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The Long Road Home from Distraction: Investigating the Time-Course of Distraction Recovery in Driving

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Abstract

Driver distraction is a leading cause of accidents. While there has been significant research examining driver performance during a distraction, there has been less focus on how much time is required to recover performance following a distraction. To address this issue, participants in the current study completed a simulated 40-min drive while being presented with distractions. Distractions were followed by a visual Detection Response Task (DRT) to assess participants' resource availability and potential capacity to respond to hazards, as well as continuous measures of driving performance including their ability to maintain a consistent speed and lane position. We examined recovery for a 40s period following three types of distraction: cognitive only, cognitive+visual, and cognitive+visual+manual. Since safe driving requires cognitive, visual, and manual resources, we expected recovery to take longer when the distraction involved more of these resources. Consistent with this, each additional level of distraction further slowed DRT response times and increased speed variability during 0-10s post-distraction. However, DRT accuracy was equally impaired for all conditions during 0-20s post-distraction, while lane position maintenance from 0-10s post-distraction was only impaired when the distraction included a manual component. In addition, while participants in all three conditions exhibited some degree of post-distraction impairment, only those in the cognitive+visual+manual condition reduced their speed during the time when distracted, suggesting drivers show limited awareness of the potential persistent consequences of distraction.

Keywords: Driver safety; Distraction; Simulation; Detection Response Task

1. Introduction

A driver is considered to be distracted when their resources are directed away from the primary task of safely controlling a vehicle. Driver distraction accounts for a significant proportion of all road accidents, with U.S statistics from 2014 – 2015 showing that nearly 10% of driving fatalities involved distracted drivers (National Highway Traffic Safety Administration, 2016). Drivers are increasingly at risk of being distracted by technology in the vehicle, both from personal devices (e.g. phones) and in-vehicle systems (e.g. entertainment, navigation, communication). Such distractions may lead drivers to look away from the road, become inattentive, and/or remove their hands from vehicle controls as they continue to drive.

While significant research efforts have been devoted to understanding the effects of distraction on driver performance and safety *during* the time that the driver is distracted (for a review see Young & Regan, 2007), very little work has investigated how quickly and effectively drivers can recover *after* distraction. Distraction recovery is an important issue, as numerous studies in the basic experimental psychology literature have shown that switching tasks, such as when a driver shifts between processing the distracting information and controlling their vehicle, can lead to substantial and long-lasting perceptual and cognitive costs (Di Lollo et al., 2005; Enns et al., 2001; Monsell, 2003; Rogers & Monsell, 1995; Visser et al., 2004). Such costs, in turn, might be expected to impair driver performance for a significant period before resources can be reallocated.

1.1. Detection Response Task

Several driving studies have found evidence consistent with this expectation. For example, Reyes and Lee (2008) examined hazard detection using a modified visual Detection Response Task (DRT) that required participants to detect a cyclist in a simulated driving environment. DRT performance has been shown to index both driver's general resource availability (Bowden et al., 2017; Miura, 1986; Patten et al., 2006; van Winsum, 2018) and their capacity to respond quickly and accurately to an unexpected hazard in the driving environment (Strayer et al., 2013). Reyes and Lee (2008) distracted drivers with a cognitive task for 1-4 minutes and compared their DRT performance with undistracted driving both during and after the cognitive task. They found that the cognitive distraction reduced drivers' ability to detect the cyclist during the distraction, and that this impairment persisted into the one-minute period after the distraction ended.

Strayer et al. (2016, 2017) also used a DRT to measure recovery from cognitive distraction (in this case, issuing voice commands to a digital assistant) in real world driving. While Reyes and Lee (2008) were only able to make the general conclusion that the distraction induced impairment persisted into the one-minute post-distraction period, Strayer et al. sorted their DRT response time data according to how long after the distraction had ended each DRT target was presented. This more fine-grained analysis indicated that DRT response times were significantly elevated for 18 to 27s post-distraction.

The purpose of the current study was to replicate and expand upon the findings of Reyes and Lee (2008) and Strayer et al. (2016, 2017) to further understand the recovery of driver performance and safety following distraction. There are two main areas where the current research expands on previous studies. Firstly, while previous research only used cognitive distractions, in the current study we assess recovery from distractions that required a combination of visual, manual, and/or cognitive resources in order to better simulate the demands of a realistic driving experience. Secondly, while past studies focused on DRT response time recovery, the current study also looks at the recovery of other safety-critical driving behaviors including lane keeping and speed control.

1.2. Visual, Manual, and Cognitive Resources

As reviewed above, research examining the time course of recovery from distraction has focused predominantly on cognitive distraction. However, while this is no doubt a key source of impairment, there are a range of different secondary tasks that can distract drivers. These tasks can be broadly categorized as visual, manual, and cognitive components of the distraction (Boehm-Davis & Remington, 2009). The visual component involves the driver looking away from the road, mirrors, or other safety-relevant vehicle displays such as the speedometer, in favor of the secondary task (e.g. looking at a billboard advertisement). The manual component involves physical distraction, where the driver moves their hands (or conceivably feet) away from the vehicle controls to perform a secondary task (e.g. drinking a coffee or texting). Lastly, the cognitive component involves mental distraction, where the driver has allocated cognitive resources (attention, memory, etc.) away from driving to perform a secondary task (e.g. mentally preparing for a meeting at work).

With these three components in mind, the first aim of the present work is to determine whether post-distraction impairment is greater, and/or recovery from distraction slower, when the secondary (distracting) task shares more resource requirements with the primary (driving) task. Multiple resource theory suggests that some secondary tasks will interfere more with a concurrent primary task than others based on competition for limited resources (Wickens, 2002). For example, greater interference is predicted when a secondary task shares the same sensory modality as the primary task since both require access to the same limited pool of resources. Given that the primary task of driving safely involves a combination of cognitive, visual, and manual resources, we would expect recovery to take longer when the secondary task taps into more of these resources. To test this, participants completed a simulated driving task while allocated to one of three different distraction conditions: cognitive-only, cognitive+visual, and cognitive+visual+manual. We hypothesized that each additional level of distraction would increase the magnitude of post-distraction performance impairment and/or slow the post-distraction recovery of performance.

