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Understanding the 'Look but Fail to See' Error

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Abstract

Collisions at intersections, which involve a car driver pulling out into the path of another road user (often a motorcycle), have generally been attributed to a failure in the driver's visual search. These incidents have thus been described as being the result of 'look but fail to see' (LBFTS) errors. This explanation suggests that although the car driver directs their attention towards the approaching vehicle, they do not form a representation of this vehicle, indicating a perceptual error. Previous theoretical frameworks used to understand these crashes have focussed on attentional and perceptual explanations, as well as the possible influence of top-down and bottom-up factors on drivers' behaviour. While the investigation of the influence of top-down factors, such as experience and attitudes, has been continued in the current thesis by examining how these factors may affect drivers' behaviour at junctions, the thesis also considers other potential explanations for the LBFTS error, by breaking down the previous framework into specific testable stages. The structure of the thesis and the theoretical basis for it is described in an extended introduction which is followed by six specific papers presented in the format in which they have been published or submitted for publication.

The first paper in the thesis describes an online survey completed by 579 motorcyclists and 102 car drivers exploring their opinions about junction crashes. The second paper describes a systematic review exploring the role of experience in drivers' visual search strategies. After this there are a series of four papers describing seven different studies conducted in a high-fidelity driving simulator and a validation of one of these studies with drivers in an instrumented car driving real roads in Nottingham. These papers describe the development of a methodology for exploring junction crossing behaviour in a simulator and revealed that drivers are prepared to accept risker gaps in front of approaching motorcycles compared to cars. One critical finding was that drivers' representations for approaching vehicles were often surprisingly poor. There were occasions when drivers failed to report critical approaching vehicles, with these significantly more likely to be motorcycles than cars. These report failures were not predicted by how long the driver fixated on the approaching vehicle, but by drivers' subsequent visual search after fixating on the vehicle. One possible interpretation of these findings is that working memory may play a critical role in understanding junction crashes, with new information interfering with the retention of other safety critical information. A new framework for understanding the role of working memory in such situations is presented, along with proposals for practical interventions to prevent this crash.

Executive Summary

Intersections are a common location for traffic crashes throughout the world, with a large number of these crashes involving motorcycles. Many crashes at junctions involve 'right of way' (ROW) violations with one road user pulling out into the path of another one without ROW. Many of these instances have been put down to 'look but fail to see' (LBFTS) errors, where a car driver reports being careful and attentive with their visual checks but nonetheless fails to see an oncoming road user. A previous framework by Crundall, Clarke, Ward and Bartle (2008) which was created to understand these instances divided the car driver's visual process into three components: Look, Perceive and Appraise. The aim of the current thesis was to extended this framework by breaking down these stages into more distinct, theoretically testable stages which have not been specifically investigated by previous research. The second aim was to improve the previous methodology used to study junction crashes, by using a more immersive driving simulator. The increased flexibility of this driving environment allowed for all specific stages of the extended framework to be experimentally tested.

Papers 1 and 2 include exploratory work which used online questionnaires and pre-existing research, synthesised in a systematic review and meta-analysis. In Paper 1, car drivers' and motorcyclists' opinions about junction crashes demonstrated social aspects of in-group bias, with both groups more likely to blame the other group for general junction crashes. However, this in-group bias was reduced when the context became more specific. Overall, it was generally agreed that a car driver's lack of observation causes them to violate a motorcyclist's ROW in typical LBFTS error instances, indicating the crashes occur due to a visual error. Paper 2 was a systematic review and meta-analysis to formalise previous research which has investigated changes in drivers' eye movements as a function of driving experience. The results showed that differences in novice drivers' and experienced drivers' visual search are not so apparent when the studies are pooled together compared to individual studies, with novice drivers only having significantly narrower horizontal spread of search compared to experienced drivers, with no differences in fixation durations, vertical spread of search and sampling rate. Drivers' visual search was also seen to be sensitive to the additional factor of method type, with it being concluded that measuring drivers'

visual search in immersive driving environments is key to revealing potential visual search differences between these groups.

Papers 3, 4 and 5 consist of experimental work conducted in Nottingham University's driving simulators. Firstly, Paper 3 investigated the effect of cycling experience on drivers' visual attention towards vehicles approaching a junction from constant distances (near, medium, far). Results suggested that there was no difference in drivers' visual attention towards pedal cycles, or any other vehicle, as a function of cycling experience. While all drivers did not direct as much attention towards pedal cycles approaching from a far distance compared to other vehicles types, drivers' broad visual search strategies suggested that they scan the junction appropriately in order to look for potential approaching vehicles. However, this study revealed that there was a lot of variation in drivers' gap acceptance behaviour when vehicles are presented at constant distances, with many drivers failing to pull out in front of vehicles at any distance.

Therefore, in Paper 4, a more efficient gap acceptance procedure was developed to create instances where drivers would pull out in front of approaching vehicles. A new adaptive thresholding procedure was developed by applying methods from visual psychophysics to a gap acceptance driving task, to estimate each individual driver's gap acceptance threshold for both approaching cars and motorcycles separately. Drivers were exposed to vehicles approaching from a wide variety of distances, with the estimated threshold representing the distance of an oncoming vehicle at which the driver has a 50% probability of accepting the gap. It was found that drivers accepted smaller (risker) gaps in front of motorcycles compared to cars, as well as thresholds witnessed in the high-fidelity driving simulator being more representative of real-world gap acceptance thresholds compared to the medium fidelity driving simulator.

Using this gap acceptance procedure, the experimental work reported in Paper 5 focussed on investigating drivers' representations of approaching vehicles on occasions where they chose to pull out in front of these vehicles. Drivers' memory for and estimated location of approaching vehicles was measured. While drivers had a general tendency to estimate vehicles to be closer to them than they actually were, with this bias being larger for cars compared to motorcycles, it was the occasions where drivers completely failed to report an approaching vehicle which was the most striking finding. It was found that drivers failed to recall vehicles on between 13% and 18% of occasions, despite the driver having already fixated on the vehicle. These report failures were not predicted by whether drivers looked at the approaching vehicle, but were predicted by what the driver had looked at after fixating the vehicle. From this series of experiments, it was concluded that many junction crashes that have been attributed to LBFTS errors on real roads may have been misclassified, and actually occur due to a memory deficit, suggesting that these crashes should be referred to as the result of 'Saw but Forgot' (SBF) errors. Due to this finding, a new framework for understanding decision making at junctions was created, known as the Perceive Retain Choose (PRC) model. This model emphasises the role of short-term memory in such situations, allowing for novel countermeasures that may prevent SBF crashes in the future.

Finally, a validation study is reported in Paper 6 which directly compares drivers' visual search strategies on the road and in the high-fidelity driving simulator, in both low and medium demand junction situations. Participants drove a continuous route around Nottingham which contained junctions, with these same situations being recreated in the simulator. The medium demand situations were uncontrolled junctions that required an active scanning of the junction by the driver to decide whether it was safe to pull out. In low demand situations the same manoeuvres were performed but no active scanning was needed since the manoeuvres were required by the road geometry, or controlled by traffic signals. It was found that the size and frequency of drivers' head movements were comparable in both the driving simulator and on the road however, there were differences in subtler measures, with drivers' mean fixation durations being longer in the simulator compared to on-road, particularly in low demand situations. It was concluded that while drivers' general visual search strategies in the simulator are representative of real-world driving, driving simulators may only be useful tools for investigating visual attention at junctions when the demand is at least moderate.

Acknowledgements

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Firstly, my greatest thanks goes to my primary supervisor, Dr. Peter Chapman, as without his guidance, support and encouragement throughout the years, this PhD would not have been possible. I have thoroughly enjoyed working under his supervision, and can only hope we can continue to work together in the future.

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Finally, I would like to thank my family and friends for their endless support and encouragement throughout my 7 years at the University of Nottingham. Special thanks are given to my Father, whose commitment and determination towards his own career has always encouraged me to strive to achieve. Secondly, many thanks are given to my Mother for her patience, faith and confidence in me to complete my PhD. Finally, I would like to thank my grandparents for their love and encouragement throughout my time at university. It is this support network which has been the foundation of my success.

