



Discussion

Examining the relationship between driver distraction and driving errors: A discussion of theory, studies and methods

Kristie L. Young*, Paul M. Salmon

Monash University Accident Research Centre (MUARC), Building 70, Monash University, Clayton, Victoria 3800, Australia

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ABSTRACT

Over the past two decades the concept of driver distraction has been the focus of intense research attention. One aspect of distraction for which there has been limited systematic research, however, is its role in driver error causation. This article presents a review of the distraction literature with a view to elucidating what is currently known about the types of driving errors that distraction contributes to and the mechanisms by which distraction induces these errors. The review revealed a number of fundamental gaps in our knowledge, including the number and nature of errors made by drivers when distracted; the mechanisms by which distraction causes errors; whether and how distraction disrupts drivers' ability to recover from errors; and how system-wide factors moderate the relationship between distraction and error. In closing, we attempt to identify the most appropriate theoretical and methodological approach to drive the integrated study of distraction and error forward. We conclude that it is only through the adoption of a systems approach that integrated countermeasures can be proposed and implemented to mitigate driver errors caused by distraction.

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1. Introduction

Having both been previously identified as contributory factors in road traffic crashes (e.g., Klauer et al., 2006; Treat et al., 1979), driver distraction and driver error are two currently popular concepts within road safety research (e.g., Salmon et al., 2010a; Young and Lenné, 2010). Although the two phenomena are ostensibly related to one another, there has been little exploration of how they are related and what the effects of one are on the other. The aim of this paper is to attempt to clarify the link between the two concepts by presenting the findings from a review of the literature on driving distraction which was undertaken to determine what is currently known about the types of driving errors that distraction contributes to and the mechanisms by which distraction induces these errors.

1.1. Driver distraction

Driver distraction is acknowledged internationally as a significant road safety concern (Regan et al., 2008). Despite the complexities of driving, drivers regularly engage in various non-driving-related activities. However, attention is a finite resource and driving performance can begin to degrade if drivers fail to devote sufficient attention to the driving task at critical moments

because they are engaged in another task. This phenomenon is referred to as driver distraction.

Although many definitions exist, driver distraction is conceptualised by Lee et al. (2008) as a diversion of attention away from activities critical for safe driving towards a competing activity. Researchers typically distinguish between a range of different types of distraction, namely visual, cognitive and physical (manual) distraction; all of which have been shown to have disparate effects on driving performance (e.g., Amditis et al., 2010; Engstrom et al., 2005; Lansdown et al., 2004).

A large and expanding body of research has found that engaging in distracting activities negatively effects driving performance in a range of ways, including reduced longitudinal (Rakauskas et al., 2004; Strayer and Drews, 2004) and lateral control (Engstrom et al., 2005; Reed and Green, 1999); reduced situation awareness (Kass et al., 2007); and impaired response times to roadway hazards (Burns et al., 2002; Lee et al., 2001). These degradations have been shown to translate into an increased risk of crash involvement, with estimates indicating that secondary task distraction is a contributing factor in up to 23% of crashes and near-crashes (Klauer et al., 2006). The taxonomy provided in Table 1 classifies various distraction sources for which something is known about their crash risk or contribution. It also contains the types of distraction (visual, cognitive, physical) associated with each distraction source and information regarding the odds of being involved in a crash or near-crash associated with each source and the percentage of distraction-related crashes in which the source has been found to be a contributing factor. Taken

* Corresponding author. Tel.: +61 3 9905 1258; fax: +61 3 9905 4363.

E-mail addresses: kristie.young@monash.edu (K.L. Young), paul.salmon@monash.edu (P.M. Salmon).

Table 1

Distraction sources and their associated crash risk and contribution to crashes.

Major source category	Specific source	Distraction type	Odds of crash/near-crash ^a	% of distraction crashes that source contributes to ^b
Technology-based	Talking on mobile phone	C, P	1.3–9.0	2.1–8.8 ^c
	Dialling/answering mobile phone	V, P	2.8	0.0–8.8 ^c
	Radio CD, or cassettes, MP3 player	C, V, P	0.6 ^d –2.3 ^e	0.0–8.5
	Text messaging	C, V, P	23.2	
	Other device (PDA, blackberry)	C, V, P		0.0
Non-technology based	Moving object in vehicle	V, P	8.8 ^f	1.4
	Animal or insect inside vehicle	V, P	6.4	2.1–6.9
	Reading/writing	C, V, P	3.4	0.0
	Passenger/children	C, V, P	0.3–0.5	0.0–18.7
	Eating/drinking	V, P	1.0 ^g –1.6 ^h	0.0–5.2
	Personal grooming/hygiene	V	0.4–3.1	0.0
	Vehicle/climate controls	V, P		1.4–7.4
	Vehicle mirrors and instrument panel	V, C		1.4
	Smoking	V		0.0–3.8
	Non-moving object in vehicle	V, P	1.4 ⁱ	
	Trying to find destination/location, lost	V, C		5.9
	Reaching for objects	V, P		2.8
	Sneezing/coughing/itching	P		<1.0
	Daydreaming/lost in thought	C		2.8–11.2
External-to-vehicle	Outside event/object	V, C	3.7	0–9.7
	Crash, roadside incident, other traffic	V, C		3.8
	Scenery/landmarks	V, C		1.7–2.9
	Advertising/billboards	V, C		<1.0
	Pedestrian/cyclist	V, C		0
Other/unknown				10.4

C = cognitive, V = visual, P = physical.

