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The effect of cognitive distraction on perception-response time to unexpected abrupt and gradually onset roadway hazards

Pamela D'Addario[a,b,*], Birsen Donmez[b]

[a] MEA Forensic Engineers & Scientists, 22 Voyager Court South, Toronto, ON, M9W 5M7, Canada
[b] University of Toronto, Department of Mechanical and Industrial Engineering, 5 King's College Road, Toronto, ON, M5S 3G8, Canada

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ABSTRACT

Objective: A driving simulator study was conducted to investigate the effect of cognitive distraction on different stages of perception-response time (saccade latency, processing time, and movement time) to unexpected roadway hazards, both when the hazard onset is abrupt and when it is gradual.
Background: Prior studies, which typically focus on overall response times, have demonstrated that distraction, including cognitive distraction, leads to an increase in response times. Studies have also shown that response times differ depending on the type and location of the hazard. However, there is limited research into the effect of cognitive distraction for gradually developing hazards (e.g., a left-turn across path vehicle), as existing research primarily focuses on abrupt hazard onsets (e.g., lead vehicle braking).
Method: Twenty-four participants were presented with three different emergency roadway hazards, including one abrupt onset hazard (a pedestrian stepping onto the roadway from in front of a parked vehicle) and two gradually developing hazards (an oncoming vehicle turning left across the driver's path and a vehicle accelerating perpendicularly into the driver's path from the right). Half of the participants completed a delayed digit recall task (cognitive distraction condition), the other half did not (control condition).
Results: The left-turn across path hazard was particularly characterized by the long processing period (initiation of the saccade towards the hazard to initial motor response), whereas the pedestrian hazard was more notable for the shortest saccadic latency (hazard onset to the start of the saccade towards the hazard). Cognitive distraction led to a significant increase in brake reaction time for the right-incursion vehicle hazard, in processing time for the left-turn across path hazard, and a marginally significant increase in saccadic latency for the pedestrian and right-incursion vehicle hazards.
Conclusion: Hazard ambiguity due to gradual onset, such as with the left-turn across path hazard, appears to increase the processing duration before a response is executed, especially when distracted. Abrupt hazard onset appears to induce shorter saccadic latencies than gradual onsets likely due to a stronger attentional capture property. However, cognitive distraction may increase saccadic latencies for these types of hazards.

1. Introduction

Driving requires the execution of many complex abilities, and failures in these abilities can lead to devastating results (Hancock and Scallen, 1999). Although crash rates are declining (NHTSA U.S. Department of Transportation, 2012; Transport Canada, 2013), motor vehicle collisions are still a leading cause of death and injury. About 1.24 million people are killed due to motor vehicle collisions globally each year and an additional 20–50 million sustain non-fatal injuries (World Health Organization, 2013). Driver error, including failures in hazard perception and response, is a commonly reported major cause of traffic collisions (Horswill and McKenna, 2004; Smiley and Brookhuis, 1987; Wang et al., 1996).

Drivers' ability to perceive and respond to a hazard is bound by their 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 and Hollands, 2000). While operating a motor vehicle, there are many sources that compete for mental and physical resources, including those related to the primary driving task and a variety of secondary activities (Hurts et al., 2011). These secondary activities are commonly referred to as driver distractions, which can be in various forms, including visual, auditory, biomechanical, and cognitive (Ranney et al., 2000). These different forms do not occur in pure isolation from one another and all

* Corresponding author at: MEA Forensic Engineers & Scientists, 22 Voyager Court South, Toronto, ON, M9W 5M7, Canada.
E-mail addresses: pamela.daddario@meaforensic.com (P. D'Addario), donmez@mie.utoronto.ca (B. Donmez).

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distractions can be said to have a cognitive component (NHTSA, 2010).