Declaration

This thesis, and the work conducted in the thesis has been generated as the result of my own original research. The systematic review described in Paper 2 was conceived as part of an MSc Module, but conducted during the PhD registration. I would like to thank Adam Sellers (an MSc intern student) who acted as the second independent reviewer for the papers in this review. In Paper 3, the recruitment for Study 1 (n=40) was completed during my dissertation project for the degree of Psychology Research Methods (MSc). These data, along with data collected for Study 2 (n=40) during the PhD, were completely reanalysed together for the current thesis and for the purpose of publication. I would also like to thank Lauren Furlong who helped with the participant recruitment and testing for Study 2. I declare that all other parts of the thesis have not been presented, in this form or any other form, to this university or any other in the application for a degree.

I am first author on all accepted or submitted manuscripts in the thesis, which clearly demonstrates my contribution to the work and writing of the papers. Each manuscript features either my primary supervisor or both supervisors as contributing authors, to acknowledge their help in experimental design, analysis and revisions of the manuscripts. Paper 5 has the added contributing author, Karl Miller, who also helped with the design and testing of participants in Study 1 in this paper. Studies 2 and 3 reported in Paper 5 were conducted solely by myself.

There are two further papers submitted or published during the course of the PhD registration for which I am also first author. The first of these (Robbins, Russell & Chapman, 2019) refers to work that I started as an undergraduate and continued during the PhD registration, but which is outside the theoretical scope of the PhD. The second of these (Robbins, Rogers, Walton, Allen & Chapman, under review) is mentioned in the discussion section, but has not been included as part of the thesis to keep the length down.

1.Introduction

1.1. The Prevalence of Junction Crashes

Intersections are common locations for traffic crashes throughout the world, with around 24% of fatal crashes occurring at junctions in Europe (European Commission, 2015). More specifically in 2017, 36% of all fatalities on UK roads occurred at junctions, which was the highest percentage out of all the countries in Europe (European Commission, 2017). In the US, it is thought that approximately 50% of all injury related crashes occur at intersections, or are intersection related. In addition, approximately 30% of fatal road traffic crashes occur at intersections (NHTSA, 2016). Due to the prevalence of junction crashes worldwide, these road segments have become a target for a wealth of research, with the main aim of understanding why so many crashes occur.

The most common junction crash is known as a 'Right of way' (ROW) crash, with this being not only the most common cause of multi-vehicle crashes throughout Europe (Rumar, 1990; De Lapparent, 2006), but also worldwide. This highly prevalent crash has been reported in the US (Hurt et al., 1981) and Australia (Haworth et al., 2005), as well as in developing countries such as Malaysia, Taiwan and Vietnam (Hsu, Sadullah & Dao, 2003). These ROW crashes occur when a motorist infringes on an oncoming vehicle's right of way, which usually occurs when a car driver pulls out of a junction onto a main carriageway (Pai, 2011). ROW crashes are by far the most common motorcycle crash in the UK, with them being three times more likely to occur at junctions than any other road situation (Hole & Langham, 1997). In these instances, on two thirds of occasions the car driver pulls out of a junction into a main carriageway, and collides with an oncoming motorcycle (Hurt, 1981; Clarke, Ward, Bartle & Truman, 2007). Brown (2002) stresses that in many of these instances, the car drivers reported being careful and attentive in their visual checks, by having looked in the appropriate direction towards the approaching vehicle, but nonetheless failed to see the oncoming motorcycle and person which they collided with. These instances are commonly interpreted as examples of 'Look But Fail To See' (LBFTS) errors (Brown, 2002).

1.2. The ‘Look but Fail to See’ error

An in-depth study in the UK, focussing on 1790 accident cases from the Midland police forces, identified that 38% of fatal road crashes involving a motorcycle were categorised as ROW crashes, with the LBFTS error being one of the primary causes, accounting for around 25% (Clarke et al., 2007). These percentages suggest that this corresponds to approximately 90 deaths per annum in the UK. Based on international crash statistics, it is possible to estimate that up to 100,000 fatalities per year may come from LBFTS crashes (World Health Organisation, 2018). The name of this crash implies that the oncoming vehicle was there to be seen by the car driver, and has also been reported to be visible according to witnesses of these crashes (Williams & Hoffmann, 1979). Motorcycle riders have their own term for such events – ‘SMIDSY’ (“Sorry Mate I Didn’t See You”).

Previous research has found that motorcycles are more likely to be undetected by a car driver on the road compared to an oncoming car (Williams & Hoffmann, 1979), hence this crash being more prevalent with motorcycles compared to other motor vehicles (however, see Cercarelli et al., 1992 & De Craen et al., 2014 for evidence suggesting that car drivers are just as liable to commit LBFTS errors with oncoming cars). In 2017, motorcyclists were involved in 6043 casualty related crashes per billion passenger miles compared to car drivers who were involved in 238 casualty related crashes (DfT, 2017). Motorcyclists are a category of road users who are particularly exposed to the risk of injury or death due to fatal crashes compared to a car driver (Shinar, 2012), and often referred to as vulnerable road users. Many research studies agree that the car driver is primarily to blame in the majority of these crashes, with it estimated that car drivers are to blame for 65% of occasions in the UK (Brown, 2002) and two thirds of occasions in the US (Hurt et al., 1981).

The nature of the LBFTS error in terms of police at-the-scene reporting is rather unclear. Police officers in the UK complete STATS 19 forms when a crash occurs, filling out an accident record, a vehicle record (for each vehicle) and a casualty record (Haigney, 1995). The accident record contains general information on the time/date of accident, weather, light conditions and road type. The vehicle file contains details about the vehicle and the driver such as age, gender, vehicle type, first impact point on the vehicle, and the vehicle manoeuvre. The casualty record provides details about each casualty, as well as the injury severity (Pai, 2009). In addition to this, the police officer has to provide factors that are thought to have contributed to the crash, for example, poor turn/manoeuvre, failure to look properly or failure to judge the other person's path or speed. In cases which are attributed to LBFTS instances, the contributory factor is categorised as a perceptual error, with the driver claiming to not have seen the road user before the collision. Previous research which analysed police post-crash interviews found that both 'distraction' and 'look but fail to see' errors were the most common perceptual errors to be made by drivers (Sabey & Staughton, 1975). However, it is also stated very clearly on the STATS 19 form that the contributory factors being reported reflect the officer's opinions at the time of reporting, and may not be the result of extensive investigation (DfT, 2011). This reporting of crashes still raises the question of whether these LBFTS errors recorded by police are genuine LBFTS errors, and not simply excuses offered by drivers in order to mitigate blame. It is possible that drivers are sometimes deliberately claiming a failure in detecting the oncoming road user when another factor may be responsible for the crash, for example committing a driving violation such as accepting a risky gap between traffic.

If these LBFTS errors are genuine, it is unclear whether the error is caused by a failure to look at the vehicle, a failure to become consciously aware of the vehicle, or a failure to correctly appraise the situation, for example by misjudging the motorcycle's speed or distance. Data from STATS 19 forms cannot distinguish between these, and therefore it is possible that LBFTS errors can be sometimes used a basket term encompassing many subsidiary explanations, ranging from perceptual, attentional, motivational or decision-making errors. There is a general need to assess such crashes in more depth (Pai, 2009), as causality cannot be fully established from these subjective reports. Therefore, the LBFTS error needs to be investigated objectively though the testing of theoretical frameworks and driving experiments.

1.3. Current Framework for Understanding Car-Motorcycle Interactions

There has been one theoretical framework developed to understand car-motorcycle interactions on the road, helping distinguish between the potential attentional and perceptual explanations which could cause junction crashes, and providing a way of testing these individual components of driving behaviour. Crundall, Clarke, Ward and Bartle (2008) developed a framework that described the factors that can influence a car driver's detection, discrimination and appraisal of a motorcycle at a junction, by dividing the visual process into three components, see Figure 1.1. As LBFTS crashes in particular are thought to be explained in terms of a visual error, the framework represents this crash by highlighting the different points where the visual process may break down, potentially leading to a crash. These causes were represented by asking three questions.