^a Odds ratios from Redelmeier and Tibshirani (1997), McEvoy et al. (2007a), Klauer et al. (2006), Olson et al. (2009).^b Based on McEvoy et al. (2007b), Gordon (2005) and Dingus et al. (2006).^c Studies did not distinguish between talking, dialling and answering, hence the same figures are used for all tasks.^d Adjusting radio.^e Inserting/retrieving CD.^f Reaching for moving object.^g Drinking from open container.^h Eating.ⁱ Reaching for non-moving object.

together, the crash data contained in Table 1 suggests that distracting activities that require high levels of visual–manual resources are associated with a relatively higher crash risk than those tasks that require largely cognitive resources.

Distraction is a complex, multifaceted phenomenon and, despite being the subject of intense research worldwide, there is still much we do not understand about its mechanisms and its relationship with other aspects of human cognition and behaviour such as driver state and situation awareness. One aspect of distraction for which there is limited systematic research is its relationship with driver error; that is, is the nature (number and type) of errors made by distracted drivers and how this might differ from errors made by undistracted drivers, the mechanisms by which distraction contributes to errors and what effect distraction might have on error recovery.

1.2. Driver error

Previous research indicates that driver error is a significant contributor to road trauma. Estimates suggest that driver error is a causal factor in 75% (Hankey et al., 1999), or even up to 95% (Rumar, 1990) of road crashes. As with driver distraction, there have been numerous attempts to define human error and no one universally accepted definition exists. One definition that is widely adopted is that offered by Reason (1990), who defines error as:

“a generic term to encompass all those occasions in which a planned sequence of mental or physical activities fails to achieve its intended outcome, and when these failures cannot be attributed to the intervention of some chance agency” (p. 9).

Like its definition, numerous classification schemes and models of human error exist (e.g., Embrey, 1986; Hollnagel, 1998; Norman, 2001; Rasmussen, 1982). None, however, have achieved the popularity of the slips, lapses, mistakes and violations scheme proposed by Reason (1990). According to Reason, slips are the most common error type and represent those errors where an incorrect action was performed, although the intention was correct (e.g., erroneously pressing the accelerator rather than the brake when intending to stop). Lapses occur when people unintentionally fail to perform an action and are associated with memory failures (e.g., forgetting to lock the car). Mistakes originate at the planning, rather than the execution level and involve a person intentionally performing an incorrect action (e.g., a driver accelerating toward a red light when they should be braking). While errors occur while people are operating within the rules and procedures of a system, violations include behaviours that intentionally or unintentionally deviate from these rules and procedures (e.g., travelling above the speed limit). Reason's error classification scheme has been applied widely in the road transport domain, through the extensive application of the Driver Behaviour Questionnaire (DBQ) across different countries and driver groups. More recently, Stanton and Salmon (2009) developed a driver-specific error taxonomy based on a review and synthesis of the error-related research conducted in road transport to date. This taxonomy outlines five categories of driving errors along with five categories of causal factors (see Table 2).

Although human error research has a long tradition in safety critical domains such as aviation, nuclear power and patient safety (Jou et al., 2011; Kontogiannis and Malakis, 2009; Shappell et al., 2007; Taib et al., 2011), relatively little research has systematically exam-

Table 2

Driver error taxonomy including underlying psychological mechanisms (adapted from Stanton and Salmon, 2009).

Underlying psychological mechanism	External error mode	Example
<i>Action errors</i>		
Action execution	Fail to act	Fail to check rear view mirror
Action execution	Wrong action	Press accelerator instead of brake
Action execution	Action mistimed	Brake too early or too late
Action execution	Action too much	Press the accelerator too much
Action execution	Action too little	Fail to press the accelerator enough
Action execution	Action Incomplete	Fail to turn the steering wheel enough
Action execution	Right action on wrong object	Press accelerator instead of brake
Action execution, planning and intention	Inappropriate action	Following too close, race for gap, risky overtaking
<i>Cognitive and decision making errors</i>		
Perception	Perceptual failure	Fail to see pedestrian crossing
Perception	Wrong assumption	Wrongly assume a vehicle will not enter path
Attention	Inattention	Nearly hit car in front when queuing
Attention	Distraction	Distracted by secondary task
Situation assessment	Misjudgement	Misjudged speed of oncoming vehicle, misjudge gap
Perception	Looked but failed to see	Looked at roadway but failed to see pedestrian
<i>Observation errors</i>		
Memory and recall	Failed to observe	Failed to observe area in front of vehicle
Memory	Observation incomplete	Failed to observe side mirror when changing lanes
Situation assessment	Right observation on wrong object	Failed to observe appropriate area
Memory and recall	Observation mistimed	Looked in drivers side mirror too late when merging
<i>Information retrieval errors</i>		
Situation assessment	Misread information	Misread road sign, traffic control device or road markings
Situation assessment	Misunderstood information	Perceive information correctly but misunderstand it
Situation assessment	Information retrieval incomplete	Only part of required information retrieved
Situation assessment	Wrong information retrieved	Read wrong information from road sign
<i>Violations</i>		
Action execution, planning and intention	Intentional violation	Overtake on double lines, intentionally exceed speed limit
Action execution	Unintentional violation	Unintentionally exceed speed limit