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. Cognitive distraction has been shown to result in a delay in driver response times (Bruyas and Dumont, 2013; Caird et al., 2008). The effects were commonly examined 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 the delays occur. As will be discussed below, there is not much research on the different stages of driver response time for roadway hazards in general. And as for cognitive distraction, Recarte and Nunes (2003) is the only study we could find investigating different response time stages; however, the authors used a light stimulus that the participants had to respond to rather than a more ecologically valid form of road hazard. The focus of our research is on the effects of cognitive distraction on the ability to perceive and respond to different emergency roadway hazards, with the response time broken down into substages corresponding to the human information processing model.

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 (Olson, 1989; Smiley and Caird, 2007). 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 et al., 1984; Shinar, 2007). Perception-response time can also inform the design of advanced driver assistance systems to increase hit and correct rejection rates and minimize false alarms and misses. For example, an understanding of which stages of the information processing may be impaired in a given context and to what extent (e.g., perception of peripheral hazards during a cell-phone conversation) can guide designers to deliberately support those particular stages (e.g., a pedestrian detection alert). There is also considerable interest in driver response times from accident investigators who are frequently required to assess a driver's actions leading up to a collision for litigation purposes. Understanding how cognitive distraction delays response time can help establish if it contributed to causing a collision.

Theoretically, perception-response time is defined by a series of stages: detection, identification, decision, and response (Olson, 1989; Olson and Sivak, 1986), which are very closely related to the stages of human information processing (Wickens and Hollands, 2000). Practically, however, perception-response time is most commonly divided into two stages: perception time (which starts when a stimulus is presented and ends at the onset of foot motion) and movement time (which starts at the onset of foot motion and ends when the foot touches the brake pedal).

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 to start the perception time interval. 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 starting points such as when a vehicle first starts to accelerate into a driver's path (Lechner and Malaterre, 1991; Mazzae et al., 2003; McGehee et al., 1999) or when a pedestrian first steps onto the roadway (Broen and Chiang, 1996). These starting points seem to correspond with the first opportunity the driver likely has to identify the object as a hazard; however, they are somewhat arbitrary and do not provide any information about when a driver actually first detects the hazard. When applying these research results for accident investigation purposes, this limitation is typically overcome by adopting a starting point analogous to the one used in a given study. 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, and fog (Muttart, 2004; Olson and Farber, 2003), or when there is ambiguity as to when an object or event transitions from being a non-hazard to a hazard (e.g., left-turn across path vehicle).

Based on some of the more recent uses of eye movement recordings in the driving environment and in the context of hazard perception (Huestegge et al., 2010; Kledus et al., 2010; Velichkovsky et al., 2002), it has been shown that eye movements have 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. For example, Kledus et al. (2010) conducted an on-road study where driver eye movements were used to try and determine the moment an object is perceived under nighttime conditions; the change in gaze direction towards the object could often be directly linked to a subsequent avoidance response. Ciceri et al. (2013) used eye-movement recordings in a driving simulator to examine the effects of different roadside features (e.g., signage) on the time from the onset of a pedestrian hazard (start of motion) up to a shift of the driver's gaze direction toward the pedestrian, similar to the saccade latency interval used in our study, which will be defined in more detail later.

As noted earlier, Recarte and Nunes (2003) was the only study that we could identify which considered how different perception-response stages are affected by cognitive distraction; however, the authors did not utilize an ecologically valid roadway hazard. A better understanding of the effects of cognitive distraction on different stages of perception-response time for emergency roadway hazards can provide insight to researchers, government, and manufacturers to design better traffic systems. To address this research gap, our study made use of eye movement recordings and motor responses in a driving simulator to divide perception-response time into three disjoint and exhaustive stages: saccade latency, processing time, and movement time. Driver perception-response times to three different roadway hazards were measured, including an oncoming vehicle turning left across the driver's path, a pedestrian stepping onto the roadway from in front of a high-sided parked vehicle, and a vehicle accelerating perpendicularly into the driver's path from the right. The hazards presented to the drivers were designed such that they warranted emergency avoidance maneuvers. The effects of cognitive distraction on the individual perception-response time stages were evaluated for each hazard.