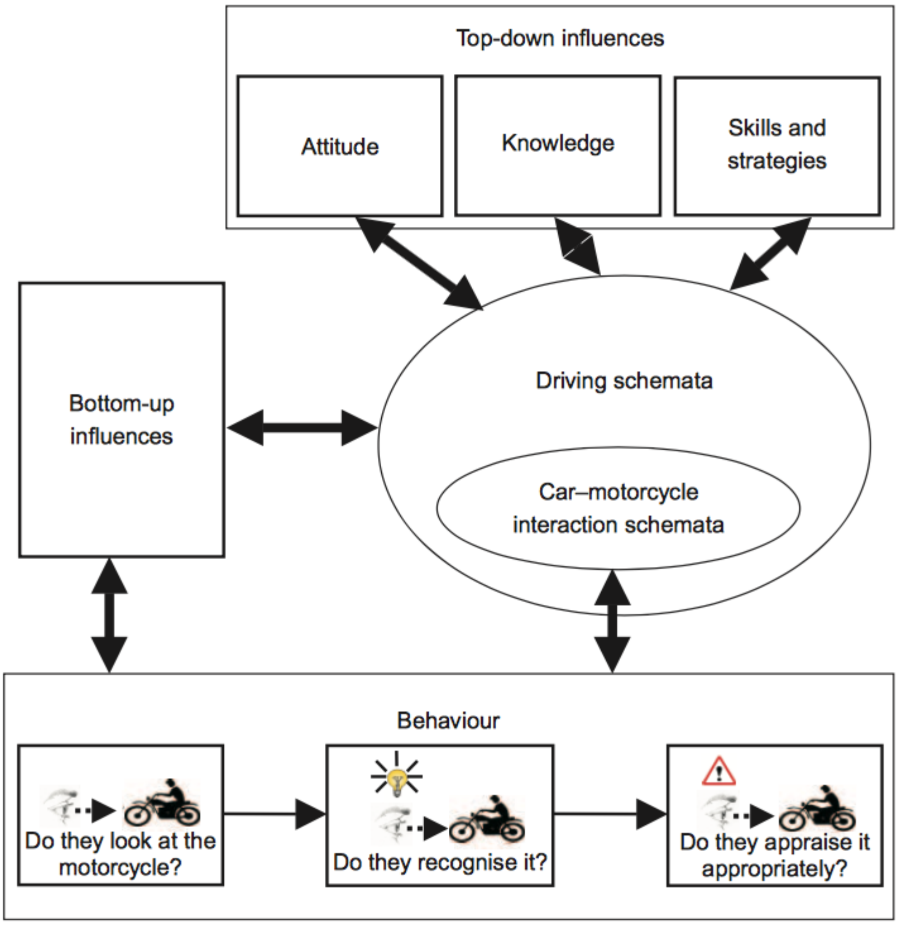

Figure 1.1: A current framework developed by Crundall, Clarke, Ward and Bartle (2008) to understand car-motorcycle interactions on the road. The main section of this framework breaks down the visual process into three stages as a way of investigating junction crashes that have previously been attributed to the LBFTS error. Copyright source for this figure is the Crown.

Firstly, did the driver look at the approaching motorcycle? This refers to whether the driver oriented their eyes in the correct direction of the motorcycle. Secondly, did the driver perceive the approaching motorcycle? It could be possible for the driver to look directly at a motorcycle yet completely fail to register it, therefore failing to form a representation. It is important that the driver identifies the vehicle as a motorcycle before acting. Finally, did the driver correctly appraise the approaching motorcycle in terms of the level of risk that it poses, for example in the gap judgement decision ('would I be able to pull out safely before the motorcycle reaches the junction?').

In addition, the framework indicates that a driver's schema is the most immediate influence on the above behaviours. A schema is a mental structure that helps guide behaviours in the world (Bartlett, 1932). This act of categorisation has been applied to the driving literature (Land & Furneaux, 1997), with schemata containing general laws about driving such as where to look in a given situation, what to expect and what to do with this information. It is also thought that there will be sub-schemata for more specific behaviours, for example, a car-motorcycle interaction schema (Crundall, Bibby, Clarke, Ward & Bartle, 2008). This will guide actions and behaviour in car-motorcycle interactions. Bottom-up and top-down information can influence these schemata, with bottom up influences referring to physical properties of the visual world, such as colour and movement which potentially attract our attention. Top-down influences include drivers' attitudes such as conceptions and misconceptions about driving, drivers' knowledge, referring to their understanding of the world, and drivers' skills which are developed through training and experience. Early driving schemata research has also pointed out that schema are rarely taught, and are instead built up from exposure and experience of situations (Land & Furneaux, 1997).

1.4. Previous Research investigating the LBFTS error

There have been a few studies which have specifically investigated drivers' visual attention towards oncoming vehicles at intersections, directly testing the different visuals stages of the framework. In regards to the first visual stage, which focuses on drivers' ability to look at an approaching vehicle, one study by Labbett and Langham (2006) presented participants with video clips of T-junctions with approaching cars and motorcycles, and recorded their eye movements while these videos were playing. It was found that novice drivers fixated on oncoming motorcycles sooner than more experienced drivers, revealing that problems may be associated with looking at the motorcycle in the first instance. The authors suggested that this may be related to over-learned visual strategies of experienced drivers, implying that junction crashes could be caused by experienced drivers fixating too late on the oncoming vehicle.

Once the current framework for understanding car-motorcycle interactions had been developed, a series of studies were conducted which focussed on distinguishing between the perceive and appraisal stages of the visual process. The first study by Crundall, Humphrey and Clarke (2008) was designed to investigate where the visual process breaks down, by comparing car drivers' abilities to perceive and appraise the risk of approaching motorcycles and cars. Drivers were presented with still images of junctions for either 250ms or 5000ms, with cars and motorcycles approaching at constant distances (near, intermediate and far). Drivers were instructed to press a button if any vehicles were present. It was found that when the stimuli were presented briefly i.e. 250ms, drivers were impaired in their ability to perceive motorcycles compared to cars, demonstrated by participants spotting more cars than motorcycles. However, when participants were given sufficient time to appraise the situation, the type of vehicle made no difference on their judgement. They concluded that the difficulty was not in adequately responding to a motorcycle, but due to the first fixation, which reflects the participant's ability to perceive the motorcycle. This meant that drivers were failing in their ability to process the vehicle sufficiently, by recognising and identifying the vehicle as a motorcycle.

This research was extended by Crundall, Crundall, Clarke and Shahar (2012), who again investigated drivers' visual attention at T-junctions by presenting participants with video clips of cars and motorcycles approaching from near, intermediate and far distances. An additional manipulation involved comparing car drivers with drivers who also rode a motorcycle (dual drivers), to investigate the effect of direct motorcycle experience. In this study, drivers had to press a button when they would pull out of the junction, and were given a single foot pedal to respond to hazards. The results suggested that dual drivers had the safest responses, indicated by increased fixation durations towards oncoming motorcycles. When comparing the experienced and novice car drivers, it was found that experienced drivers fixated for less time on oncoming motorcycles than novice drivers. The authors inferred that a driver's ability to perceive an oncoming motorcycle was the problem, with experienced drivers not spending enough time fixating on the motorcycle in order to identity and categorise the vehicle as a motorcycle. Their interpretation of these results was that experienced drivers do not realise they are looking at a motorcycle and terminate their gaze away prematurely due to decreased expectancy of motorcycles. They concluded that junction crashes occur due to a perceptual error, and that experience in riding a motorcycle can change car-motorcycle interactions, resulting in safer visual search strategies.

However, the reported differences between experienced and novice drivers' visual attention on approaching vehicles are potentially consistent with the exact opposite interpretation of these results, with support from both accident statistics and previous literature. It may be the case that experienced drivers fixate for less time on approaching vehicles because they are able to identify the oncoming vehicle as a motorcycle in a shorter time before moving on. Previous research has found that longer fixation durations are associated with a difficulty in processing stimuli (Rayner, 1998), and LBFTS accident reports indicating that there are no differences in the amount of reported fatal accidents with drivers between the ages of 17-21 years (12.90%) and 30-64 years (12.24%) (Brown, 2002), with these ages reflecting the ages of the novice and experienced groups used in the study. Given that the study did not find any differences between experienced and novice drivers' appraisal, measured by of the number of safe manoeuvres made in front of vehicles, this behaviour does not seem to suggest that experienced drivers had problems in identifying approaching motorcycles.