ined the nature of and, in particular, the factors contributing to driver error (Stanton and Salmon, 2009). Two recent studies that have examined the nature of errors made by drivers found evidence that distraction is one of a number of factors that contribute to drivers committing errors (Sandin, 2009; Staubach, 2009).

1.3. The link between driver distraction and driver error

It makes intuitive sense that that being distracted can lead to drivers making a range of errors. As discussed earlier, there is a large body of knowledge on how distraction can impact a range of driving behaviours and performance measures. However, we currently have a limited understanding of the relationship between driver distraction and driver error and how other factors, such as environmental, vehicle or road infrastructure design, can moderate this relationship.

Although several error taxonomies exist, the link between distraction and different error types is often not clear. A number of taxonomies simply list distraction as the driving error itself, rather than as a causal factor (e.g., Reason et al., 1990; Sabey and Staughton, 1975; Sabey and Taylor, 1980). These taxonomies do not consider what the error type following the distraction episode actually is; thus, offering no insight into the nature of the errors that are associated with distracted driving. For example, according to these taxonomies, if a distracted driver was unable to stop successfully at a red traffic signal, the driver's misjudgement of, or failure to see, the traffic signal and stopping distance immediately following the distraction would not be captured; rather, the distraction itself would be listed as the error. Other taxonomies do list distraction as a causal factor in driver errors, but do not indicate the mechanisms by which it contributes (e.g., Staubach, 2009; Wierwille et al., 2002). For instance, Wierwille and colleagues list internal and external distraction as one of the factors that contribute to recognition errors, but do not elaborate on *how* distraction contributes to these errors.

In an in-depth examination of 474 crashes, Staubach (2009) found that a significant number of crossroads, lane departure and

same direction crashes were the result of errors caused by the driver being distracted. Likewise, Sandin (2009) sought to identify the factors underlying the most common errors and violations occurring at intersections (i.e., a failure to yield, or running a traffic light or sign). Sandin found that distraction contributed to a range of errors occurring at intersections including missing a sign or read traffic signal, misjudging the timing of amber lights, and failure to see other vehicles. While these, and other studies (e.g., Klauer et al., 2006), leave little doubt that distraction has a role to play in the causation of driver errors that lead to road crashes, as with the error taxonomies, they provide few insights into the mechanisms by which distraction causes errors or disrupts drivers' ability to recover from errors. From a theoretical perspective, understanding the driver distraction/driver error relationship and the mechanisms by which distraction contributes to error is important for improving our knowledge of the consequences of distraction and the mechanisms through which it leads to crashes. From a practical perspective, understanding the role of distraction in driver errors can inform the development of better countermeasures to mitigate distraction and errors through training and technology (e.g., Intelligent Transport Systems) and wider road system design.

Driver distraction may contribute to errors through a range of means: by affecting cognitive processes such as perception, planning, decision making, and situation awareness, as well as by interfering with vehicle control tasks. The driver error taxonomy developed by Stanton and Salmon provides a useful framework to guide the discussion of the role of distraction in driver error, as it allows us to explore the processes by which distraction contributes to five broad categories of driving errors and how they might differ across error types.

2. Distraction disrupts natural driving performance variation leading to action errors

The road system, like any other complex socio-technical system, is constantly changing. Drivers must continuously make dynamic

adjustments or adaptations to their driving behaviour in response to these changes in the road environment. For example, drivers will adjust speed to account for speed changes of a lead vehicle or an increase in pedestrian activity, or will make micro steering corrections to stay on course. Road crashes are relatively rare occurrences, thus, for the most part, this performance variability is successful at avoiding incidents (Hale and Heijer, 2006). But, under what conditions does performance variability breakdown? Evidence suggests that distraction is one such condition, and this can lead drivers to commit a range of errors. In this section, we consider how distraction can disrupt normal driving performance variation to lead to action, or performance/control, errors.

Degradation in lateral position control is a commonly used measure to evaluate the effects of distraction on driving performance. A number of studies have shown that visual–manual load in particular, contributes to increased lane keeping or tracking performance variation and loss of lateral control (Engstrom et al., 2005; Greenberg et al., 2003; Wilschut et al., 2008; Young et al., 2011a). Research with mobile phones has found, for example, that drivers make a greater number of lane position deviations and excursions and have a higher standard deviation of steering wheel angle while dialling a mobile phone, and that this loss of lateral control can occur even when driving on straight roads with low traffic (Alm and Nilsson, 1995; Caird et al., 2008; Green et al., 1993; Reed and Green, 1999). Research also suggests that drivers make a greater number of lane deviations and excursions when manually entering address details into a route guidance system or when following navigation instructions that are presented visually, rather than verbally (Dingus et al., 1995; Tijerina et al., 1998). Other in-vehicle information system (IVIS) tasks that impose a visual–manual load, such as tuning the radio and interacting with a CD player, have also been shown to impair drivers' ability to maintain lateral vehicle control (Jancke et al., 1994; Wikman et al., 1998).