1.3. Continuous Performance Measures

The second aim of the current study was to more thoroughly investigate the specific aspects of driver performance that are impaired following distraction. As mentioned above, the DRT has been used in past studies as it provides a useful indicator of drivers' available cognitive resources and potentially their capacity to respond to hazards. However, the DRT differs in many respects from other driving tasks that must be continuously performed in order to ensure safe driving. These other driving tasks are more likely to be carried out concurrently with the distraction, rather than being suspended completely as is assumed by models that conceptualize distractions as series of brief primary task interruptions (e.g. Altmann & Trafton, 2002). For example, maintaining a consistent speed and lane position, or updating situation awareness of the environment, are all likely to continue during periods of distraction because of the rapidly-changing nature of the driving environment.

There is evidence in the driver distraction literature that cognitive distractions impair performance on some of these continuous measures. Cognitive distractions, such as talking on a phone or to a passenger, have been shown to reduce available resources during the period when the driver is distracted to the detriment of both speed control (Harbluk et al., 2007; Horberry et al., 2006; Rogers et al., 2011) and lane position control (see Choudhary & Velaga, 2017 for a summary). However, these studies did not test whether there would also be a residual impairment on these continuous measures after distraction has ended, and if so, how long such impairments persist for. To investigate this issue we examined lane-keeping control and speed control both during distraction and post-distraction.

1.4. Summary and Hypotheses

To summarize, the current study investigates the recovery of driver performance and safety following distraction by examining DRT response time as well as the continuous driving measures of lane keeping and speed control. The current study assesses recovery from distractions requiring a combination of visual, manual, and/or cognitive resources. We examine the extent to which each additional resource required by the distraction increases the magnitude of the post-distraction performance impairment and/or slows the post-distraction recovery of performance. Specifically, we predicted that the cognitive condition would have more costs compared to baseline, the cognitive/visual condition would have more costs than the cognitive condition, and the cognitive/visual/manual condition would have more costs than the cognitive/visual condition.

2. Method

2.1. Participants

One-hundred and sixty five undergraduate students from the University of Western Australia participated in exchange for course credit, with 55 participants allocated to each distraction condition: cognitive (Cog), cognitive/visual (Cog+Vis), cognitive/visual/manual (Cog+Vis+Man). Participants received an AUD$3-5 bonus at the end of the experiment as a performance incentive. Participants were required to have at least a probationary driver's license. Eight participants were excluded and replaced, seven for technical failures and one for not completing the experiment.

Table 1. Participant details including medians with standard deviations in brackets

Condition	Age (years)	Gender	Years licensed
Cog	19 (3.7)	M = 20, F = 35	1.5 (3.4)
Cog+Vis	19 (4.7)	M = 25, F = 30	1.5 (5.0)
Cog+Vis+Man	19 (6.4)	M = 25, F = 30	1.5 (5.0)
Total (N = 165)	*19 (5.1)*	*M = 70, F = 95*	*1.5 (4.9)*

2.2. Stimuli

2.2.1. Driving simulator. Simulators have been shown to be a valid proxy for real world driving, with similar patterns of driving performance results found for both instrumented vehicles and simulators (Reed & Green, 1999; Underwood et al., 2011). The driving simulator used Oktal's SCANeR Studio software (version 1.4) and consisted of three parallel 27 inch monitors housed in an Obutto cockpit, supporting a 135° wide-field video display. The central monitor represented the front windscreen view and included a digital speedometer (Figure 1). Two side mirrors and a central rear-vision mirror were also presented. Participants were seated approximately 85 cm from the central monitor and controlled the simulated automatic transmission vehicle using a Logitech computer steering wheel and pedal set. The simulated vehicle and environment were configured for right-hand drive vehicle and road conditions. Participants drove along a continuous four-lane road and did not to turn off the main road at any time. They were instructed to keep to the far-left lane of the road and that no other vehicles would appear in their lane. The other three lanes had light density traffic (~5 vehicles per minute). The participants' vehicle speed and position data was continuously recorded at 1000 Hz and down-sampled to 50 Hz for further analysis.

Figure 1. The left panel shows the driving simulator with the tablet device positioned next to the steering wheel. The right panel shows the central monitor view of the driving environment with rear-view mirror and digital speedometer displayed. A DRT target is presented above the horizon on the left.

2.2.2. Distracting task. The distracting task was presented on a Samsung Galaxy tablet (8-inch display) mounted in the cockpit to the right of the steering wheel and within reach of the participant. A headset with microphone was worn by participants to receive distracting task questions and record verbal responses. A custom-built Android application presented single digit addition problems (e.g. “3 + 7”) as the distracting task (Harbluk et al., 2007). Problem presentation and response differed depending on the condition. The end of each one-minute distraction was signaled differently depending on the condition.

For participants in the Cog+Vis+Man condition, questions were displayed on the tablet screen. To answer a question, participants manually typed their answers using a number pad displayed on the tablet. At the end of each one-minute distraction, the question currently displayed on the tablet disappeared and was replaced by a message instructing participants that the simple addition task had ended.

In the Cog+Vis condition, questions were displayed on the tablet screen. To answer a question, participants said their answers out loud into the headset microphone. At the end of each distraction, an auditory tone was provided in addition to the visual end message.

In the Cog condition, questions were presented by a computer-generated voice via the headset while the tablet screen remained blank. To answer a question, participants said their answers out loud. Since the tablet remained blank throughout this condition, the end of each distraction was signaled by an auditory tone only.

In all three conditions, an auditory chime provided feedback after each question was answered to acknowledge that an answer had been recorded. Participants were presented with a total of ten one-minute distractions in the experiment. Distractions were separated by 60s, 90s, or 120s to ensure that distraction onset could not be predicted.

2.2.3. Detection Response Task. The visual DRT is relatively unobtrusive and adds little demand to a task through its inclusion (Jahn et al., 2005). In the current experiment, the DRT required participants to detect peripherally presented red dot targets (0.34° of visual angle) at random locations on the central display within an area 2° to 4° above the horizontal midline, and 11° to 23° to the left of the participants' forward viewpoint (Bowden et al., 2017; Martens & Van Winsum, 2000). These locations are similar to where pedestrians and street signs typically appear in a driver's field of view (Olsson & Burns, 2000; Patten et al., 2006). Each target remained on screen for a maximum of 2s, or until a response was made. To respond, participants were instructed to press a button on the steering wheel with their right thumb as quickly as possible when a dot appeared, without taking their hands off the steering wheel.