The hazards used in our experiment were selected as they are common events that drivers experience and can be categorized as abrupt (pedestrian) and gradual onset (left-turn across path vehicle and accelerating right-incursion vehicle) events. According to the hazard classification framework proposed by Pradhan and Crundall (2016), the gradual onset hazards in our study correspond to hazards with a behavioral precursor (or a clue), where the precursor (i.e., vehicles that eventually move into a driver's path) is the same object as the hazard but has not yet become hazardous, whereas the abrupt onset pedestrian hazard corresponds to a hazard with an environmental precursor, such that the high-sided vehicle that the pedestrian appeared from in front of could identify a location of the scene that may hide hazards. Underwood et al. (2013) found faster driver perception-response times to abrupt onset hazards than gradual onsets, likely due to their ability to readily capture attention. Further, gradual onset hazards likely require higher levels of situation awareness on the precursor (which is behavioral rather than environmental), as the driver has to not only monitor but also anticipate how the hazard develops. Given that hazard onset can affect response times, we factor the abruptness of hazard onset in the interpretation of our results.

2. Methods

2.1. Participants

Twenty-four participants (11 male and 13 female) aged 25–40 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 email

Fig. 1. MiniSim driving simulator utilized in the experiment; the faceLAB cameras are mounted on the dashboard on both sides of the instrument panel.

listservs and posters at the University of Toronto and online advertising. 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 C$15/hour.

2.2. Apparatus

Participants operated a PC-based, quarter-cab MiniSim^{TM} driving simulator developed by the University of Iowa's National Advanced Driving Simulator (Fig. 1). The simulator uses three 42-inch 1024 × 768 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. Driving data was recorded at 60 Hz.

A faceLAB^{TM} 5 eye-tracking system, developed by Seeing Machines, was integrated into the simulator. This 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. These data were also recorded at 60 Hz. EyeWorks software, developed by EyeTracking Inc., recorded the simulator center screen video at 20 Hz with the gaze data from the faceLAB system overlaid. Mean angular error was reported by the system for each participant during calibrations; this metric had an average of 0.9 degrees across participants, with a standard deviation of 0.4, minimum of 0.3, and maximum of 2.6 degrees.

2.3. Experimental design

Each participant completed one experimental drive with three emergency hazard events that were presented in the following order: left-turn across path, pedestrian, and right-incursion. Half of the participants were randomly chosen to complete their drive while simultaneously performing a cognitive secondary task. The experiment was a 2 × 3 mixed factorial design with task condition (control and distraction) as a between-subjects factor and event type (left-turn across path, pedestrian, and right-incursion) as a within-subject factor.

2.4. Cognitive distraction task

A delayed digit recall (1-back) task was used for the cognitive distraction condition. Participants were required to listen to several prerecorded series of single-digit numbers and respond verbally with the digit that was presented one position previously or 1-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 s. There was a brief pause of about 7 s between each series of 10. The 1-back task procedure used was based on the research and protocol developed by the MIT AgeLab (Mehler et al., 2009; Reimer, 2009). The participants assigned to the distraction condition performed the 1-back task all throughout their experimental drive.

2.5. Description of roadway hazards

The roadway environment was an urban route with several parked vehicles and buildings lining the streets. 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. They were presented with three unexpected roadway hazards that warranted an emergency avoidance response in the following order: (1) left-turn across path hazard at an intersection, (2) pedestrian stepping onto the roadway mid-block from in front of a parked vehicle on the right, (3) vehicle accelerating perpendicularly into the driver's path from the right at an intersection. Participants were also presented with a variety of other familiar roadway events throughout the drive, such as lead vehicle braking events and vehicles changing lanes ahead of the subject's vehicle.