Reduced lateral control or tracking performance during periods of visual–manual demand is believed to result from the build up of lane position errors (Engstrom et al., 2005). When visual attention is diverted from the roadway, drivers tend to maintain periods of a fixed steering angle, making a lower number of micro steering corrections (Godthelp et al., 1984). With fewer micro steering corrections, heading errors can accumulate requiring drivers to make large steering movement which can, in turn, lead to lane weaving and possibly lane excursions. That is, visual–manual distraction interrupts drivers' natural lateral performance variability of using micro steering corrections to continuously adjust vehicle heading to maintain their lateral position, thereby leading to errors in lateral control. The failure by distracted drivers to perform micro steering corrections can be represented by the error 'fail to act' from Stanton and Salmon's taxonomy; however, whether these heading errors are due to biomechanical interference (e.g., removal of hands from steering wheel or reduced/exaggerated steering inputs) or failure to attend to the visual cues relevant to maintaining lateral position because the driver's eyes are diverted from the road, or a combination of both of these factors has not been adequately addressed in the distraction literature.

Distraction can also disrupt drivers' performance variation in relation to longitudinal control; namely, speed and headway maintenance. Several on-road and simulator studies have found greater variation in driving speeds and throttle control when drivers are using a mobile phone or with other in-vehicle devices or tasks (Charlton et al., 2002; Crisler et al., 2008; Rakauskas et al., 2004; Reed and Green, 1999; Santos et al., 2005). While the effects of distraction on headway maintenance appear less robust than for speed, increases in time headway variability have been found in studies examining text messaging (Hosking et al., 2009) and searching scrollable lists on a portable music player (Young et al.,

2011b). Research has also found that while performing mobile phone tasks, drivers are delayed in adapting their speed to changes in the speed of a lead vehicle (Brookhuis et al., 1991; Lamble et al., 1999). It is clear from these studies that distracting tasks can divert drivers' attention away from speed and headway monitoring and result in speed and headway errors such as excessive and minimum speed errors and following too closely. Although open to various theoretical interpretations, possible explanations for the mechanisms underlying the effects of distraction on longitudinal control errors is biomechanical interference or that drivers fail to observe the perceptual cues required to maintain a consistent speed and headway; for example, changes in closing speed or visual angle to a lead vehicle and changes in the rate of objects moving past the vehicle (Andersen et al., 2004; Gibson, 1979). That is; these errors may result from improper lookout by distracted drivers due to excessive periods spent with their eyes off the roadway; a hypothesis supported by evidence that a large proportion of the tasks for which these errors have been observed are those with a high visual, rather than cognitive load (e.g., dialling, text messaging, scrolling lists).

3. Distraction disrupts visual scanning behaviour and situation awareness leading to observation errors

Drivers' detection and responses to roadway events and hazards are considered crucial aspects of driving performance. Drivers are continually required to detect and respond to a range of information and events, including traffic signs and signals, lead vehicles braking, changes in road curvature and so on. To respond effectively, drivers must have an accurate awareness of their driving environment and what events are taking place around them. Interruptions to drivers' visual sampling of the road environment caused by distracting activities reduces drivers' situation awareness and is an important contributor to road crashes (Salmon et al., 2011).

Both visual and cognitive secondary tasks have been shown to alter drivers' visual search patterns, thereby leading to a range of observation errors including late detection of events and even the complete failure to observe relevant information or detect hazards. Visual tasks can contribute to late or missed detection of events in one of two ways: first, if drivers glance away from the roadway too often or for long periods, their awareness of what is occurring in the traffic scene and their ability to detect rapidly unfolding events is diminished. Secondly, drivers may not glance back to the roadway long enough between their off-road glances to get back 'in-the-loop' and maintain their situation awareness (Senders et al., 1967). In particular, tasks that take drivers eyes off the road for extended periods of time have been associated with an increased risk of being involved in a collision. In a simulation study, for example, Horrey and Wickens (2007) found that over 80% of the crashes in their study were attributable to drivers glancing inside the vehicle for longer than 1.6 s. Klauer et al. (2006) also found in a naturalistic driving study that glances of more than 2 s inside the vehicle increased the odds of crashing by three times.