No DRT targets were ever presented during the distraction. To accurately assess recovery from distraction, the timing of DRT target delivery was constrained in several ways during the first 60s following a distraction. The first target was always presented 2s, 4s, 6s, 8s, or 10s post-distraction, and the interval between consecutive targets was between 6s-16s. Therefore, across the ten distractions during the experimental session, participants were presented with exactly two DRT targets from 2-60s post-distraction at 2s intervals. By the end of the experiment, participants had therefore seen two targets at 2s post-distraction, two targets at 4s post-distraction, two targets at 6s post-distraction, and so on. The temporal positioning of target presentation during the first 60s post-distraction was counter-balanced across participants. From 60s post-distraction until the onset of the next distraction, DRT targets continued to appear but the interval between consecutive targets was randomly varied between 6s-16s.

2.3. Procedure

Participants first completed a 10 minute training scenario where they were instructed to drive safely at a speed limit of 50 km/h. During this training participants practiced the DRT and the distracting task specific to their condition. After training was complete participants were informed that they would start the experiment with an AUD$5 bonus that would be reduced if they drove either too slowly or too quickly. The aim of the bonus was to incentivize participants to travel close to the speed limit, as they would in real-world driving. The experiment was completed in two 15-20 minute halves, with a short self-paced rest break (usually 2-5 minutes) available between each half. Each half contained five one-minute distractions. The first four minutes of each half included the DRT with no distracting task. The data to establish baseline driving and DRT performance was collected at the start of the second half of the experiment (excluding the first 30s where the participant was still accelerating to 50 km/h). The entire experiment took approximately 45 minutes to complete.

3. Results

3.1. Data Analysis

There were three dependent variables of interest in this study: DRT performance, speed, and lane-keeping. Regarding DRT performance, the primarily measure of interest was response time, but DRT accuracy data was also analyzed to check that RT differences could not be accounted for by changes in response accuracy (i.e., speed-accuracy trade-offs).

Participants' ability to maintain a consistent position in their lane (lane-keeping) was assessed using the standard deviation of the car's position with respect to the center of the lane. Participants' ability to maintain a consistent speed (speed variability) was measured using the standard deviation of car speed. In addition to speed variability, the average speed was also examined to ensure that any change in speed variability was not accounted for by changes in average speed (e.g. accelerating post-distraction could result in the greater speed variability).

To facilitate comparison across measures, all data was analyzed in 10s time windows (0-10s, 10-20s, 20-30s, and 30-40s) for up to 40s post-distraction[1]. The magnitude of post-distraction cost was calculated at each 10s time period by subtracting each participant's baseline (see Figure 2) from their individual average on each variable.

In the analyses below, we first present the full factorial ANOVA model and follow up with planned contrasts that directly parallel our hypotheses (Rosenthal & Rosnow, 1985). The three planned contrasts include comparing: (1) Cog condition costs with zero-cost baseline[2] to determine the impact of cognitive distraction relative to baseline, (2) Cog+Vis condition costs with Cog condition costs to determine the added impact of visual distraction, and (3) Cog+Vis+Man condition costs with Cog+Vis condition costs to determine the added impact of manual distraction. Results of these contrasts are presented along with point (effect size) and interval (95% confidence) estimates (Cumming, 2014).

Distraction task accuracy was at ceiling, Cog+Vis+Man (M = .98), Cog+Vis (M = .97), and Cog (M = .97), indicating that participants were appropriately engaged in the simple addition task.

[1] Strayer et al. (2016, 2017) showed that the DRT RT impairment following a difficult cognitive distraction in a real-world driving study was eliminated at between 18 and 27s post-distraction. Note that here we used a less complex distracting task, but we decided to analyse our data for up to 40s post-distraction to ensure we captured the full recovery.

[2] Since we are comparing costs (value subtract baseline) for each variable, the first contrast compares Cog costs with zero to determine whether they are elevated from baseline. If there was no difference from zero, then there were no significant costs.

3.2. Detection Response Task

3.2.1. DRT Accuracy. Consistent with Strayer et al. (2016), DRT responses were scored as correct if they were made up to 500ms after target offset. Any responses made outside this window were coded as false alarms. The number of DRT false alarms made per participant was low (M = 1.62, 95% CI [1.38, 1.86]), and did not differ between the three conditions, $F < 1$.

First, we checked to ensure that there were no systematic differences in DRT accuracy between conditions that could cloud our subsequent analyses of DRT RT. A one-way ANOVA conducted on baseline DRT accuracy (hits) found no differences between the Cog (M = .97, 95% CI [.96, .99]), Cog+Vis (M = .96, [.94, .97]), and Cog+Vis+Man (M = .95, [.93, .97]) conditions, $F(2,162) = 2.28$, $p = .11$.

Figure 2 presents the DRT accuracy costs for each condition during the post-distraction period (value subtract baseline), where a positive number indicates a post-distraction cost. A 3 (condition: Cog+Vis+Man, Cog+Vis, Cog) x 4 (time: 0-10s, 10-20s, 20-30s, 30-40s) mixed-ANOVA revealed a main effect of time, $F(3,486) = 10.7$, $p < .001$, $\eta_p^2 = .06$, and a marginal interaction between condition and time, $F(6, 486) = 2.01$, $p = .062$, but no effect of condition, $F(2,162) = 1.17$, $p = .314$.

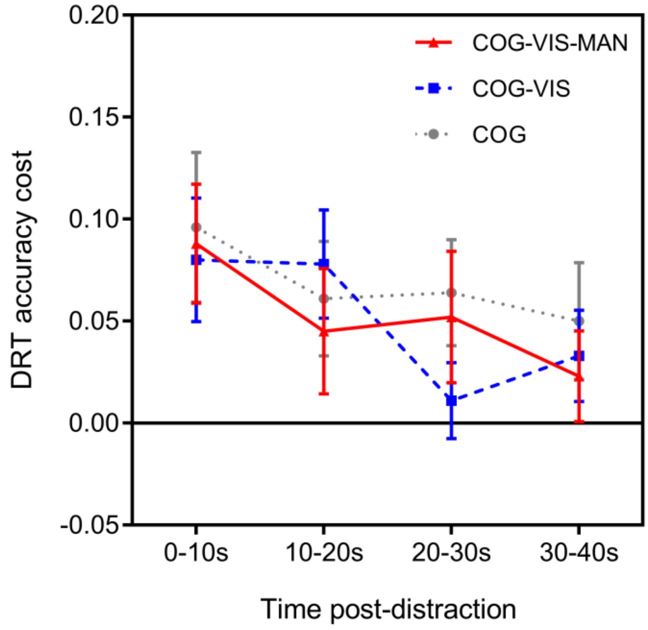

Figure 2. DRT accuracy cost relative to baseline for each distraction condition. Results are grouped into 10s post-distraction intervals, with 0s representing the end of the distraction. Error bars represent 95% between-subject confidence intervals.