2.5.1. Left-turn across path hazard

The left-turn across path hazard consisted of an oncoming vehicle turning left across the path of the subject's vehicle at a traffic-signal controlled intersection. There were two through lanes and a dedicated left-turn lane in either direction at the intersection, with the subject's vehicle in the left through lane (Fig. 2). On approach to the intersection, participants followed a lead vehicle that was programmed to maintain a time gap of 3.5 s. 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 s, the left-turning vehicle started to accelerate across the path of the subject's vehicle at a constant rate of 2.0 m/s^2, which is within the range of left-turn acceleration rates found in the literature (Happer et al., 2009; Yan et al., 2007). TTA was calculated based on the time it would take the front of the subject's vehicle to reach the projected collision point (in this case where its path and the left-turning vehicle's path would intersect) if it continued at a constant speed.

2.5.2. Pedestrian hazard

The pedestrian hazard occurred at a mid-block location, without 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 s. At a time-to-arrival (TTA) of 2.5 s, a pedestrian stepped out from in front of a large parked vehicle into the subject vehicle's path (Fig. 3). 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 et al., 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.

2.5.3. 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

Fig. 2. Example screen captures of simulator center screen display on approach to the intersection with the left-turn across path hazard (time progresses from top to bottom image). The green dots and green lines represent the participant's gaze location and gaze trail, respectively (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Fig. 3. Example screen captures of simulator center screen display on approach to the pedestrian hazard (time progresses from top to bottom image). The green dots and green lines represent the participant's gaze location and gaze trail, respectively (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

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 (Fig. 4). When the TTA was 3.5 s, 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). 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.

2.6. Dependent variables

The majority of the dependent variables were directly related to the participant's perception-response time and its subcomponents, as illustrated in Fig. 5. These variables included:

- Saccade latency (SL) started at hazard onset, defined as the start of motion of each hazard, and ended at the start of the first continuous eye movement towards the hazard after onset (i.e., the end of the previous fixation and start of the first saccadic movement towards the hazard). A similar measure was used by Ciceri et al. (2013) and Recarte and Nunes (2003), although termed time to first fixation in Ciceri et al. (2013) and perception time in Recarte and Nunes (2003) with both ending when the stimulus was first glanced at.
- Processing time (PT) started at the end of SL and ended when the driver first started to release the accelerator pedal. Accelerator release time (ART) was the combination of SL and PT. If a participant had already released the accelerator pedal before hazard onset, both PT and ART were treated as missing values. This definition is slightly different than the SAE J2944 (2015) standard which came out after our study was completed. The standard ends ART with complete pedal release.
- Movement time (MT) was the time between the start of the accelerator pedal release and the initial contact with the brake pedal, as previously used by Olson and Sivak (1986) and Fitch et al. (2010).
- Brake reaction time (BRT) was from hazard onset up until initial brake pedal contact and follows the SAE standard (2015).
- Steer reaction time (SRT) was from hazard onset up until the start of an abrupt shift in the steering wheel angle, with a minimum steering rate of 15 degrees/second and a resulting overall change in steering wheel angle of 10 degrees. The definition is in line with the SAE standard on steering reaction time but has further constraints as it focuses on an abrupt steering response.

With the exception of the start of the first saccadic movement towards the hazard, which was extracted from manual video coding of the

Fig. 4. Example screen captures of simulator center screen display on approach to the right-incursion hazard (time progresses from top to bottom image). The green dots and green lines represent the participant's gaze location and gaze trail, respectively (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

eye-tracking data by the first author, all of the start and end points of the dependent variables introduced above were extracted from the simulator output parameters.

2.7. Procedure

Participants first reviewed and signed an informed consent document. A brief overview of the experiment and equipment was given. The eye-tracking system was calibrated. Each participant was then provided with instructions and time to practice the 1-back task. After practicing the 1-back task, each participant undertook a practice drive to familiarize themselves with the operation of the simulator in the absence of any surrounding traffic. The practice drive lasted a minimum of 5 min, but participants were free to continue driving until they felt comfortable. Partway through the practice drive, participants also practiced performing the 1-back task while driving. The roadway environment for the practice drive was also an urban route with several parked vehicles and buildings lining the streets.