It is not just the removal of drivers' eyes from the roadway that leads to the late or missed detection of information and events. Cognitive tasks that do not necessarily required eyes off road time can also alter drivers' visual scanning patterns leading to impaired event detection. In response to purely cognitive load, drivers have been shown to concentrate their gaze in the central region of the roadway, often at the expense of peripheral scanning (Harbluk et al., 2007; Recarte and Nunes, 2000, 2003; Victor et al., 2005). This effect is referred to as spatial gaze concentration or the gaze concentration effect and has been associated with reduced event detection performance (Recarte and Nunes, 2003; Victor et al., 2008) and less frequent checking of rear-view and side mirrors and vehicle instruments, including the speedometer (Brookhuis

et al., 1991; Gärtner et al., 2001; Recarte and Nunes, 2000, 2003). While central gaze concentration by drivers may be seen as a positive strategy to cope with increased load by focusing their attentional resources on the area of the roadway most likely to contain relevant information (i.e., the road centre), it may also lead to the late detection of events occurring or commencing in areas peripheral to the driver's focus of attention. To the knowledge of the authors, however, this effect has not been empirically verified.

Research using the Lane Change Test (LCT) also offers insights into the effects of distraction on observation errors. The key task of the LCT requires drivers to detect and respond to 18 roadside signs indicating the correct lane of travel. Numerous studies using the LCT have found that drivers' ability to detect and respond correctly to the lane change signs is impaired by the performance of a competing task such as interacting with navigation, phone and entertainment devices (Bruyas et al., 2008; Engström and Markkula, 2007; Harbluk et al., 2009). In the absence of detailed eye glance measures, however, it is often unclear from studies if the signs were missed by drivers (observational/perceptual error) or if drivers in fact saw the signs but misread them (information encoding/retrieval error). Indeed it is probable that with more extensive research some distraction-related errors may be re-classified into different error types than those originally assigned. It is only through the application of detailed and comprehensive data collection measures that the mechanisms underlying the role of distraction in certain error types can be fully established and correct error classification occur.

4. Distraction disrupts cognitive processing leading to information encoding and retrieval errors

Research has shown that in addition to resulting in impaired detection and response, distraction can result in attention being withdrawn from the processing of relevant information in the driving environment and this can lead to information retrieval errors. In particular, drivers' memory for objects or information occurring in the road environment has been shown to be impaired by engagement in distracting activities. When drivers are distracted it is thought that they, consciously or unconsciously, reallocate their attention from less relevant information in the driving scene to the secondary activity and to highly relevant driving-related information (Strayer et al., 2003). This reallocation of attention can result in drivers missing or having impaired memory for certain objects in the road scene, such as traffic or direction signs and billboards. Interestingly, a number of studies have found that drivers may not react to, or recall an object or event even if they have visually fixated on it (Rumar, 1990; Strayer et al., 2003, 2004). This implies that the memory deficit can result from disruptions in the processing of visual information rather than drivers simply failing to look at particular objects. Strayer et al. (2004), for example, found that when conversing on a hands-free phone, drivers' were less likely to create a durable memory of objects in the driving scene and accurately recognise them at a later point. These memory deficits occurred even though drivers had fixated on the objects in question. Moreover, memory deficits were found for objects of both high and low relevance to driving, suggesting that drivers do not make a conscious decision to reallocate their attention to only information highly relevant to safe driving.

An important question remains as to whether the observed impairments in recognition memory results from disruptions to the encoding of information at the point of fixation or in the retrieval of information at a later point. Impairments in encoding may delay drivers' recognition and reaction to a hazardous event, while deficits in information retrieval may lead to navigation errors if direction information cannot be recalled. Research by Strayer et al. (2003) provides some evidence that it is the former which

may result in the memory impairments observed with distracted drivers; however, further research is needed to establish this and also the consequences of both types of information processing deficits on performance and safety outcomes.

5. Distraction disrupts decision making leading to cognitive and decision-making errors

Driver distraction has been found to be detrimental to drivers' decision making processes, particularly when performing complex or unexpected driving tasks and manoeuvres. In a seminal study of mobile use while driving, Brown et al. (1969) concluded that distraction has a minimal impact on the more automatic driving skills, such as steering, but can critically impair decision-making. They found that performing the cognitive phone tasks while driving impaired drivers' judgments of whether it was possible or safe to drive through narrow gaps, an effect that was more pronounced for gaps smaller than the vehicle.

More recently, work by Cooper and colleagues has sought to further examine the effects of distraction on drivers' decision making during complex driving tasks – left hand turns across on-coming traffic and weaving to avoid pop-up targets (Cooper and Zheng, 2002; Cooper et al., 2003). In a test-track study, Cooper et al. (2003) found that, when using a mobile phone, drivers decelerated less during a short trigger weaving task; meaning that they travelled substantially faster during the weave manoeuvre and had a lower safety margin than when not distracted. It was also found that phone use was associated with significantly riskier decision making during a left-turn gap selection task, with drivers accepting shorter gaps. Moreover, these riskier gap selection decisions were exacerbated by adverse road conditions, with distracted drivers failing to adjust their gap selections to accept only longer gaps under wet conditions. Importantly, Cooper et al. found that the effect of distraction on decision making was moderated by the complexity of the driving task. The phone tasks appeared to have minimal impact on decision making errors in response to commonly encountered situations such as traffic signal changes, where drivers tended to adopt more conservative decision making responses to account for their attention being diverted.