DRT accuracy difference scores between each distraction condition, and accompanying planned contrasts, are presented in Table 2. Except for the 20-30s post-distraction interval, there were no significant differences between the distraction conditions. Given differences were found at this interval, and are not found for other key dependent variables below, we do not interpret these effects any further. As can be seen in Figure 2, the cognitive-only distraction condition differed from baseline throughout the 40s post-distraction period, although with declining magnitude over this time. As will be seen below, this difference was present for several other dependent variables as well, and we will consider its origins further in the General Discussion section.

Table 2. Summary of planned contrasts in 10s time windows post-distraction for DRT accuracy.

Time post-distraction	Comparison	M_{diff}	95% CI	*t*	*p*	Cohen's *d*
0-10s	COG vs. baseline	-.10	[-.13, -.06]	5.25	<.001	.71
	COG+VIS vs. COG	.02	[-.03, .06]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-.01	[-.05, .03]	>1	*n.s*	.
10-20s	COG vs. baseline	-.06	[-.09, -.03]	4.33	<.001	.58
	COG+VIS vs. COG	-.02	[-.06, .02]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.03	[-.01, .07]	1.64	*n.s*	.
20-30s	COG vs. baseline	-.06	[-.09, -.04]	4.93	<.001	.66
	COG+VIS vs. COG	.05	[.02, .08]	3.34	.001	.64
	COG+MAN+VIS vs. COG+VIS	-.04	[-.08, .00]	2.21	.030	.42
30-40s	COG vs. baseline	-.05	[-.08, -.02]	3.53	.001	.48
	COG+VIS vs. COG	.02	[-.02, .05]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.01	[-.02, .04]	>1	*n.s*	.

3.2.2. DRT Response Time. A one-way ANOVA conducted on baseline median RTs for accurate DRT responses confirmed that there was no difference between the Cog (*M* = 575ms, 95% CI [553, 597]), Cog+Vis (*M* = 570ms, [547, 593]), and Cog+Vis+Man (*M* = 571ms, [548, 593]) conditions, $F < 1$, $p = .95$.

Figure 3 presents the DRT RT costs for each condition during the post-distraction period, where a positive number indicates a post-distraction cost. A 3 (condition: Cog+Vis+Man, Cog+Vis, Cog) x 4 (time: 0-10s, 10-20s, 20-30s, 30-40s) mixed-ANOVA revealed main effects of both condition, $F(2,162) = 9.16$, $p < .001$, $\eta_p^2 = .10$, and time, $F(3,486) = 125.4$, $p < .001$, $\eta_p^2 = .44$, and an interaction between condition and time, $F(6,486) = 7.95$, $p < .001$, $\eta_p^2 = .09$.

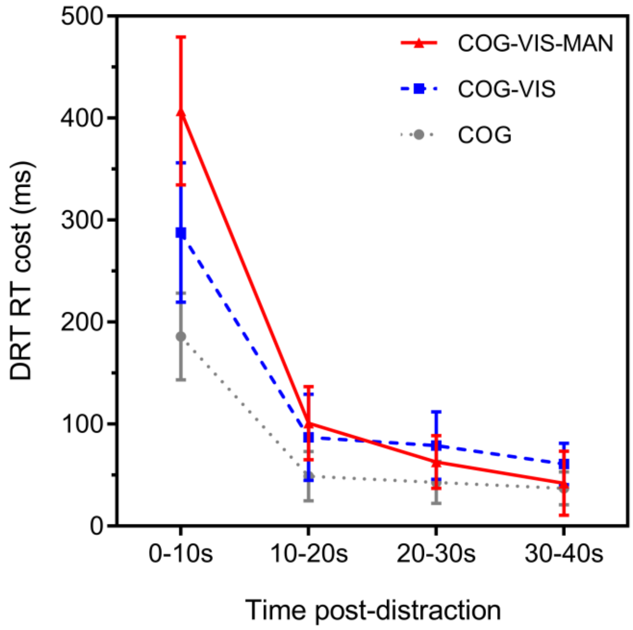

Figure 3. DRT response time cost relative to baseline for each distraction condition. Results are grouped into 10s post-distraction intervals, with 0s representing the end of the distraction. Error bars represent 95% between-subject confidence intervals.

As summarized in Table 3, the findings for DRT response time indicate that the type of distraction differentially affected recovery from distraction during the first 10s, with each additional level of distraction (cognitive, visual, and manual) contributing to the magnitude of the post-distraction impairment. There was, however, no significant difference between conditions in the time periods after 10s post distraction. Similar to the finding with DRT accuracy, while costs for the cognitive condition decreased over time, they remained significantly elevated throughout the 40s post-distraction period.

Table 3. Summary of planned contrasts in 10s time windows post-distraction for DRT Response Time (RT) in milliseconds.

Time post-distraction	Comparison	M_{diff}	95% CI	*t*	*p*	Cohen's *d*
0-10s	COG vs. zero	186	[144, 229]	8.81	<.001	1.19
	COG+VIS vs. COG	101	[22, 181]	2.53	.013	.48
	COG+MAN+VIS vs. COG+VIS	120	[21, 218]	2.41	.018	.46
10-20s	COG vs. zero	49	[25, 74]	4.07	<.001	.55
	COG+VIS vs. COG	38	[-10, 86]	1.55	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	14	[-41, 69]	>1	*n.s*	.
20-30s	COG vs. zero	43	[23, 64]	4.26	<.001	.57
	COG+VIS vs. COG	36	[-3, 74]	1.85	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-17	[-58, 25]	>1	*n.s*	.
30-40s	COG vs. zero	37	[21, 54]	4.57	<.001	.62
	COG+VIS vs. COG	23	[-2, 49]	1.80	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-19	[-19, 18]	1.02	*n.s*	.

3.3. Lane-keeping

Lane-keeping performance was calculated as the standard deviation of a participant's position on the road with respect to the center of the lane, where a positive number corresponds to more variability in lateral position and therefore poorer lane-keeping. A one-way ANOVA conducted on baseline lane-keeping performance found there was a difference between the Cog (M = .12, 95% CI [.11, .13]), Cog+Vis (M = .12, [.11, .13]), and Cog+Vis+Man (M = .15, [.13, .17]) conditions, $F(2,162) = 6.72$, $p = .002$. Follow-up *t*-tests indicated that the Cog+Vis+Man condition had poorer baseline lane-keeping than both Cog+Vis, $t(108) = 2.94$, $p = .004$, and Cog, $t(108) = 2.75$, $p = .007$, conditions, whereas there was no difference between the other two conditions, $t < 1$. This difference in lane-keeping at baseline was not expected, but may possibly reflect the fact that participants were anticipating the need to remove their hands from the wheel to respond to the distracting task.