Following the practice drive, participants were given a short break during which they were monitored for any signs of simulator sickness. The experimental drive was then started, and took approximately 15 min. Participants were told that their driving behaviour and eye movements would be 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 truly unexpected responses, participants were not told that the true intention of the experiment was to measure their response times to emergency roadway hazards.

3. Results

The effect of distraction on the individual stages of the brake reaction time, as well as the overall brake reaction time was analyzed. Mixed linear models were built using PROC MIXED in SAS 9.3. Although participants were instructed to drive at 70 km/h, there were speed variations. Therefore, participant speed at hazard onset was included as a covariate in the models. In addition to the analysis of main effects, planned contrasts were performed using the ESTIMATE statement to compare differences between task conditions for each event type. Descriptive statistics are presented in Table 1. Steer reaction time (SRT) is only reported for the left-turn across path hazard, as there were few instances of steering response to the other two hazards.

3.1. Saccade latency (SL)

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 saccade latency, with SLs on average 0.23 s longer while executing the 1-back task (Fig. 6). Planned contrasts conducted across event types revealed significantly shorter saccade latencies for the pedestrian hazard than the left-turn across path hazard ($t(35) = -3.74$, $p = .0007$) and the right-incursion vehicle hazard ($t(35) = -3.56$, $p = .001$), with an average decrease of 0.44 and 0.41 s, respectively. The effect of task type on saccade latency was marginally significant for the pedestrian ($t(35) = -1.87$, $p = .07$) and right-incursion vehicle hazards ($t(35) = -1.85$, $p = .07$), with longer saccade latencies while performing the 1-back task by an average of 0.28 and 0.29 s, respectively.

3.2. Processing time (PT)

There was a significant main effect of event type on processing time

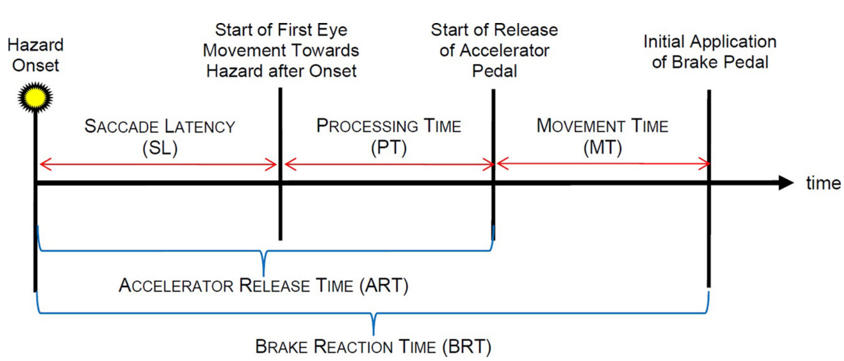

Fig. 5. Dependent variables: Subcomponents of driver perception-response time.

Table 1
Descriptive statistics for each of the three event types, separated by task condition.

Event Type	Task Condition	Control						Distraction					
	Dependent Variables (seconds)	SL	PT	MT	ART	BRT	SRT	SL	PT	MT	ART	BRT	SRT
Left-Turn Across Path 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	5	11	9	9	9	9	2
	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	3	10	8	8	8	8	4
	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[a]	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	

[a] Negative value means the subject began to release the accelerator before the start of the first saccadic eye movement towards the hazard.

(F(2,28) = 19.58, $p < .0001$). Processing time for the left-turn across path hazard was found to be significantly longer than for the pedestrian hazard (t(28) = 5.92, $p < .0001$) and the right-incursion vehicle hazard (t(28) = 4.65, $p < .0001$), by an average of 0.55 and 0.45 s, respectively (Fig. 6). Performing the 1-back task resulted in significantly longer processing times for only the left-turn across path hazard (t(28) = -2.41, p = .02), with an average increase of 0.32 s.