It is also possible that distraction might degrade drivers' decision making in terms of their selection of responses to hazards. Distraction may, for example, impair drivers' ability to select an appropriate response to successfully avoid a hazard (e.g., swerving rather than braking) rather than simply delaying the response *per se*. Impairments in drivers' response selection have important implications for road safety and are discussed in further detail in the section on error recovery. First, however, it is interesting to map the specific error types listed in Stanton and Salmon's (2009) taxonomy to identify, based on the current literature, which error modes can be by-products of distraction.

6. Linking distraction to driver error types

Table 3 displays Stanton and Salmon's driver error taxonomy and indicates those error types that have been shown in the current literature to have driver distraction as a causal factor (amongst other contributing factors). While many gaps are present in the table, a range of error types can be identified as having distraction as a causal factor. As discussed earlier, however, it is possible that the classification of distraction-induced errors presented here could change as we gain a greater understanding of the mechanisms underlying the relationship between distraction and particular error types. For example, a failure to respond to a traffic sign could initially be classed as an observation error, but may through further investigation be revealed as an information retrieval error,

Table 3
Error types defined by Stanton and Salmon (2009) and their link to distraction.

Underlying psychological mechanism	External error mode	Distraction as a causal factor	Distraction example
<i>Action errors</i>			
Action execution	Fail to act		
Action execution	Wrong action		
Action execution	Action mistimed		
Action execution	Action too much	✓	Distraction leads to steering overcorrection (e.g., Alm and Nilsson, 1995; Young et al., 2011a)
Action execution	Action too little	✓	Distraction leads to steering undercorrection (e.g., Engstrom et al., 2005; Greenberg et al., 2003)
Action execution	Action incomplete	✓	Failure to turn steering wheel enough leading to heading errors (e.g., Engstrom et al., 2005; Reed and Green, 1999)
Action execution	Right action on wrong object		
Action execution, planning and intention	Inappropriate action		
<i>Cognitive and decision making errors</i>			
Perception	Perceptual failure	✓	Failure to see signs, signals and hazardous events (e.g., Horrey and Wickens, 2007; Klauer et al., 2006)
Perception	Wrong assumption		
Situation assessment	Misjudgement	✓	Misjudge speed of oncoming vehicle and gaps when turning (e.g., Brown et al., 1969; Cooper et al., 2003)
Perception	Looked but failed to see	✓	Look at signs but fail to respond or cannot recall information (e.g., Bruyas et al., 2008; Strayer et al., 2004)
<i>Observation errors</i>			
Memory and recall	Failed to observe	✓	Failure to observe areas to periphery of vehicle, mirrors, instruments, etc. (e.g., Brookhuis et al., 1991; Recarte and Nunes, 2003)
Memory	Observation incomplete		
Situation assessment	Right observation on wrong object		
Memory and recall	Observation mistimed		
<i>Information retrieval errors</i>			
Situation assessment	Misread information	✓	Misread road sign, traffic control device or road markings (e.g., Bruyas et al., 2008; Harbluk et al., 2009)
Situation assessment	Misunderstood information	✓	Perceive information correctly but misunderstand it (e.g., Engström and Markkula, 2007)
Situation assessment	Information retrieval incomplete	✓	Look at signs but later cannot recognise part or all of content (e.g., Strayer et al., 2003, 2004)
Situation assessment	Wrong information retrieved		
<i>Violations</i>			
Action execution, planning and intention	Intentional violation		
Action execution	Unintentional violation		

whereby the driver fixated on the sign but misread the information. It is also noteworthy that, similar to a number of other error taxonomies, Stanton and Salmon's taxonomy lists distraction and inattention as error outcomes rather than as casual factors. In light of the literature reviewed, it is more appropriate to consider concepts such as distraction as factors that contribute to and moderate error occurrence, rather than being considered as the error type *per se*; that is, distraction should be viewed as a factor that influences an outcome rather than as the outcome itself. Distraction and inattention as error types have therefore been removed from Table 3.

7. Distraction and error recovery

While distraction has been shown to contribute to a host of driver errors, less is known about how distraction might affect the error recovery processes employed by drivers. In particular, it is not well understood whether and how distraction might disrupt the steps taken by drivers that would otherwise be sufficient to recover from an error and avoid an incident or collision. There are two possible mechanisms by which being distracted might interfere with the error recovery process: first, drivers' attention being diverted from the roadway may result in drivers detecting that they have made an error too late to initiate a successful response. Alternatively,

distraction might interrupt the development, selection, or implementation of an appropriate and successful error recovery strategy even if the error is detected in time to initiate a recovery response; that is, it impairs a driver's ability to apply a decision rule to successfully execute a response. Distraction may, therefore, manifest at various points in the error recovery process: error detection, response selection, or response implementation.

It is clear that research is needed to explore the relationship between driver distraction and error recovery, including the mechanisms by which distraction may interrupt successful recovery strategies. A clear understanding of the link between driver distraction and error recovery will play an important role in distraction countermeasure development, including informing driver training and the design of distraction mitigation systems in terms of optimal warning timing and content.