More recently, Lee at al. (2015) conducted a cross cultural study whereby UK drivers and Malaysian drivers were compared in their ability to perceive or appraise motorcycles at junctions. Given that Malaysian drivers are exposed to more motorcycles in everyday driving, the authors suggested that they would have increased expectancy of approaching motorcycles on the road. Using the same methodology as Crundall, Humphrey and Clarke (2008), participants were presented with static images of junctions with cars and motorcycles approaching from near, intermediate and far distances. It was found that there were no differences between Malaysian and UK drivers in their ability to perceive approaching motorcycles, demonstrated by similar accuracy in spotting motorcycles. However, they did find that Malaysian drivers were better at perceiving motorcycles at further distances. Despite this, the accident rates involving motorcycles in Malaysia, considering the exposure effect, are not lower than those in the UK. A potential explanation for this was provided by a second experiment, which found that Malaysian drivers were more likely to judge it was safe to pull out in front of the motorcycle compared to UK drivers, suggesting that they have riskier appraisal which may contribute to the high accident rates.

1.4.1. Problems with Research Methodology

These research studies have started to formally test possible causes for junction crashes by using laboratory-based experiments. However, one of the most obvious limitations of this research is the use of static images and video clips of junctions in order to measure drivers' gap acceptance and visual attention towards oncoming vehicles. These methodologies fail to meet fundamental requirements when studying drivers' behaviour at junctions, and in particular when studying the LBFTS error.

Firstly, these methods fail to provide drivers with the additional demands which everyday driving involves, for example vehicle control. From the previous research studies discussed, the most methodologically advanced laboratory experiment was the one conducted by Crundall, Crundall, Clarke and Shahar (2012) which provided participants with a hand-held button to indicate manoeuvres, and a single foot pedal to respond to hazards. Previous researchers who used a medium-fidelity driving simulator with all vehicle control elements to study hazard perception (Crundall, Chapman & Trawley, 2012) stressed the advantage of the driver remaining in control of the vehicle at all times during testing, as the resources required to scan for hazards are shared with resources required for normal driving. This suggests that the simulator is not only more realistic than fixed videos, but allows for performance limitations to be uncovered that would not be present when testing a driving skill in isolation.

It can be argued that previous experiments have merely been observation tasks, with the task either not requiring drivers to decide when to pull out at the junction or using simple button pressing measures. Given that junction manoeuvres are associated with a multi-stage task, with drivers having to firstly direct attention to all relevant potential hazards (look and perceive), and then act on this information by accepting a safe gap in the traffic (appraise), drivers' have more resources available in these simple observation tasks compared to when the task requires drivers to make a full manoeuvre.

Previous methodology may also underestimate the impact of some factors upon appraisal, for example, drivers' ability to predict the behaviour of other road users. Previous research by Lee and Sheppard (2016) who investigated the effect of motion on drivers' ability to predict the intention of other road users, found that drivers are more accurate in their judgements when they are presented with dynamic stimuli compared to static, with drivers benefiting from the additional information such as the deceleration of vehicles and the progression of the vehicle's location. This is particularly important when investigating junction manoeuvres, as once a driver has detected an oncoming vehicle, they must judge whether they have sufficient time to pull out, requiring an estimate of the vehicle's time-to-arrive (Horswill et al., 2005). Previous research has also found that object size can affect these judgements, commonly termed the size-arrival effect (DeLucia, 1991). This illusion leads to the prediction that larger vehicles such as cars may be judged to arrive sooner than smaller vehicles such as motorcycles (Caird & Hancock, 1994). These potential problems with the appraisal of approaching motorcycles highlight the need to use dynamic immersive stimuli.

Finally, the visual field which drivers have access to while driving in real world contexts cannot be represented by these previous methods. Although Crundall, Crundall, Clarke and Shahar (2012) improved previous methodology by using a multi-screen video test which provided participants with a wide view which allowed them to turn their head left and right towards conflicting traffic, even this visual field is still not the same as the view in a real car. Alberti et al. (2014) found that drivers' behaviour changes as a function of field of view, with a wide field of view reducing the likelihood of crashes and eliciting safer responses when navigating around hazards. This suggests that in order to generalise findings to real world driving situations, methods which restrict the drivers' field of view could be argued to be insufficient.

One of the main aims of the current thesis is to improve previous methodology by investigating junction crashes using simulated driving. Due to the simulators' ability to provide participants with experimental driving tasks where they can approach a junction multiple times and decide when to complete the manoeuvre, as well as the simulators' flexible nature in terms of allowing vehicles to be added to the task in a systematic and controlled way, this creates potential for the current framework to be extended by breaking down this complex behaviour further.

1.5. Proposed Extension to the Framework

1.5.1. Justification for the Extended Framework

The framework developed by Crundall, Clarke, Ward and Bartle (2008) includes the initial components needed to understand the potential causes of junction crashes, in particular the LBFTS error when making a distinction between attentional and perceptual explanations which can be experimentally tested. However, as can be seen by the previous research studies, there has been no consensus in conclusions when determining where a car drivers' visual process breaks down when interacting with a motorcycle approaching a junction. While some studies conclude that it's the driver's ability to look or perceive the approaching motorcycle that is the problem, by analysing drivers' eye movements on and towards the approaching vehicle, others conclude that the cause is the driver's ability to correctly appraise the situation and behave appropriately.

This inconsistency in results could be partly due to problems with the different types of simple methodology as discussed above, but could also be due to the fact that this framework only breaks down the visual process into three crude stages, without breaking these down further into specific cognitive errors in terms of search and situational awareness. For example, the time course of drivers' visual checks at the junction could involve search that is either too early or too late. In terms of appraisal, there are many possible explanations for a driver unsafely pulling out in front of a motorcycle which the current framework does not distinguish between, for example, a driver forming a distorted representation of the oncoming vehicle's speed, a driver's distorted decision caused by a reduced feeling of threat for oncoming motorcycles, or a driver failing to retain a full representation of the surrounding environment when deciding to pull out of the junction.

For this reason, there is a need for the coarse stages in the current framework to be broken down into more theoretically testable stages, which will allow researchers to be more accurate in pinpointing where the failure in drivers' visual search occurs. This is extremely important for both the replication of results and for targeting specific interventions. In addition, the use of a high-fidelity driving simulator to conduct these experiential tasks also allows for the task to be more generalised i.e. different vehicle types, vehicle distances, and numbers of vehicles. These changes make it possible to test specific processes involved in this complex dynamic behaviour.

An extension to the Crundall, Clarke, Ward and Bartle (2008) framework was created, using the three initial questions which highlight the points where the visual process may break down, along with the errors that can occur at each stage, as well as the two outcomes that can result from successful visual search. See Figure 1.2 for the extended flow diagram.