Figure 4 presents the lane-keeping cost for each condition both during and after the distraction, where a positive number indicates that lateral position was more variable compared to baseline. First, we examined whether lane-keeping costs differed *during* the distraction period as a function of condition and relative to baseline. A one-way ANOVA conducted on lane-keeping costs during the distraction found there was a difference between the Cog (*M* = -.01, 95% CI [-.02, .00]), Cog+Vis (*M* = .00, [-.01, .00]), and Cog+Vis+Man (*M* = .06, [.04, .09]) conditions, $F(2,162) = 37.5$, $p < .001$. Follow-up *t*-tests indicated that the Cog condition lane-keeping was less variable than zero, the Cog+Vis condition had more variable lane-keeping than the Cog condition, and the Cog+Vis+Man condition had more variable lane-keeping than the Cog+Vis condition (see Table 4). Therefore compared to driving without distraction, participants were slightly better at maintaining a consistent lane-position in the cognitive-only distraction condition and were not impaired by the cognitive+visual distraction. However, the addition of a manual component to the distraction caused a large impairment in participants' lane-keeping ability during the distraction.

A 3 (condition: Cog+Vis+Man, Cog+Vis, Cog) x 4 (time: 0-10s, 10-20s, 20-30s, 30-40s) mixed-ANOVA in the post-distraction period revealed a main effect of time, $F(3,486) = 13.4$, $p < .001$, $\eta_p^2 = .08$, and an interaction between condition and time, $F(6,486) = 12.6$, $p < .001$, $\eta_p^2 = .14$. There was no main effect of condition, $F(2,162) = 2.38$, $p = .096$. As summarized in Table 3, the addition of a manual component to the distracting task increased the magnitude of the post-distraction lane-keeping cost during the first 10s post-distraction. Apart from this, there were no significant differences between conditions in the time periods after 10s post-distraction. Taken together, these results demonstrate that only distractions including a manual component impair lane-keeping performance during the distraction, and for up to 10s post-distraction.

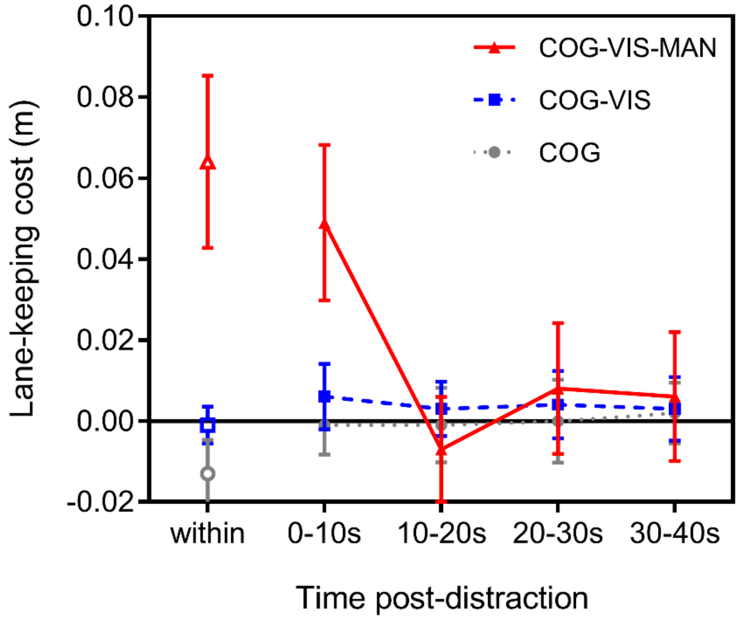

Figure 4. Lane-keeping (standard deviation of lateral position in meters) cost relative to baseline for each distraction condition. Results are grouped into 10s post-distraction intervals, with 0s representing the end of the distraction. Lane-keeping cost within the time period of the distraction is included (hollow points). Error bars represent 95% between-subject confidence intervals.

Table 4. Summary of planned contrasts within the distraction and in 10s time windows post-distraction for lane position variability (SD) in meters

Time post-distraction	Comparison	M_{diff}	95% CI	*t*	*p*	Cohen's *d*
During distraction	COG vs. zero	-.013	[-.021, -.004]	3.02	.004	.41
	COG+VIS vs. COG	.012	[.002, .021]	2.47	.015	.45
	COG+MAN+VIS vs. COG+VIS	.065	[.043, .087]	5.96	<.001	1.14
0-10s	COG vs. zero	-.001	[-.009, .006]	>1	*n.s*	.
	COG+VIS vs. COG	.007	[-.003, .018]	1.39	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.043	[.022, .063]	4.12	<.001	.77
10-20s	COG vs. zero	-.001	[-.010, .009]	>1	*n.s*	.
	COG+VIS vs. COG	.004	[-.008, .015]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-.010	[-.025, .004]	1.42	*n.s*	.
20-30s	COG vs. zero	.004	[-.011, .010]	>1	*n.s*	.
	COG+VIS vs. COG	.004	[-.009, .017]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.000	[-.014, .022]	>1	*n.s*	.
30-40s	COG vs. zero	.003	[-.005, .010]	>1	*n.s*	.
	COG+VIS vs. COG	.001	[-.010, .012]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.002	[-.015, .020]	>1	*n.s*	.

3.4. Speed

3.4.1. Speed Variability. Speed variability was calculated as the standard deviation of a participant's speed in km/h, where a larger number corresponds to poorer speed control. A one-way ANOVA conducted on baseline speed variability confirmed that that there was no difference between the Cog (M = 1.20, 95% CI [1.10, 1.30]), Cog+Vis (M = 1.15, [1.06, 1.23]), and Cog+Vis+Man (M = 1.26, [1.17, 1.34]) conditions, $F(2,162) = 1.50$, $p = .227$.