3.3. Movement time (MT)

There was a significant main effect of event type on movement time (F(2,28) = 3.54, p = .04) (Fig. 6). Movement time for the left-turn across path hazard was significantly longer than for both the pedestrian (t(28) = 2.42, p = .02) and the right-incursion vehicle hazards (t(28) = 2.08, p = .047), with average increases of 0.17 and 0.15 s, respectively. There was a marginally significant effect of task condition on movement time for the left-turn across path hazard (t(28) = 1.99, p = .056), where movement times were on average 0.20 s quicker while performing the 1-back task.

3.4. Brake reaction time (BRT)

There was a significant main effect of event type (F(2,28) = 88.49, $p < .0001$) and task condition F(1,22) = 5.89, p = .02) on brake reaction time, with an average increase in BRT of 0.26 s with cognitive distraction (Fig. 6). The highest BRT was observed with the left-turn across path hazard, followed by the right-incursion vehicle hazard, and then the pedestrian hazard. BRTs to the pedestrian hazard were significantly lower than BRTs to the left-turn across path 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 s, respectively; BRTs to the left-turn across path hazard were significantly longer than to the right-incursion vehicle hazard, with an average increase of 0.64 s (t(28) = 6.67, $p < .0001$). Planned contrasts looking at the effect of task type revealed that BRTs to the right-incursion vehicle hazard were significantly longer while performing the 1-back task (t(28) = -2.17, p = .04) by an average of 0.37 s. The effect of distraction on BRTs to the left-turn across path hazard was marginally significant (t(28) = -1.74, p = .09), with an average increase of 0.24 s.

3.5. Steer reaction time (SRT) – left-turn across path hazard

An analysis of steer reaction times was conducted only for the left-turn across path hazard due to the low number of steering responses to the other hazards. An independent t-test was conducted to compare the control and distraction conditions, revealing no significant effect (t(14) = -0.52, p = .61). The steer direction in response to the left-turn across path hazard was primarily towards the right, or away from the encroaching left-turning vehicle. Of the participants who steered in response to the left-turn across path hazard, over 80% chose to steer to the right and in all but two cases (about 88%) also braked.

4. Discussion

In a driving simulator study, we investigated the effect of cognitive distraction on driver perception-response times to a variety of emergency roadway hazards, including both abrupt and gradual onset hazards. Eye movement recordings and motor responses were used to divide perception-response time into three disjoint stages, with the effect of cognitive distraction assessed at each stage, as well as for the total brake reaction time. Our approach was consistent with Recarte and Nunes (2003), but we utilized more ecologically valid roadway stimuli compared to the light stimuli used in their study. Using actual road hazards in place of simpler visual stimuli also gave us the opportunity to investigate different hazards, in particular in terms of their gradual vs. abrupt onset. Varying effects were found across different stages and for different types of hazards; investigating response time stages separately in addition to in combination can provide a better understanding as to how information is processed in the driving environment.

A large body of previous research has shown that perception-response time is dependent on a variety of factors, including the type of stimuli (Green, 2000; Muttart, 2005). Not surprisingly, we also found a significant main effect of event type on total brake reaction time and almost all response time stages; hence, the participants responded differently to the different hazards presented to them. Mean saccade latencies for the pedestrian hazard were significantly shorter than for the left-turn across path hazard 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 and Jonides, 1984). The pedestrian stepped onto the roadway from in front of a parked vehicle and was not visible to participants on approach. This abrupt