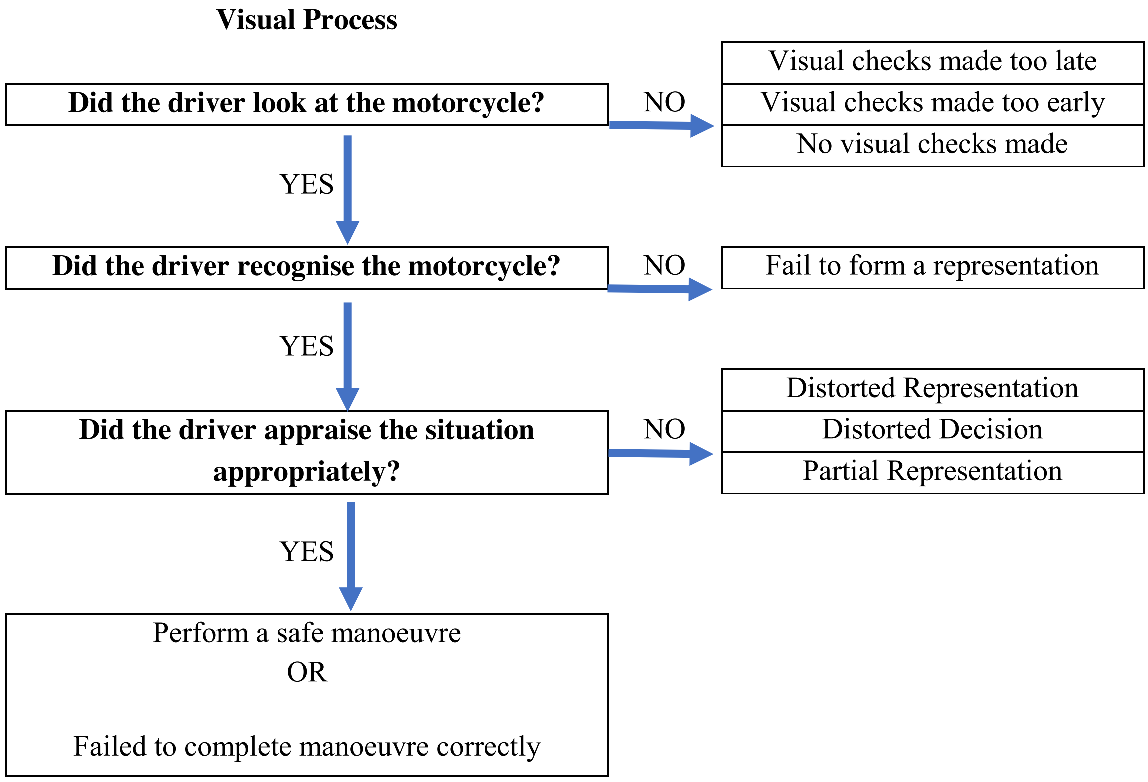

Figure 1.2: An extension of the Crundall Clarke, Ward and Bartle (2008) framework which breaks down the three initial visual processes further to display additional errors which can be experimentally tested.

1.5.2. Theoretically Testable Stages of the Extended Framework

In the initial framework, the criterion for a driver successfully looking at the oncoming vehicle was simply whether the driver directed their gaze in the direction of the oncoming road user. However, this aspect of visual attention could be broken down even further by focussing on the time course of these visual checks. Current visual processing theories suggest a distinction between two mechanisms when viewing a natural scene, a perceptual process which extracts information about the visual input at around 80ms, and a higher-level decision process evaluating the relevance of this information to generate appropriate behavioural responses at around 150ms post stimulus (Vanrullen & Thorpe, 2001).

With this in mind, firstly it could be the case that the driver fails to make any visual checks in the direction of the oncoming vehicle, suggesting that junction crashes categorised as LBFTS errors occur due to the driver failing to perform any visual checks towards the oncoming road user. While this may be possible on habitually empty roads, drivers have been seen to consistently look to the left and right of a junction before proceeding through an intersection in both simulated environments and on real roads (Shechtman et al., 2009). A second potential explanation is that the driver fails to make their visual checks at the appropriate time. If the driver looks to one side of the junction, and appraises the situation as safe it does not necessarily mean that the situation will still be safe when they actually start their manoeuvre. Information gained from an early look to one side may no longer be relevant after extensive time spent looking elsewhere. Conversely, it could be possible that the driver makes a visual check after having committed to the manoeuvre, by which time it is too late to abort the manoeuvre if an oncoming road user is detected. A distinction needs to be made been these possible visual search strategies.

In regards to a driver’s ability to perceive an approaching vehicle, the framework developed by Crundall, Clarke, Ward and Bartle (2008) suggests that a driver may make the correct visual checks towards the vehicle but completely fail to identify it. Previous measures that have been used to determine whether a driver has identified an oncoming vehicle as a motorcycle include the amount of visual attention drivers devote towards the approaching vehicle, as well as laboratory experiments instructing participants to behaviourally acknowledge an oncoming vehicle by pressing one of two buttons to report whether an oncoming vehicle was present in the scene or not (Crundall, Humphrey & Clarke, 2008). This previous behavioural method of testing drivers’ ability to perceive an oncoming vehicle does not explicitly test drivers’ categorisation of the vehicle, e.g. motorcycle, pedal cycle, car or large vehicle, with drivers only acknowledging an approaching stimulus. The framework by Crundall, Clarke, Ward and Bartle (2008) highlights that for a driver to form an accurate representation of the stimulus, it is important that the driver identifies and categorises the vehicle as a motorcycle before acting. Therefore, an explicit categorisation of the approaching vehicle, as well as the direction the vehicle is approaching from are important in regards to the future appraisal of the situation.

The final visual stage of the framework is the appraisal stage, which refers to whether the driver appraises the situation correctly in terms of the risk the oncoming vehicle poses, and whether they can safety pull out in front of the vehicle. This visual phase can be broken down into three potential errors, with the first referred to as a distorted representation. A distorted representation refers to when a driver has formed a representation of the approaching vehicle however, this representation is misleading due to other possible factors. It may be that a distorted representation occurs when a driver misinterprets an approaching motorcycle's speed or distance. An established finding by DeLucia (1991) is that smaller objects are perceived to arrive later than larger objects, suggesting that a motorcycle's estimated time-to-arrive will be later than that for a car. This finding is similar to the concept of visual looming, with the rate of expansion of a car being easier to detect (above detection threshold) than that of a smaller motorcycle (Wann et al., 2011). In order to investigate drivers' distorted representations in more depth, more explicit tests of drivers' situational awareness need to be experimentally investigated such as estimating the location and speeds of vehicles approaching the junction.

The second possible explanation for incorrect appraisal is a distorted decision. It is possible for a driver to decide, based on a distorted motorcycle schema, to behave differently around oncoming motorcycles compared to other vehicles. As highlighted by Crundall, Clarke, Ward and Bartle (2008), as well as additional perceptual models such as the Neisser's perceptual cycle model (Neisser, 1976), schemata play a key role in determining behaviour, which are influenced by both the physical properties of the world and drivers' attitudes in terms of their knowledge and experience. These influences can, either singly or in combination, distort a car drivers' decision when pulling out in front of a motorcycle at a junction. Previous research has found strong differences in car drivers' and motorcyclists' schemas, indicating that at an intersection, car drivers focus on the intersection itself and in front of the vehicle, whereas cyclists and motorcyclists had a strong focus on other traffic approaching the junction and their behaviour around the intersection (Salmon at al., 2014). With this in mind, car drivers' attitudes and experience may elicit a distorted decision around motorcycles, for example, a car driver believing they have ROW over a smaller road user at an intersection and therefore choosing to accelerate out of the junction. This behaviour could also be explained in terms of an assessment of risk, with a car driver choosing to accept a smaller gap in front of an approaching motorcycle due to perceiving them to be less threatening compared to cars (Simmel, 1944).

Finally, the third possible explanation is termed a partial representation. A partial representation invites the possibility that drivers may have initially formed a complete representation of all vehicles approaching the junction however, these representations may be incomplete or absent at the time they chose to pull out. This could be because information has changed since the time of acquisition, or because the driver has forgotten relevant information. Given that a junction manoeuvre is a short, dynamic behaviour that requires the integration of information across head and eye movements, it likely that relevant information is stored in drivers' working memory, which has been argued to have a limited capacity (Baddeley, 1974). Therefore, it is possible that information which has previously been fixated could be subject to decay or interference from other traffic in the visual scene. Again, in order to investigate whether drivers have a full representation of all vehicles surrounding them, drivers' memory for vehicles at the time they pull out of the junction could be explicitly investigated.

For completeness of the model, there are two potential outcomes that could occur when the driver has made all the necessary visual checks and has decided to pull out of the junction. More often than not, a driver will perform a safe manoeuvre at the junction. However, it could also be possible that the driver simply fails to perform the manoeuvre correctly due to problems with vehicle control (e.g. attempting to pull out in the wrong gear). In such cases a LBFTS error may be simply an excuse offered by the driver to cover their incompetence in basic vehicle control.

1.6. Thesis Overview

The following section will give a brief overview of the six papers and their included studies that make up the core content of the thesis, as well as an overview of how each of these papers contribute to the new extended framework, which is summarised in Figure 1.3. In addition, this section will also detail how each study evolved through the development of methodology and theory.

As previously highlighted, police at-the-scene reporting appears to agree that car drivers are primarily to blame when colliding with a motorcycle, particularity in situations which are thought to resemble the LBFTS error, with the car driver having violated the oncoming motorcyclist's ROW. However, much of this opinion has been generated from accident stories which are interpreted by the police officer (Clarke et al., 2004). Although this is an important source of data, it is also useful to investigate whether the road users involved in such collisions (car drivers and motorcyclists) agree with this attribution of blame. Given that these collisions are caused by some level of interaction between both a car driver and motorcyclist, these road user groups may differ in their attribution of blame depending on the situation that is being presented.