Figure 5 presents the speed variability cost for each condition both during and after the distraction, where a positive number indicates that speed was more variable compared to baseline. A one-way ANOVA conducted on costs *during* the distraction found there was a difference between the Cog (M = .14, 95% CI [.07, .21]), Cog+Vis (M = .23, [.17, .29]), and Cog+Vis+Man (M = .27, [.20, .34]) conditions, $F(2,162) = 4.06$, $p = .019$. Follow-up *t*-tests indicated that the Cog condition was more variable than zero, the Cog+Vis condition was more variable than the Cog condition, and the Cog+Vis+Man condition was no different than the Cog+Vis condition (see Table 5). These results demonstrate that during cognitive distraction, participants had more difficulty maintaining a consistent speed compared to baseline. The addition of a visual component to this distraction further increased the speed variability, while the addition of a manual component did not.

A 3 (condition: Cog+Vis+Man, Cog+Vis, Cog) x 4 (time: 0-10s, 10-20s, 20-30s, 30-40s) mixed-ANOVA in the post-distraction period revealed a main effect of time, $F(3,486) = 15.2$, $p < .001$, $\eta_p^2 = .09$, and an interaction between condition and time, $F(6,486) = 6.88$, $p < .001$, $\eta_p^2 = .08$. There was no main effect of condition, $F(2,162) = 2.00$, $p = .139$. As summarized in Table 5, during first 10s post-distraction, the addition of each distraction component increased the speed variability cost. After this time period there was no difference between conditions, but costs remained significantly elevated throughout the 40s post-distraction period.

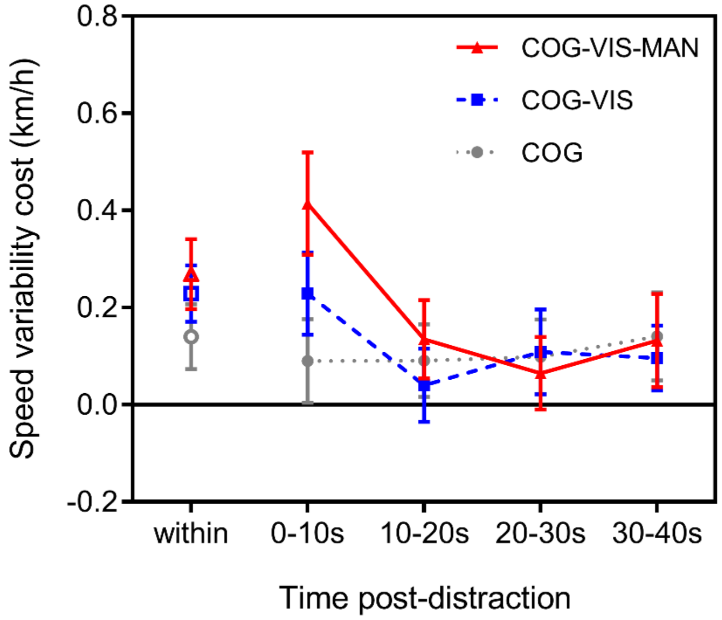

Figure 5. Speed variability (standard deviation of speed in km/h) cost relative to baseline for each distraction condition. Results are grouped into 10s post-distraction intervals, with 0s representing the end of the distraction. Speed variability cost within the distraction is included (hollow points). Error bars represent 95% between-subject confidence intervals.

Table 5. Summary of planned contrasts within the distraction and in 10s time windows post-distraction for speed variability (SD) in km/h

Time post-distraction	Comparison	M_{diff}	95% CI	*t*	*p*	Cohen's *d*
During distraction	COG vs. zero	.14	[.07, .21]	4.18	<.001	.56
	COG+VIS vs. COG	.09	[.00, .18]	2.02	.045	.39
	COG+MAN+VIS vs. COG+VIS	.04	[-.05, .13]	>1	*n.s*	.
0-10s	COG vs. zero	.09	[.00, .18]	2.09	.041	.28
	COG+VIS vs. COG	.14	[.02, .26]	2.29	.024	.43
	COG+MAN+VIS vs. COG+VIS	.19	[.05, .32]	2.74	.007	.52
10-20s	COG vs. zero	.09	[.02, .17]	2.46	.017	.33
	COG+VIS vs. COG	-.05	[-.16, .05]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.09	[-.02, .20]	1.71	*n.s*	.
20-30s	COG vs. zero	.10	[.02, .17]	2.59	.012	.35
	COG+VIS vs. COG	.01	[-.10, .13]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-.04	[-.16, .07]	>1	*n.s*	.
30-40s	COG vs. zero	.14	[.05, .23]	3.11	.003	.42
	COG+VIS vs. COG	-.04	[-.15, .07]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.04	[-.08, .15]	>1	*n.s*	.

3.4.2. Average Speed. Poorer DRT performance, increased lane position variability, and increased speed variability all reflect the potential costs to safety associated with distraction. Conversely, a reduction in the average speed may reflect strategic behavior, where distracted participants compensate for the distraction by slowing their speed. To assess this, the median speed in km/h for each time period was analyzed. Baseline speed was close to the speed limit of 50km/h. A one-way ANOVA on median speed at baseline confirmed that there was no difference between the Cog (*M* = 49.5, 95% CI [49.2, 49.8]), Cog+Vis (*M* = 49.2, [48.9, 49.6]), and Cog+Vis+Man (*M* = 49.2, [48.8, 49.7]) conditions, $F < 1$, $p = .457$.

Figure 6 presents the average speed difference for each condition both during and after the distraction, where a negative number indicates that speed was reduced compared to baseline. A one-way ANOVA conducted on median speed *during* the distraction found there was a difference between the Cog (*M* = -.10, 95% CI [-.29, .09]), Cog+Vis (*M* = .-22, [-.40, -.04]), and Cog+Vis+Man (*M* = -.88, [-1.20, -.55]) conditions, $F(2,162) = 11.9$, $p < .001$. Follow-up *t*-tests indicated that the Cog condition was no different than zero, and the

Cog+Vis condition was no different than Cog, but participants in the Cog+Vis+Man condition travelled more slowly during the distraction than those in the Cog+Vis condition (see Table 6). This suggests that the participants only reduced their speed during the distraction when there was a manual component.

A 3 (condition: Cog+Vis+Man, Cog+Vis, Cog) x 4 (time: 0-10s, 10-20s, 20-30s, 30-40s) mixed-ANOVA in the post-distraction period revealed main effects of both condition, $F(2,162) = 5.35$, $p = .006$, $\eta_p^2 = .06$, and time, $F(3,486) = 4.37$, $p = .005$, $\eta_p^2 = .03$, and an interaction between condition and time, $F(6,486) = 2.16$, $p = .046$, $\eta_p^2 = .03$. Following the distraction, Table 6 shows that only participants in the Cog+Vis+Man condition reduced their speed significantly during the first 20s. This suggests that distractions where the hands needed to be removed from the steering wheel were the only ones to prompt participants to slow their speed, and that they took at least 20s to return to their baseline speed post-distraction.

