreversible hearing loss?
21. Have you ever participated in an experiment involving a driving simulator?
22. If yes, what was the experiment like?
23. Do you regularly play video games involving driving?

Some people tend to experience a type of motion sickness, called simulator sickness, when driving the simulator. The next few questions are asked to help us identify if you might be prone to simulator sickness.

24. If you have used a driving simulator before, did you experience simulator sickness?
25. Do you frequently experience migraine headaches?
26. Do you experience motion sickness?
27. Do you experience claustrophobia?
28. Are you pregnant?

# Appendix B: Informed Consent Form

**TITLE:** Driver Perception-Response Time to Roadway Events and the Effect of Cognitive Distraction

**INVESTIGATORS:**

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You are being asked to take part in a research study. Before agreeing to participate in this study, it is important that you read and understand the following explanation of the proposed study procedures. The following information describes the purpose, procedures, benefits, discomforts, risks and precautions associated with this study. It also describes your right to refuse to participate or withdraw from the study at any time. In order to decide whether you wish to participate in this research study, you should understand enough about its risks and benefits to be able to make an informed decision. This is known as the informed consent process. Please ask the investigator to explain any words you don't understand before signing this consent form. Make sure all your questions have been answered to your satisfaction before signing this document. You can contact the Office of Research Ethics at ethics.review@utoronto.ca or 416-946-3273, if you have any questions about your rights as a participant.

**Purpose:**

This study investigates the effect of cognitive distraction on driver behaviour, in particular, driver response times to roadway events. As a participant you will be asked to operate a driving simulator and respond to a variety of events with and without the execution of a secondary cognitive distraction task. Eye movements will be recorded throughout the study. These recordings will be used to sub-divide the response time interval and investigate the effects of cognitive distraction at each stage.

**Procedures:**

This study contains three phases separated by 5 minute breaks. In the first phase you will receive an introduction to the experiment and the eye-tracking equipment will be calibrated. You will also be given an introduction and time to practice the cognitive distraction task. Finally, you will perform a practice drive to familiarize yourself with the simulator. In the second and third sessions you will operate the driving simulator and will be presented with a variety of roadway events. Your driving behaviour will be continuously recorded. The only difference between the second and third session is that in one of the sessions you will also be executing a secondary cognitive task while operating the simulator.

**Risks:**

The potential physical risks that are anticipated for participants in this study include simulator sickness. Some people tend to experience a type of motion sickness, called simulator sickness, when driving the simulator. During the experiment, you will be closely monitored for any signs of simulator sickness and are encouraged to notify the experimenter if you begin to feel uncomfortable or sick. If you start to feel sick at any time during the experiment you can withdraw from the study and will still be compensated as per the hourly rate.

We do not foresee any psychological, social, or legal risks for any participants.

**Benefits:**

The potential direct benefits to participants for their involvement in this study is that they will be able gain a better appreciation of how cognitive distraction affects their driving behavior in a safe environment. This may lead to overall safer real-world driving habits. Participants will also benefit from receiving compensation for their participation.

There are several benefits of conducting this study to the scientific community and society. This study will generate new insights on how drivers respond to roadway events and the effect of cognitive distraction on those responses. The use of eye movement recordings will help look at the effects of cognitive distraction on different stages of the response time interval. This information has practical benefits in the context of traffic safety by aiding in the development of distraction mitigation strategies and the design of safer in-vehicle technologies.

**Compensation:**

You will receive $15 per hour for your participation at the end of the study. This experiment should take about two hours.

**Confidentiality:**

All information obtained during the study will be held in strict confidence. You will be identified with a study number only. No names or identifying information will be used in any publication or presentations. No information identifying you will be transferred outside the investigators in this study.

**Participation:**

Your participation in this study is voluntary. You can choose not to participate or withdraw at any time.

**Questions:**

If you have any general questions about the study, please call the principal investigator, Pamela D'Addario at 647-328-0366, or email her at pamela.daddario@mail.utoronto.ca.

**Consent:**

I have had the opportunity to discuss this study and my questions have been answered to my satisfaction. I consent to take part in the study with the understanding that I may withdraw at any time. I have received a signed copy of this consent form. I voluntarily consent to participate in this study.

| ______________________ | ______________________ | ________________ |
|---|---|---|
| Participant Name (Please Print) | Signature | Date |

I confirm that I have explained the nature and purpose of the study to the participant names above. I have answered all questions.

| ______________________ | ______________________ | ________________ |
|---|---|---|
| Investigator's Name | Signature | Date |

# Appendix C: Secondary Distraction Task (1-back) Instruction Script

During one of your simulated driving sessions you will be asked to perform a cognitive distraction task while driving. The distraction task being used is called the 1-back task.

Each trial will consist of a set of 10 single digit numbers. 1-back simply means that as I read each list of 10 numbers, you are to repeat out load the number *BEFORE* the last number that you just heard. For example, if I were to say 3, you would say nothing, then if I said 2, you would say 3, then if I said 6, you would say 2, and so on.