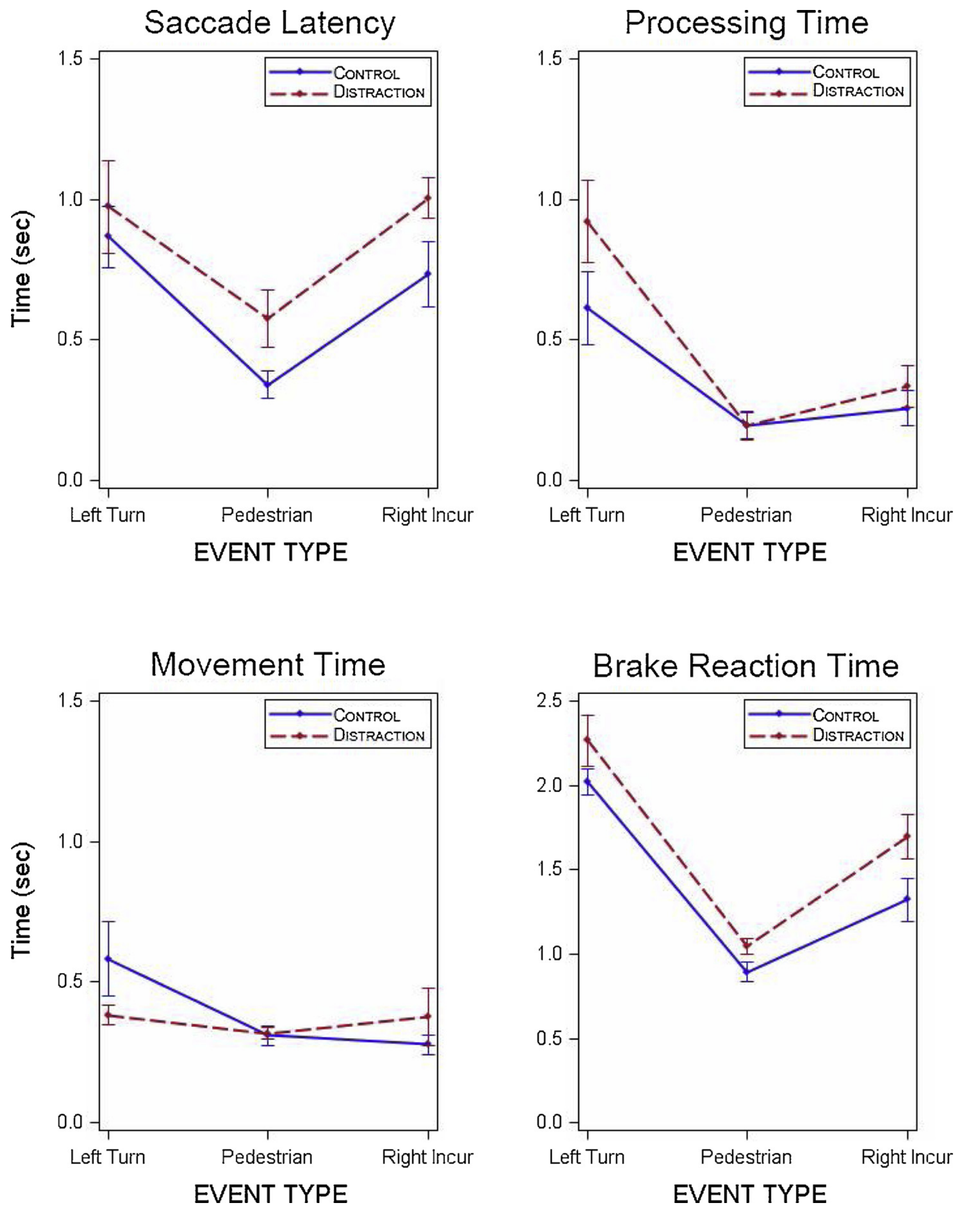

Fig. 6. Mean saccade latency, processing time, movement time, and brake reaction time by event type and task condition (error bars represent standard errors).

appearance likely captured driver's visual attention more readily than the gradual onset of motion of the other two hazards. We also considered the possibility that the highly salient white truck that the pedestrian emerged from in front of captured subject's attention, even before the pedestrian became visible. However, the eye-tracking data shows that in only one case was the participant already looking at the white truck when the pedestrian emerged. Another potential contributing factor for the shorter saccade latencies to the pedestrian hazard is the shorter time to arrival (TTA) at hazard onset. The pedestrian emerged from in front of the parked truck with a TTA of 2.5 s, whereas the TTA at the onset of the left-turn across path and right-incursion hazards were 3.5 s. Research has found that shorter TTA's lead to shorter response times (Mazzae et al., 2003; Wang et al., 2016). Processing and movement times in response to the left-turn across path hazard were found to be significantly longer than for the pedestrian and right-incursion vehicle hazards. 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 it would take longer to determine if a collision is imminent, and then choose how to respond for this type of hazard.