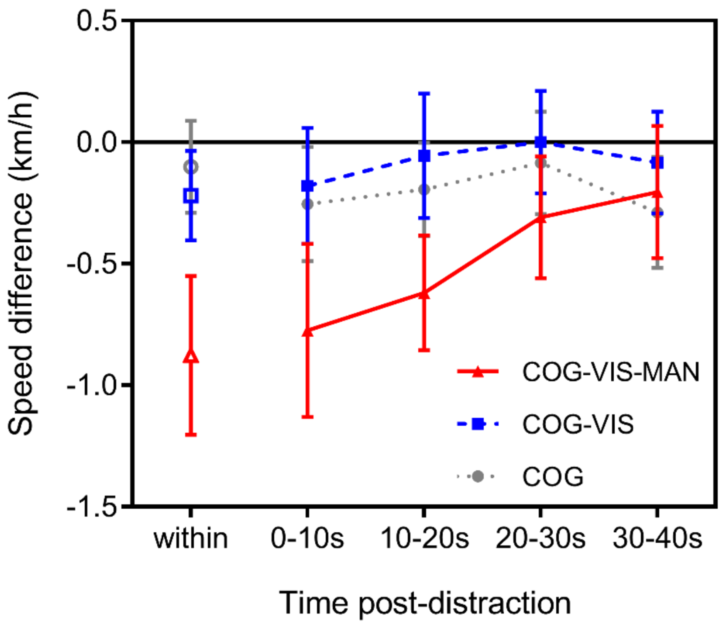

Figure 6. Median speed difference (km/h) relative to baseline or each distraction condition. Results are grouped into 10s post-distraction intervals, with 0s representing the end of the distraction. Median speed difference within the distraction is included (hollow points). Error bars represent 95% between-subject confidence intervals.

The difference in speed variability costs between conditions reported in the previous section may partially be explained by participants in the Cog+Vis+Man condition travelling slower during the distraction and then increasing their speed after the distraction ended. However this explanation would not account for the speed variability cost differences between the Cog condition and zero, and between the Cog and Cog+Vis conditions, since neither slowed their average speed significantly during the distraction. Therefore at least some of the speed variability cost reported in the previous section likely reflects recovery from the distraction rather than simply variability associated with acceleration following distraction-related slowing.

Table 6. Summary of planned contrasts within the distraction and in 10s time windows post-distraction for average speed in km/h

Time post-distraction	Comparison	M_{diff}	95% CI	*t*	*p*	Cohen's *d*
During distraction	COG vs. zero	-.10	[-.29, .09]	1.07	*n.s*	.
	COG+VIS vs. COG	-.12	[-.38, .14]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-.66	[-1.03, -.29]	3.51	.001	.67
0-10s	COG vs. zero	-.25	[-.49, -.02]	2.17	.035	.29
	COG+VIS vs. COG	.07	[-.26, .11]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	.-59	[-1.02, -.17]	2.78	.006	.53
10-20s	COG vs. zero	-.19	[-.39, .00]	2.03	.048	.27
	COG+VIS vs. COG	.14	[-.18, .46]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-.56	[-.91, -.22]	3.24	.002	.62
20-30s	COG vs. zero	-.08	[-.30, .13]	>1	*n.s*	.
	COG+VIS vs. COG	.09	[-.21, .38]	>1	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-.31	[-.63, .01]	1.89	*n.s*	.
30-40s	COG vs. zero	-.29	[-.52, -.06]	2.54	.014	.34
	COG+VIS vs. COG	.21	[-.10, .51]	1.33	*n.s*	.
	COG+MAN+VIS vs. COG+VIS	-.12	[-.46, .22]	>1	*n.s*	.

4. General Discussion

While it has been well established that distractions have a detrimental effect on driving safety during the time that a driver is distracted, comparatively little research has investigated how drivers recover following a distraction (see Reyes & Lee, 2008; Strayer et al., 2016, 2017). To this end, the aim of the current study was to determine whether post-distraction impairment is greater, and/or distraction recovery slower, when a distracting task shares more resource requirements with the primary task of driving safely. We investigated the recovery from three different types of distraction (cognitive-only, cognitive+visual, and cognitive+visual+manual) in a simulated driving environment. It was predicted that each additional level of distraction would increase the magnitude of post-distraction performance impairment and/or slow the post-distraction recovery of performance. Driver performance was assessed by examining DRT response time recovery as well as the continuous driving measures of lane keeping and speed control. Overall, this study found that one-minute distractions negatively impacted performance for up to 40s post-distraction, and that the type of distracting task differentially impacted the recovery from distraction.

4.1. Detection Response Task

The DRT reflects drivers' resource availability (Bowden et al., 2017; Miura, 1986; Patten et al., 2006; van Winsum, 2018) and their capacity to respond appropriately to hazards in the driving environment (Strayer et al., 2013). Here, DRT performance was significantly impaired following distraction – with the addition of cognitive, visual, and manual components to the distracting task each contributing to RT increases from 0-10s post-distraction. However, after 10s, there was no difference between distraction conditions. This finding is consistent with previous research demonstrating that distraction leads to residual impairments (Reyes & Lee, 2008; Strayer et al., 2016, 2017), and suggests that the initial magnitude of impairment is dependent on the type of distraction.

The DRT is often characterized as a measure of general cognitive load in particular (Crundall et al., 2002), and has previously been shown to be less sensitive to visual or manual (motor) demands compared to cognitive (Conti et al., 2014). However, our finding that the post-distraction DRT impairment magnitude was dependent on distraction condition is somewhat inconsistent with this characterization, since the addition of visual and manual distraction components further slowed DRT responding. Instead, our results support the recent findings of van Winsum (2018) who demonstrated that both cognitive and visual task demands can increase DRT RTs. van Winsum showed that increasing visual distraction resulted in poorer target detection in the peripheral visual field while increasing cognitive distraction instead led to more general interference.