8. Discussion

This paper has reviewed the existing distraction literature to examine what is known about the types of driving errors that distraction contributes to and postulate about the mechanisms by which distraction may induce drivers to commit a range of error types. Previous studies into the role of driving errors in road traffic

crashes suggest that observation and recognition errors, decision making errors, and action execution errors are those most prominent in road traffic crashes (Najm et al., 1995; Treat et al. 1979). Our review leads us to conclude that different forms of driver distraction play a role in specific driver error types from within these three categories as specified by Stanton and Salmon's (2009) driving error taxonomy. This finding suggests that further investigation into the role of distraction in the driving errors which are known to lead to road traffic crashes is warranted. While the review leaves little doubt that distraction has a role to play in the causation of driver errors that lead to road crashes, none of the studies discussed have systematically examined the role of distraction in driver error causation, by linking distraction to the specific error types included in the various error taxonomies. Similarly, the theories, models and taxonomies developed for both concepts fail to address the relationship in a systematic and detailed manner (e.g., Reason et al., 1990; Sabey and Taylor, 1980; Sheridan, 2004; Wierwille et al., 2002). As a consequence, even when taken together, the distraction and error literature provide few insights into the relationship between distraction and error.

A more systematic examination of the relationship between the concepts of driver distraction and driver error will have a range of theoretical and practical benefits. From a theoretical perspective, gaining a better understanding of the driver distraction/driver error relationship is important for advancing our knowledge of both concepts. In regard to driver error, it will provide insights into one the key factors that contribute to drivers making errors, which will in turn advance current error models and taxonomies to include more detailed information about contributing factors. In regard to distraction, it will provide greater knowledge regarding the consequences of distraction for driving performance and safety and the mechanisms through which it leads to incidents and crashes. This can in turn inform the development of more a comprehensive model of driver distraction that includes information on distraction outcomes and their associated mechanisms; such a detailed model is currently lacking in the distraction literature.

From a practical perspective, understanding the role of distraction in driver errors and the factors that moderate it can inform the development of better countermeasures to mitigate distraction and consequently lead to a range of safety benefits. For example, training programs could be targeted to inform drivers of how distracting activities can lead to a range of driving errors and what strategies they can take to avoid or minimise these. It can also inform better in-vehicle technology design so that systems are designed to reduce engagement in certain activities or behaviours that lead to errors. Finally, it can also inform wider road system design to remove those elements that exacerbate the negative effects of distraction on errors and make use of those elements that support drivers to minimise the impact of distraction.

It is clear from the review that much further research is needed in this area. Based on the review, it is concluded that there are four major knowledge gaps surrounding the role of distraction in error causation: (1) how distraction affects the number and nature of errors made by drivers and if this differs from undistracted drivers; (2) the mechanisms by which distraction causes errors; (3) whether and how distraction disrupts drivers' ability to recover from errors; and (4) how other factors, such as environmental, vehicle or road infrastructure design, can moderate the relationship between driver distraction and driver error.

That distracted driving leads to a range of errors is incontestable, with a large and growing body of research testifying to this. To date, however, distraction studies have only examined driver error indirectly, focussing on variations in a specific set of driving performance measures that occur as a result of driver engagement in various activities. There is a need, however, for a broader evaluation of how distraction affects the number and nature of errors

made by drivers using the error types identified in the error literature (e.g., how distraction contributes to speeding errors rather than just how it affects mean speed or speed variability). Comparisons also need to be drawn between the errors made by drivers when distracted versus not distracted to identify the key mechanisms through which distraction contributes to accidents. This should include further examination of how different distraction types may differentially contribute to the same error outcomes. Such knowledge would contribute to the development of taxonomies and models of distraction which can then be used to make *a priori* assumptions about the likely impact of newly proposed technologies on driver performance and errors and their likely contribution to road crashes and incidents.

The review also identified a need to develop a better understanding of what mechanisms underlie the relationship between distraction and error. The literature provides some insights into the broad mechanisms, including breakdowns in information processing, impaired visual scanning, and so on, but often the specific mechanisms and at what point in the chain of events they occur still remain unclear. For example, while it is clear that drivers' inability to recognise information and events occurring earlier on in road scenes are often due to information processing deficits rather than failure to fixate the events, it is uncertain if these observed impairments results from disruptions to the encoding of information at the point of fixation or in the retrieval of the information at a later point.

The third key knowledge gap is whether and how driver distraction impairs drivers' error recovery strategies. While it is clear that distraction can contribute to error occurrence, it may also affect drivers' ability to recover from errors once they occur. With a focus on how distraction contributes to performance impairments and errors, there currently exists no information on how distraction might disrupt drivers from recovering successfully from errors. Research is indicated to explore the relationship between driver distraction and error recovery, including the mechanisms by which distraction may interrupt successful recovery strategies, whether this is interrupting error detection, response selection, or response implementation.