The average unexpected brake reaction times found in our study for the control (no distraction) condition are generally in agreement with the results of other studies. For example, 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 s (Coley et al., 2008), 1.1 s (Barrett et al., 1968), and 1.3 s (Broen and Chiang, 1996). A test track study of driver responses to a pedestrian emerging from behind a curtain on the driver's right side found average brake reaction times of about 1.2 s for similar TTA's used in our study (Jurecki and Stancyzk, 2014). The mean brake reaction time to the pedestrian hazard for the control condition in our study was 1.0 s, generally in line with these other pedestrian hazard studies. Our mean brake reaction time finding for the left-turn across path hazard was 2.0 s, a value shorter than the 2.7 s reported in a recent simulator study (Attalla et al., 2018) that used a longer TTA for the event, which likely created this difference. A simulator study of an unexpected vehicle right-incursion at an intersection (McGehee et al., 1999) found a mean brake reaction time of 1.1 s. The McGehee (1999) simulator study was replicated on a test track (Mazzae et al., 2003), with a mean brake reaction time of 1.5 s on dry pavement. The mean brake reaction time found in our study for the right-incursion vehicle hazard was 1.3 s for the control condition, which is in the middle of the range of the two previous studies. It should be noted that after the presentation of the first emergency hazard in the current study, expectation of any subsequent hazards may have increased, potentially reducing response times. Future research should investigate these hazards in a counterbalanced order.

When looking at the effect of performing a cognitive secondary task on the different stages of perception-response time, the greatest effects were observed for saccade latency, with an overall average increase of 0.23 s. The overall average increase in total brake reaction times while performing the cognitive secondary task was 0.26 s. This average increase is generally consistent with those reported by a meta-analysis conducted by Caird et al. (2008). As for different event types, similar results were found for the pedestrian and right-incursion vehicle hazards. There was a marginally significant increase in saccade latency while performing the 1-back task, but no significant increases in processing or movement times suggesting that cognitive distraction likely leads to delayed detection of these particular hazards, but once detected there may not be an effect on decision and response execution.

For the left-turn across path hazard, there was no significant increase in saccade latency with distraction. 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 and Nunes, 2000; Reimer, 2009). Since the left-turn across path hazard was nominally directly ahead of the subjects, the time taken to first look at the hazard might not be affected by this cognitive visual tunneling. However, there was a significant increase in processing time, with a mean increase of 0.32 s, and a marginally significant decrease in movement time. There appears to be a delay in cognitively identifying the vehicle as a hazard, 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. The left-turn across path 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. This gradual onset hazard, or hazard with a behavioral precursor, likely required higher levels of situation awareness on the precursor to monitor and anticipate the developing hazard. 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 transitioned from a potential to an immediate hazard requiring an avoidance response. Future research should investigate when this transition from a potential to an urgent hazard occurs and its consistency across drivers. Although left-turning vehicle crashes at intersections are very common, there is very limited research available regarding driver responses to left-turning vehicles. More research is needed to investigate response time to left-turning vehicles under varying conditions.

Although interesting statistical findings emerged from our study, our sample size was limited and can in part explain the marginally significant or nonsignificant results. It is also important to note that this research used eye movements to determine when a hazard is first looked at; 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. An interesting measure to consider in future studies is subject's dwell time on the hazard prior to accelerator release and its effects on response time. Further, this study focused specifically on driver response times to daytime roadway hazards presented within about ± 10 degrees of the forward roadway. The effect of hazard eccentricity on perception-response times should be investigated in the future by calculating the angle between where subjects are looking during hazard onset and the location of the hazard itself. Future studies can also look at hazards emerging from further out in the periphery, as well as other variations, such as nighttime conditions, different age groups, and different distraction tasks. The results should also be validated with on-road studies.

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