Paper 1 therefore investigates the possibility of a distorted decision, by using an online questionnaire to directly compare car drivers' and motorcyclists' opinions about the blameworthiness of junction crashes, as well as the reasoning behind these choices, for example, the car driver was at fault as the motorcycle has ROW. Given that human behaviour has been seen to be largely influenced by a person's attitudes towards a given object (Fishbein & Ajzen, 1975), or in this case road user, this may determine their behaviour when interacting with this road user on the road, with their responses highlighting possible reasons behind a distorted decision, see Figure 1.2. More specifically, this questionnaire is related to a distorted decision in terms of drivers' assessment of risk, as a car driver may believe they can force their way out into a junction in front of a relatively unthreatening motorcycle.

The questionnaire included both general questions about the cause of and blame for junction crashes, as well as questions about specific situations which included ROW violations and overtaking crashes near junctions. It was found that road users' opinions regarding blame attribution in collisions changed depending on how specific the situation was that was being presented. When asked generally about junction crashes, car drivers' and motorcyclists' responses significantly differed, demonstrating an in-group bias. However, when the situation was more specific, this in-group bias was reduced with car drivers more likely to blame car drivers and motorcyclists more likely to blame motorcyclists. This basic finding reflects one of the classic reported biases in social psychology, with people favouring their own group, however, these judgements can be seen to be context dependent (Ratner et al., 2014). In regards to ROW crashes, both categories of road users highlighted the most common cause was a lack of observation by car drivers, therefore, given the previous literature and the findings presented in Paper 1, the following studies in the thesis focus on car drivers' behaviour and visual attention towards oncoming vehicles when approaching a junction in an experimental setting.

Paper 2 was a systematic review and meta-analysis, which was conducted to investigate whether drivers' eye movements differed as a function of driving experience. Given that junction crashes categorised as LBFTS have previously been explained by a visual deficit, this systematic literature search was able to find relevant papers which focus on drivers' visual search while driving. As eye movements are the best indicator of interpreting whether a driver looked in the direction of an approaching vehicle at a junction, as well as fixated on the vehicle long enough to form a representation, Paper 2 focuses on these first two sections of the extended framework, see Figure 1.2.

A large number of previous research studies which investigate junction crashes have also compared the visual attention of drivers that differ in experience. More specifically, there have been studies which have investigated the effect of experience on drivers' visual attention towards vulnerable road users (Crundall, Crundall, Clarke & Shahar, 2012; Beanland & Hansen, 2017). The rationale behind these studies, which is included in the original framework by Crundall, Clarke, Ward and Bartle (2008), suggests that experience and training have an immediate influence on drivers' schemata, which should ultimately influence how they behave in particular situations.

Despite a wealth of studies claiming that novice drivers' visual search differs from experienced drivers' visual search in a number of ways, the systematic review found only limited differences. When the data from individual studies was synthesised, it was found that novice drivers had a narrower spread of horizontal search compared to experienced drivers however, there was no evidence to suggest differences in fixation durations, vertical spread of search and sampling rate. Visual search measures, particularly fixation durations and horizontal spread of search, were sensitive to the inclusion of extreme experience groups i.e. learner drivers and driving instructors or police pursuit drivers, as well as the method type. It was apparent that the majority of studies included in the systematic review used simple methodology as previously discussed however, differences between novice drivers' and experienced drivers' visual search was more likely to be seen in immersive driving environments, i.e. driving simulators and on-road.

The studies in Paper 3 were the first in this series of studies to be conducted using the Nottingham Integrated Transport and Environment Simulation (NITES) facility's high fidelity driving simulator. The primary aim was to investigate whether drivers' visual search behaviour at junctions towards pedal cycles, motorcycles and cars differed, with these vehicles placed at near, medium and far distances. This particular paper was broken down into two studies, whereby in Study 1 drivers were exposed to a 'Give Way' sign and in Study 2 drivers were exposed to a 'Stop' sign at the end of the junction. This road sign manipulation was incorporated in order to develop a method where drivers would approach the junction cautiously and make an informed decision on when to pull out of the junction, based on approaching traffic.

An additional goal for the studies in Paper 3 was to investigate whether experience in a specific mode of transport alters car drivers' visual attention towards this specific road user. Given that previous research has investigated how experience on a motorcycle can alter drivers' visual attention towards motorcycles for the better (Magazzu at al., 2006; Crundall, Crundall, Clarke & Shahar, 2012), these studies aimed to extend this line of research to pedal cyclists, an often-neglected vulnerable road user in the LBFTS literature. The aim was to recruit cyclists and non-cyclists, and compare their visual attention towards approaching pedal cycles, but also to investigate whether this experience can also influence visual attention towards other road users. Given the scope of the project, cyclists were also an accessible group due to students and staff regularity cycling to work every day.

By extending this research to pedal cycles as opposed to motorcycles, this paper provides advances in regards to the look and appraise sections of the extended framework, see Figure 1.2. The studies in Paper 3 focus on all the possible errors that drivers may have in regards to looking in the direction of the approaching vehicle, with these studies being the first experimental studies to investigate drivers' broad visual search strategies towards oncoming vehicles as they approach a junction and perform a manoeuvre. In addition, given that pedal cycles are typically smaller and slower than other motor vehicles, these studies address the possible explanations of a distorted representation and a distorted decision. The results of the studies in Paper 3 found that drivers approached the junction at higher speeds and had more near crashes with approaching pedal cycles compared to motor vehicles, with it being concluded that drivers were more likely to take a chance in front of a pedal cycle compared to a motorcycle or car. This finding could be due to a distorted representation, with drivers underestimating the speed of pedal cycles. Although all vehicles were approaching the junction at identical speeds in this particular study, it is common for pedal cycles to travel at slower speeds compared to motor vehicles. It could also be possible that drivers made a distorted decision based on their opinions about pedal cyclists, for example, thinking that pedal cyclists are not rightful road users compared to larger motor vehicles and should not be sharing the road.

The main design of the studies in Paper 3 was based around previous research, with many studies studying junction behaviour using the method of constant stimuli, i.e. placing vehicles at near, medium and far distances from the junction, as this method has been seen to provide a range of responses from the driver (Crundall, Humphrey & Clarke, 2008; Crundall, Crundall, Clarke & Shahar, 2012). This method also allowed for the three vehicle types (car, motorcycle, pedal cycle) to be repeatedly presented at the three distances to participants, in order to average visual attention variables over multiple trials. The distances where chosen to elicit a range of responses from drivers, where the majority of participants would not pull out in front of a near vehicle but would pull out in front of a far vehicle. The medium vehicles were believed to be placed at a critical distance where participants had to decide whether to pass before or after the vehicle.

Although these constant distances may have been sufficient in producing a variation in responses when presenting drivers with static images of vehicles approaching a junction, this did not seem to be the case for a simulator study, causing problems for later analysis. This method produced some instances where a driver pulled out before the vehicle on all occasions, or conversely pulled out after the vehicle on all occasions. For the participants who did vary their behaviour, it did not always vary enough to compare instances where drivers pulled out in front of the vehicle as opposed to when they waited for the vehicle to pass. This meant that although general conclusions were able to be made about drivers' broad visual search towards differing road users, our conclusions were limited. The trials of particular interest were ones where drivers were willing to pull out in front of approaching vehicles, as this is ultimately what happens when a crash occurs. This limitation required the development of a more efficient and suitable method to investigate the LBFTS phenomenon.

Given the limitations of the methodology described in Paper 3, a new way of testing was devised which would elicit multiple instances where drivers would pull out in front of closely approaching vehicles. The study described in Paper 4 therefore compared drivers' gap acceptance behaviour towards oncoming motorcycles and cars at junctions, using an adaptive psychophysical technique to calculate each individual driver's gap acceptance threshold. These thresholds represent an estimate of the distance of oncoming vehicles at which the driver has a 50% probability of accepting the gap. This adaptive probit estimation approach from Watt and Andrews (1981) is based on the classical method of constant stimuli described in Paper 3, but differs as it adjusts the placement of the stimuli during the trials according to the outcome of the probit analysis (Treutwein, 1995). The specific thresholding procedure used was a QUEST Bayesian adaptive staircase procedure (Watson and Pelli, 1983).