Try to be as accurate as you can be. Let’s practice:

3 . . . . . 2 . . . . . 6 . . . . . 8 . . . . . 9 . . . . . 0 . . . . . 5 . . . . . 4 . . . . . 1 . . . . . 7

2 . . . . . 0 . . . . . 6 . . . . . 4 . . . . . 3 . . . . . 8 . . . . . 7 . . . . . 1 . . . . . 5 . . . . . 9

# Appendix D: Practice and Experimental Pre-Drive Scripts

## Practice Drive:

We are now going to start the practice drive. The drive has been designed such that you are not required to turn at any of the intersections. You simply have to follow the current road. There will not be any other moving vehicles present on the road during this practice drive and all traffic lights will be green. The purpose of this drive is for you to become familiar with the simulator. The drive will last a minimum of 5 minutes, but feel free to continue to drive as long as you need until you feel comfortable. I would like you to practice accelerating and braking, steering, and driving at various speeds.

Once you start to feel comfortable with the operation of the simulator, I would like you to practice driving at the posted speed limit of 70 km/h and staying in the left lane (or the lane closest to the centerline). This is what you will be asked to do for the following two experiment drives.

Partway through the practice drive I will play an audio file with several sets of single digit numbers and ask you to practice driving while performing the 1-back task you learned earlier. Do you remember how to perform the 1-back task? (If no, then re-read 1-back instruction script)

If during your drive you feel uncomfortable in any way, close your eyes, and let me know how you are feeling and I will stop the simulation.

## Drive A:

We are now going to start the first experimental drive. Similar to the practice drive, this drive has been designed such that you are not required to turn at any of the intersections. You simply have to follow the current road.

When the simulation starts you will be asked to put the car into Drive and move into the left lane. Throughout the drive, I ask that you stay in the left lane (or the lane closest to the centerline) and drive as close to the speed limit of 70 km/h as possible.

Please obey the general rules of the road, such as obeying all of the traffic light signals. You are asked *NOT* to pass any vehicles that may be present ahead of you at any point throughout the drive. Even if there are vehicles ahead of you, please try to stay as close to 70 km/h as possible. Your general driving behaviour, including speed, lane position, etc., as well as your eye movements will be continuously recorded. Your responses to certain typical roadway events, such as traffic lights changing states, will also be recorded. Please drive safely, as you normally would in the real world.

*If Distraction Drive:*

*Throughout the entire drive, you will be asked to perform the 1-back task. An audio file with single digit numbers will be played and your responses will be continuously recorded. Do you remember how to perform the 1-back task? (If no, then re-read practice script)*

If during your drive you feel uncomfortable in any way, close your eyes, and let me know how you are feeling and I will stop the simulation.

## Drive B:

We are now going to start the second and final experimental drive. The drive has again been designed such that you are not required to turn at any of the intersections. You simply have to follow the current road.

When the simulation starts you will be asked to put the car into Drive and move into the left lane. Throughout the drive, I ask that you stay in the left lane (or the lane closest to the centerline) and drive as close to the speed limit of 70 km/h as possible.

You are again asked *NOT* to pass any vehicles that may be present ahead of you at any point throughout the drive. Even if there are vehicles ahead of you, please try to stay as close to 70 km/h as possible. As you may have noticed from the first drive, there may be different hazards encountered throughout the drive. Please drive safely, as you normally would in the real world.

*If Distraction Drive:*

*Throughout the entire drive, you will be asked to perform the 1-back task. An audio file with single digit numbers will be played and your responses will be continuously recorded. Do you remember how to perform the 1-back task? (If no, then re-read practice script)*

If during your drive you feel uncomfortable in any way, close your eyes, and let me know how you are feeling and I will stop the simulation.

## Appendix E: Post-Experiment Questionnaire

Thank you for your participation in our simulator study. We ask that you complete the following questionnaire about yourself and your driving behaviors. Please note that all information collected will be held in the strictest confidentiality. Under no circumstances will personal data be revealed to any third party, for any purpose.

General Questions:

1. Your first name and last name
2. Compared with others your age, how would you rate your overall VISION? (If you wear glasses or contacts, rate your corrected vision when you are wearing them)

   Excellent  Good  Average  Fair  Poor
3. Compared with others your age, how would you rate your overall HEARING?

   Excellent  Good  Average  Fair  Poor
4. Compared with others your age, how would you rate your overall MEMORY?

   Excellent  Good  Average  Fair  Poor
5. On a scale of 1 to 10, with 1 being “very unsafe” and 10 being “very safe”, how safe a driver do you think you are?
6. In the past five years, how many times have you been stopped by a police officer and received a WARNING (but no citation or ticket) for a moving violation (i.e. speeding, running a red light, running a stop sign, failing to yield, reckless driving, etc.)?
7. In the past five years, how many times have you been stopped by a police officer and received a CITATION OR TICKET for a moving violation?
8. In the past five years, how many times have you been in a VEHICLE CRASH where you were the driver of one of the vehicles involved?