Central to contemporary views on both driver distraction and driver error is the notion that in order to fully understand and mitigate against either concept, the entire system, rather than its component parts, should be taken as the unit of analysis (Stanton and Salmon, 2009). A systems-based approach to distraction-related error research that focuses on a range of elements in the road system rather than on individual drivers alone is therefore advocated. In particular, this research should focus on determining what role wider system factors such as device, vehicle and roadway design, road rules and legislation, company culture, and so on, play in moderating the relationship between distraction and error and how these elements could ultimately be used to mitigate the deleterious effects of distraction. For example, the moderating effect of road infrastructure on the relationship between distraction and error is indicated as a key line of inquiry. Recent evidence derived from an on-road study of driver error indicates that poor road infrastructure design has a key role to play in error occurrence (Salmon et al., 2010b). Salmon et al. found, for example, that separation of turn signals from the other traffic signals and inconsistent signalling rules for opposing traffic contributed to a number of red light running error instances in their study. It is likely that infrastructure design has a key role to play in moderating the contribution of distraction to driver errors by either exacerbating or attenuating the effects of being distracted on the number, type or magnitude of errors made by drivers. Other system factors such as company culture, such as the pressure for employees to always be contactable, can also be hypothesised to also moderate how mobile phone distraction might contribute to driver errors. Once

established, information regarding moderating factors will form an integral part of a distraction/error model and any consequent countermeasure development.

8.1. The way forward

With a range of key knowledge gaps identified, the question now is where do we go from here? This question is particularly pertinent in relation to what is the most appropriate theoretical and methodological viewpoint to take in the examination of the distraction, error relationship. In the distraction, error and indeed the wider human factors community a systems approach is now widely advocated. Given that both are complex, multifaceted concepts, distraction and driver error require a more comprehensive description of driver behaviour than that provided by theories that only consider the individual driver. Indeed, a systems approach is essential for identifying, and determining the impact of, the wider road system factors that moderate the relationship between distraction and error.

The requirement for a systems approach becomes further apparent when considering an appropriate methodological approach to adopt when examining the role of distraction in driver errors. One issue that is likely to have prevented researchers obtaining detailed understanding of the relationship between distraction and error is the methodologies used to study both concepts. In the case of driver distraction, most studies have focussed on the effects of distraction on standard driving performance measures (e.g. lateral position, headway, speed) as opposed to specific error types. In the case of driver error, most exploration has centred on the use of the Driver Behaviour Questionnaire (DBQ; Reason et al., 1990) to identify the nature and frequency of the different driver error types made by different driver groups, or on the use of retrospective road crash analysis to identify the different error types involved (e.g. Treat et al. 1979). Although distraction is often identified in crash analysis studies, both approaches yield little information as to whether distraction is a causal factor in the errors identified.

Encouragingly, technological advances now allow more detailed data on driver distraction and error to be collected. Both concepts have seen a move towards the use of on-road instrumented vehicles either under experimental or naturalistic conditions (e.g., Klauer et al., 2006; Olson et al., 2009; Salmon et al., 2010a,b). Use of instrumented vehicles allows the opportunity to understand driver behaviour and performance in ways not previously possible. They allow researchers to collect a range of vehicle, driver and roadway data under real driving conditions that can then be combined to generate a comprehensive model of the various system elements contributing to, and moderating, distraction-related errors. For example, eye glance data can be correlated with vehicle speed data to determine that the driver did not fixate on a speed limit sign and infer that the speeding error resulted from a perceptual failure. Video data can then also be examined to determine if sign placement or the wider road environment (e.g., visual clutter) played a role in contributing to the perceptual failure. Further, combining the use of instrumented vehicles with cognitive task analysis approaches, such as Verbal Protocol Analysis and Critical Decision Method, enables more in-depth interrogation of distraction and error, allowing researchers to gain deeper insights into drivers' cognitive processes while driving. This approach will enable examination of the cognitive factors that contribute to these errors and what strategies, if any, are used by drivers to recover from errors.

Although the advantages of assessing distraction and error during real world interactions are obvious, the use of simulation should not be discounted. Indeed simulators will form an integral component of any in-depth examination of how distraction contributes to certain error types (e.g., failures in hazard detection and response) and disrupts error recovery, because they provide a safe, controlled

environment in which to place drivers in safety-critical situations that would prove too dangerous on-road. Driving simulation will also be vital to evaluating individual roadway or other system components to determine their exact moderating effects, as well as evaluating any modifications made to these system components to mitigate their contribution to distraction-related errors.

A suite of methods including on-road instrumentation and driving simulation, coupled with cognitive task analysis approaches is therefore advocated to examine in a holistic manner, how distraction influences error causation and recovery and what wider system factors moderate this relationship.

8.2. Conclusions

This paper has reviewed the existing distraction literature with a view to elucidating the types of errors that distraction contributes to and the mechanisms by which distraction induces different error types. It was concluded that the notion that distraction has a role to play in the causation of driver errors is irrefutable. However, research focussing on the role of distraction in driver error has to date been sparse and a number of key gaps in literature exist: the number and nature of errors made by drivers when distracted; the mechanisms by which distraction causes errors; whether and how distraction disrupts drivers' ability to recover from errors; and how wider system factors moderate the relationship between driver distraction and driver error. It is argued that these knowledge gaps can only be filled through the adoption of a systems approach to drive the study and modelling of distraction and error. It is only by considering the road transport system as a whole and the linkages between all of its elements that integrated countermeasures can be proposed and implemented to mitigate driver errors caused by distraction and facilitate appropriate error recovery.

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