Given that we know there is variability both within and between drivers in their gap acceptance behaviour from the previous study, this design allowed for each individual driver's gap acceptance threshold to be measured, collecting data when the participant passed before and after the target vehicle, as well as tightly measuring around the threshold decision region, where the driver may go before or after the vehicle. This threshold region is of high interest as this is where active decisions are being made by the driver, and behaviour could subtly differ as a function of approaching vehicle type. In addition, not only does estimating drivers' gap acceptance thresholds show subtle differences in how drivers are reacting around different approaching vehicles, it also gives important information itself in regards to what stimuli are equivalent for drivers in terms of their elicited behaviour, for example, a motorcycle at 60 metres may be equivalent to a car at 70 metres.

In regards to the extended framework, Paper 4 addresses two possible appraisal explanations, a distorted decision and distorted representation, see Figure 1.2. As alluded to in the framework developed by Crundall, Clarke, Ward and Bartle (2008), junction manoeuvres can be explained as a two-fold task, with drivers having to firstly direct attention to all relevant objects in the traffic scene, and the second is to act on this information, accepting a safe gap in the traffic. While many of the studies in this thesis focus on the former by investigating the different visual search strategies towards motorcycles and cars at intersections, Paper 4 focuses on the latter by simply focusing on drivers' behaviour at intersections in terms of accepting a suitable gap in traffic.

The study revealed that drivers generally accepted smaller gaps in front of motorcycles compared to cars. In terms of the extended framework this could be seen as a distorted decision. It could be possible that drivers have reduced feelings of threat for motorcycles compared to cars, or a false belief that they have ROW over the smaller oncoming road user. Alternatively, it is a possibility that this is a result of a distorted representation, with drivers misjudging the motorcycle's speed or distance from the junction. If drivers believe the motorcycle is further away than it actually is, this may result in drivers accepting risker gaps in front of motorcycles compared to cars.

An additional manipulation in Paper 4 was the fidelity of the driving simulator, comparing drivers' gap acceptance behaviour in the NITES high-fidelity driving simulator and in the NITES medium fidelity driving simulator. As there is limited research investigating drivers' behaviour at junctions using a driving simulator, it was important to investigate whether there were marked differences in drivers' gap acceptance behaviour in simulators that differ in fidelity, and how these gap acceptance estimates compared to on-road research. It was found that drivers accepted shorter gaps in the medium fidelity driving simulator compared to the high-fidelity driving simulator, with gap acceptance estimates in the high-fidelity simulator being more comparable to on-road driving studies. This suggests that the medium fidelity driving simulator was not eliciting comparable behaviour to real world driving compared to the high-fidelity simulator and therefore due to this finding, the subsequent studies in the thesis were conducted in the high-fidelity driving simulator. The possible reasons for the differences in drivers' gap acceptance behaviour in the two simulators are discussed in Paper 4, with one of the possible explanations relating to the previously mentioned limitation of a restricted field of view (Alberti et al., 2014).

In addition, the studies in Papers 3 and 4 both used a single target vehicle in all scenarios of interest when investigating drivers' gap acceptance thresholds and visual attention towards these vehicles. This has also been the most common approach for previous research (Crundall, Humphrey & Clarke, 2008; Crundall, Crundall, Clarke & Shahar, 2012). Although this design has its benefits in regards to simplifying the environment in order to understand the potential visual deficits that may occur towards approaching road users, this is not representative of many real world situations. When approaching and scanning a junction, visual attention often has to be distributed between multiple vehicles. Although the use of a single target vehicle approaching the junction could be argued to be necessary with the previous methodologies using static images of junctions (Crundall, Humphrey & Clarke, 2008), the flexible nature of a driving simulator allows for multiple vehicles to be added to scenarios and systemically varied. By including scenarios which contain multiple vehicles, this advances all stages of the extended framework, by firstly investigating whether drivers are still able to correctly look and perceive all potential sources of danger. It also creates an environment to test the possibility of a partial representation, investigating whether drivers have an accurate representation of their surrounding environment as multiple vehicles have the potential to act as a source of interference.

The methodology developed in Paper 4 was successful in creating instances where drivers would pull out in front of oncoming vehicles approaching at threshold. By using this method, it was of great interest to investigate drivers' representations of oncoming vehicles at the point where they were willing to pull out of the junction. Paper 5 consisted of a series of simulation studies which measured drivers' situational awareness for oncoming vehicles by looking at drivers' memory for and estimated location of approaching vehicles. Given that junction manoeuvres are a complex behaviour, requiring the driver to retain task relevant information in working memory while simultaneously making head and eye movements to scan around the environment (Baddeley, 2007), these studies are able to investigate the accuracy of drivers' temporary storage of visuospatial information about vehicles around them (Salway & Logie, 1995).

By investigating drivers' memory for oncoming vehicles, this explored the possible explanation of a partial representation in the extended framework, as drivers may fail to recall all approaching vehicles and therefore not have a full representation of the surrounding environment, see Figure 1.2. As drivers were also asked to estimate the location of correctly recalled vehicles, this measure also explores the possibility of a distorted representation, as drivers may have a bias in estimating certain vehicles to be closer, or further away than they actually are.

In Paper 5, there are a series of studies labelled 1, 2 and 3. Study 1 used the method of constant stimuli to investigate drivers' representations of approaching cars, motorcycles and large vehicles, with vehicles presented at near, medium and far distances, similar to the studies in Paper 3. The most surprising finding from this study was that drivers in a memory test condition failed to recall an approaching vehicle on 7.4% of trials, despite there always being two vehicles approaching the junction. On the occasions where drivers failed to recall an approaching vehicle, it was found that drivers failed to recall significantly more motorcycles than cars and large vehicles. This finding was a striking one, with clear potential relevance for understanding the LBFTS crash. However, in Study 1 there was no way of knowing whether the driver would have pulled out before or after the approaching vehicles, due to the simulation being terminated for the memory tests when the driver reached the junction, and due to the previously discussed limitations with the method of constant stimuli. The study was thus modified to make use of the thresholding procedure developed in Paper 4.

Studies 2 and 3 were designed to investigate whether memory failures still occur when a driver is willing to pull out in front of approaching vehicles. This was achieved by estimating each driver's individual threshold over a series of fixed distance trials, and then subsequently testing drivers' memory for vehicles at threshold, on occasions where they began to pull out in front of the vehicles.

Again, it was found that drivers often failed to report approaching vehicles at the junction, failing to report significantly more motorcycles than cars. It was also found that there was no difference in drivers' fixations on forgotten and remembered motorcycles however, their subsequent visual behaviour after fixating on the approaching vehicle did predict recall failures. From this series of studies, it was concluded that the results provide support for the idea of 'Saw but Forgot' (SBF) errors, with drivers fixating on, but failing to subsequently recall approaching motorcycles. In Paper 5 we propose that these findings are in at least part due to drivers' subsequent visual behaviour interfering with the previously encoded information, causing the driver to forget this when immediately tested. This proposes the novel explanation that some junction crashes could occur due to failures in short term memory, with many crashes that have previously been attributed to LBFTS errors being misclassified. While genuine LBFTS errors remain likely, it is possible that many crashes that have received this label were not the result of a failure in visual attention, but were instead caused by a failure in memory.

Finally, as aforementioned the majority of studies in this thesis have been conducted in a high-fidelity driving simulator, improving and extending previous research methodologies which investigate drivers' behaviour at junctions. However, in order to generalise these findings to real world driving behaviour, it is important to compare drivers' visual attention at junctions in the simulator to real on-road driving. Paper 6 thus reports a study which was conducted to compare drivers' visual attention on real roads with their behaviour in the simulator. The study used a within-participants design measuring visual attention at low and medium demand junctions, on the road and in the simulator, by matching the road geometries in the two environments. The NITES high fidelity driving simulator was used, as well as a fully instrumented on-road car with tracking of head and eye movements in both environments done using a head-mounted eye-tracker.

This study explores the basic visual checks that drivers make at genuine everyday junctions, see Figure 1.2, by comparing drivers' visual search strategies on the real roads to the driving simulator. In all instances throughout this experiment, drivers always made a successful manoeuvre at the junction. It was found that drivers' broad visual search patterns in terms of head movements were similar in the two environments. However, there was a difference in drivers' mean fixation durations in the two environments, with mean fixation durations being longer in the simulator compared to on-road, particularity in low demand situations. These findings suggest that a driving simulator can be a useful tool for investigating drivers' visual attention at junctions, particularly when the driving task is of at least moderate demand.