Susceptibility to Driver Distraction Questionnaire (SDDQ):

| **[Section 1: Distraction Engagement]** | Never | Rarely | Sometimes | Often | Very Often |
|---|---|---|---|---|---|

**9.** ***When driving, I:***

a. hold phone conversations.
b. manually interact with a phone (e.g., sending text messages).
c. adjust the settings of in-vehicle technology (e.g., radio channel or GPS).
d. read roadside advertisements.
e. visually dwell on roadside accident scenes if there are any.
f. chat with passengers if there are any.
g. daydream.

| [Section 2: Attitudes and Perceptions about Voluntary Distraction] | Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree |
|---|---|---|---|---|---|

**10.** ***I think it is all right to drive and:***

a. hold phone conversations.
b. manually interact with a phone (e.g., sending text messages).
c. adjust the settings of in-vehicle technology (e.g., radio channel or GPS).
d. read roadside advertisements.
e. visually dwell on roadside accident scenes if there are any.
f. chat with passengers if there are any.

**11.** ***I believe I can drive well even when I:***

a. hold phone conversations.
b. manually interact with a phone (e.g., sending text messages).
c. adjust the settings of in-vehicle technology (e.g., radio channel or GPS).
d. read roadside advertisements.
e. visually dwell on roadside accident scenes if there are any.
f. chat with passengers if there are any.

**12.** ***Most drivers around me drive and:***

a. hold phone conversations.
b. manually interact with a phone (e.g., sending text messages).
c. adjust the settings of in-vehicle technology (e.g., radio channel or GPS).
d. read roadside advertisements.
e. visually dwell on roadside accident scenes if there are any.
f. chat with passengers if there are any.

**13.** ***Most people who are important to me think it is all right for me to drive and:***

a. hold phone conversations.
b. manually interact with a phone (e.g., sending text messages).
c. adjust the settings of in-vehicle technology (e.g., radio channel or GPS).
d. read roadside advertisements.
e. visually dwell on roadside accident scenes if there are any.
f. chat with passengers if there are any.

| [Section 3: Susceptibility to Involuntary Distraction] | Strongly Disagree | Disagree | Neutral | Agree | Strongly Agree | Never Happens |
|---|---|---|---|---|---|---|

**14.** ***While driving, I find it distracting when:***

a. my phone rings.
b. I receive an audio alert from my phone (e.g., incoming text message).
c. I listen to music.
d. I listen to talk radio.
e. there are roadside advertisements.
f. there are roadside accident scenes.
g. a passenger speaks to me.
h. I daydream.

Manchester Driver Behavior Questionnaire (DBQ):

Nobody is perfect. Even the best drivers make mistakes, do foolish things, or bend the rules at some time or another. For each item below you are asked to indicate HOW OFTEN, if at all, this kind of thing has happened to you. Base your judgments on what you remember of your driving. Please indicate your judgments by selecting ONE of the options next to each item. Remember we do not expect exact answers, merely your best guess; so please do not spend too much time on any one item.

| | Never | Hardly Ever | Occasionally | Quite Often | Frequently | Nearly all the time |
|---|---|---|---|---|---|---|

**15.** ***How often do you do each of the following:***

a. Try to pass another car that is signalling a left turn.
b. Select the wrong turn lane when approaching an intersection.
c. Fail to ‘Stop’ or ‘Yield’ at a sign, almost hitting a car that has the right of way.
d. Misread signs and miss your exit.
e. Fail to notice pedestrians crossing when turning onto a side street.

**16.** ***How often do you do each of the following:***

a. Drive very close to a car in front of you as a signal that they should go faster or get out of the way.
b. Forget where you parked your car in a parking lot.
c. When preparing to turn from a side road onto a main road, you pay too much attention to the traffic on the main road so that you nearly hit the car in front of you.
d. When you back up, you hit something that you did not observe before but was there.
e. Pass through an intersection even though you know that the traffic light has turned yellow and may go red.

**17.** ***How often do you do each of the following:***

a. When making a turn, you almost hit a cyclist or pedestrian who has come up on your right side.
b. Ignore speed limits late at night or very early in the morning.
c. Forget that your lights are on high beam until another driver flashes his headlights at you.
d. Fail to check your rear-view mirror before pulling out and changing lanes.
e. Have a strong dislike of a particular type of driver, and indicate your dislike by any means that you can.

**18.** ***How often do you do each of the following:***

a. Become impatient with a slow driver in the left lane and pass on the right.
b. Underestimate the speed of an oncoming vehicle when passing.
c. Switch on one thing, for example, the headlights, when you meant to switch on something else, for example, the windshield wipers.
d. Brake too quickly on a slippery road, or turn your steering wheel in the wrong direction while skidding.
e. You intend to drive to a destination A, but you ‘wake up’ to find yourself on the road to destination B, perhaps because B is your more usual destination.

19. ***How often do you do each of the following:***

    a. Drive even though you realize that your blood alcohol may be over the legal limit.
    b. Get involved in spontaneous, or spur of the moment, races with other drivers.
    c. Realize that you cannot clearly remember the road you were just driving on.
    d. You get angry at the behaviour of another driver and you chase that driver so that you can give him/her a piece of your mind.