Another interesting feature of the DRT accuracy and RT results reported here was that neither returned to baseline performance levels by 40s post-distraction. There are two potential explanations for this effect. The first is that recovery was still not complete by 40s post-distraction. This explanation seems unlikely given that previous real-world driving studies with more demanding distracting tasks found no evidence of significant impairment past 27s (Strayer et al., 2016, 2017). Nonetheless, to test whether recovery did complete sometime after 40s, we conducted an additional analysis of the DRT RT and accuracy data available between 40-60s post-distraction was conducted for the cognitive-only condition. This analysis confirmed that the significant impairment remained up to 60s post-distraction (largest *p*'s .04 and.02, for RT and accuracy, respectively).

An alternative explanation, which we think is more likely, is that participants may experience a persistent detrimental effect when driving in situations where they are periodically expecting to be distracted. In the current experiment, the DRT performance baseline was established during a four minute section of driving with no distractions. This was then followed by a series of distractions separated by 1-2 minutes of undistracted driving where the recovery was assessed. As such, participants drove in the post-distraction period with the knowledge that additional distracting tasks were likely imminent. The effort/demand associated with maintaining the intention to respond to impending distractions may in turn have contributed to the persistent impairment in DRT performance observed here. This is consistent with task switching literature which shows that, while maintaining the expectation of an imminent task switch helps improve the efficiency of the switch itself, task switching preparation still costs performance compared to single task performance (Monsell, 2003; Ruthruff et al., 2001). There is also evidence that performance on a task can be impaired when an interrupting task is expected, but never actually performed (Loft et al., 2008; Schumacher et al., 2001).

While providing longer periods between distractions (e.g. >60s) would likely allow post-distraction costs to eventually extinguish, the current study highlights the potential for long-lasting impairments to driver safety when there are frequent distractions. Practically, the current findings suggest that performing more challenging driving maneuvers, such as lane changing, immediately after a distraction could increase the risk of accident since drivers may still be experiencing residual impairment.

4.2. Speed control

The pattern of results for speed variability, which reflects participants' ability to maintain a consistent speed while driving, followed a pattern of recovery similar to the DRT. Relative to baseline, participants were poorer at maintaining their speed while distracted, and this impairment was greater when the distraction included a visual component (see Rogers et al., 2011 for a similar finding). Following the distraction, this difference in speed variability between conditions was also present from 0-10s post-distraction. There was again a consistent increase in speed variability throughout the whole 40s post-distraction period, supporting the suggestion that driving in an environment where distractions are frequent can lead to persistent impairment in driver performance.

The speed variability results can partially be explained by changes in the average speed during and after the distraction. Our results demonstrated that participants only reduced their average speed during distractions that included a manual component. Driving more slowly could therefore be interpreted as participants actively compensating for the performance impairment caused by the distraction (Borowsky et al., 2016; Horberry et al., 2006). This is supported by survey results which show drivers tend to rate distractions including manual components, such as sending a text message, as more risky than talking on a hands-free phone or talking to a passenger (although note that drivers did not rate manually interacting with in-vehicle systems as risky, Young & Lenné, 2010). Alternatively, participants may have been unaware that the distracting task demands had led them to reduce their speed. Either way, an important practical implication for driving safety is that speed reduction only occurred in the manual distraction condition, despite the fact that significant impairments to various performance measures were observed when the distraction only included a cognitive component.

4.3. Lane-keeping

Finally, there is evidence that drivers have difficulty maintaining a consistent position within their lane under certain kinds of distraction (Choudhary & Velaga, 2017). Here, we found that during the distraction there was an increase in variability with the addition of each distraction component. Interestingly, the cognitive-only distraction condition actually showed a small improvement in lane-keeping performance during the distraction. While this may seem counter-intuitive, it is in line with several previous studies (Beede & Kass, 2006; Liang & Lee, 2010; Tractinsky et al., 2013). There are several possible explanations for this improvement, including a reduction in eye-movements towards the periphery (but see Engström et al., 2005 for more on this), the engagement of a more cautious driving strategy (Liang & Lee, 2010; Muhrer & Vollrath, 2011), and/or increased arousal (Li et al., 2018). Following the distraction, there was only a residual lane-keeping impairment for the manual condition, and this recovery was complete by 10s post-distraction. This 10s recovery likely included the time taken for drivers to reposition their hands on the wheel following the manual distraction.

4.4. Limitations

The current study generally consisted of younger, more inexperienced drivers. We focused on an inexperienced driver population because prior research has shown inexperienced drivers are disproportionately represented in accidents statistics (Palamara et al., 2013) and are more susceptible to distractions (Klauer et al., 2014). It would also be useful however for future studies to examine post-distraction recovery in an experienced driving population to determine the extent to which our effects generalize to different populations. This study used a medium-fidelity driving simulator, where participants drove in a low-complexity environment. The magnitude and duration of post-distraction impairments in a low-complexity driving environment likely underestimates the effects of distractions compared to more complex environments (e.g. higher traffic density, poor visibility, more road design complexity, etc.), since increased task demands mean that drivers have fewer resources to spare. Lastly, it should be noted that although the distracting task used here is unlike those encountered by real-world drivers, it allowed us to maintain a high level of experimental control over the resource demands of the distraction, and required similar cognitive resources to actual distractions. That said, it is possible that recovery from more realistic non-driving (e.g. sending a text message) and driving related distractions (e.g. performing an emergency brake) may differ from what is reported here due to a range of other factors such as task priority, importance, or unexpectedness. These are important factors to investigate in future studies in order to more fully understand their contributions to the lasting effects of distraction.

4.5. Practical implications

Although eliminating distractions is clearly one way to avoid the subsequent performance deficits, it could be argued that this will never be entirely achievable given technology use and the pace of modern society. Thus, it is also important to consider ways to improve recovery from distraction. There is evidence from the interruption recovery literature showing that detrimental effects can be reduced by allowing people to schedule an interruption themselves (e.g. Monk et al., 2004). One property of the distractions used in the current study was that the distraction onset was relatively unpredictable. Therefore it may be possible for some of the negative effects on driving found here to be at least partially mitigated by allowing participants some flexibility. For example, distracting tasks could commence by asking participants to indicate if/when they are ready to accept the task, and not start until readiness has been indicated.

While drivers today may be more aware of the risks associated with distracted driving, it is unlikely that many have considered how long it takes to recover from a distraction. The current study shows that for at least the first 10s following a distraction, drivers are likely to be significantly impaired and in a poorer position to respond appropriately to potential hazards. In this study, travelling at 50km/h meant that participants were impaired over a distance of approximately 138m in the ten seconds following a distraction. Further to this and potentially more concerning is the longer lasting impairment to the DRT and speed variability, which highlights the potential dangers of driving in an environment where frequent distractions are likely.

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