In summary, there are two key questions motivating the research described in the papers. The first question concerns general ways in which drivers' visual search and crossing behaviour might differ at junctions depending on the type of vehicles that are approaching. The second question concerns the types of representations that drivers might have of oncoming vehicles when they pull out at a junction. One surprising conclusion is that some junction crashes that have been traditionally attributed to LBFTS errors may be cases where a relevant oncoming vehicle has been seen, but has been forgotten by the time the driver actually pulls out into the junction.

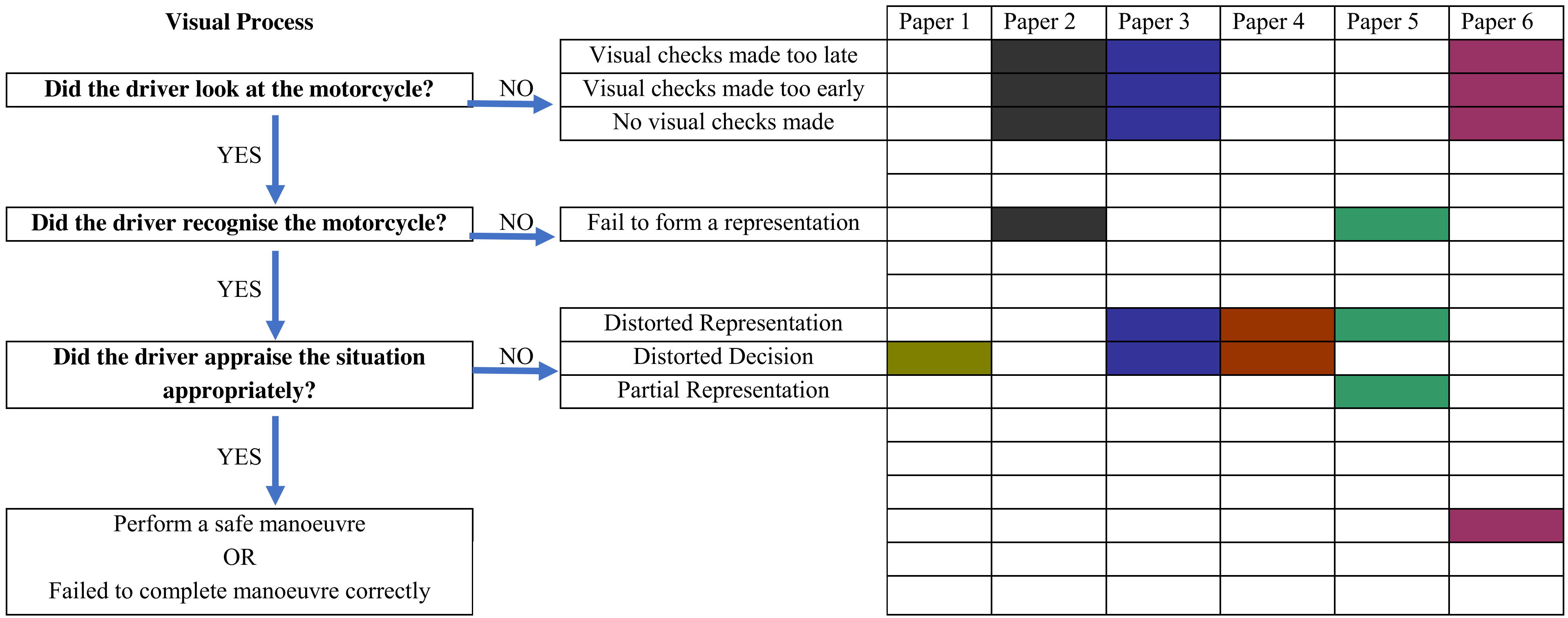

Figure 1.3: An overview of which papers in the thesis contribute to each section of the extended framework in the form of a Gantt chart.

Paper 1

Comparing car drivers’ and motorcyclists’ opinions about junction crashes

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Comparing car drivers' and motorcyclists' opinions about junction crashes

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ABSTRACT

Motorcyclists are involved in a disproportionate number of crashes given the distance they travel, with a high proportion of these crashes occurring at junctions. Despite car drivers being solely responsible for many road crashes involving a motorcycle, previous research has mostly focussed on understanding motorcyclists' attitudes towards their own safety.

We compared car drivers' (n = 102) and motorcyclists' (n = 579) opinions about junction crashes using a web-based questionnaire. Motorcyclists and car drivers were recruited in similar ways so that responses could be directly compared, accessing respondents through driver/rider forums and on social media. Car drivers' and motorcyclists' opinions were compared in relation to who they believe to be blameworthy in situations which varied in specificity, ranging from what road user they believe is most likely to cause a motorcyclist to have a road crash, to what road user is at fault in four specific scenarios involving a car and motorcycle at a junction. Two of these scenarios represented typical 'Right of way' (ROW) crashes with a motorcycle approaching from the left and right, and two scenarios involved a motorcycle overtaking another vehicle at the junction, known as 'Motorcycle Manoeuvrability Accidents' (MMA). Qualitative responses were analysed using LIWC software to detect objective differences in car drivers' and motorcyclists' language.

Car drivers' and motorcyclists' opinions about the blameworthiness of accidents changed depending on how specific the situation was that was being presented. When respondents were asked about the cause of motorcycle crashes in a general abstract sense, car drivers' and motorcyclists' responses significantly differed, with motorcyclists more likely to blame car drivers, demonstrating an in-group bias. However, this in-group favouritism was reduced when asked about specific scenarios, especially in MMA situations which involve motorcyclists manoeuvring their motorcycles around cars at a junction. In the four specific scenarios, car drivers were more likely to blame the car driver, and motorcyclists were more likely to blame the motorcyclist. In the typical ROW scenarios, the responses given by both road users, as analysed by the LIWC, show that the law is taken into account, as well as a large emphasis on the lack of observation given around junctions, especially from car drivers. It is concluded that the perception of blameworthiness in crashes is very much dependent on the details of the crash, with a more specific situation eliciting a fairer evaluation by both car drivers and motorcyclists.

1. Introduction

Research into road safety has increasingly focused on road users' attitudes, opinions, values and beliefs which are important in understanding how they perceive and accept different levels of risk on the road (O'Connell, 2002; Musselwhite et al., 2010). Despite this, there has been little research investigating road users' opinions towards common hazardous road situations, which could provide an important insight into why crashes occur. In the current paper, we are particularly interested in the opinions different types of road users (car drivers and motorcyclists) have towards the same road situations.

Motorcyclists represent a specific and important issue for road safety, as motorcyclists are involved in a remarkably high number of road crashes given the distance they travel (e.g. DfT, 2015a). Moreover, when they are involved in these crashes they are more likely than car drivers to be injured and killed in the crashes, with motorcyclists being typically referred to as one category of vulnerable road users (Shinar, 2012). The combined effect of frequency and severity is shown in crash statistics that reveal that in the U.K. motorcyclists in 2014 were involved in 122.3 fatalities per billion miles travelled compared with 1.8 fatalities per billion miles for car drivers (DfT, 2015a).

In the U.K., the most common motorcycle crash occurs at junctions, typically with another road user violating an oncoming motorcyclist's 'right of way' (ROW), by pulling out of a side junction onto a main carriageway (Clarke et al., 2007). In many of these instances it is a car that is pulling out into the junction. Afterwards the car driver often

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reports being careful and attentive with their visual checks but nonetheless having failed to see the approaching motorcycle. This is commonly termed the 'Look But Fail To See' error (Brown, 2002), and motorcycle riders have their own term for such events – 'SMIDSY' ("Sorry Mate I Didn't See You"). Although it is possible that the driver in these cases has failed to see an oncoming motorcyclist, it is also possible that they are sometimes deliberately claiming a failure in visual attention when another factor may be responsible for the crash. One possibility is that the car driver does not want to admit to a deliberate driving violation, such as accepting a risky gap between traffic. For this reason, research efforts have focussed on understanding motorcycle crashes at junctions by investigating both car drivers' gap acceptance behaviour around motorcycles (Keskinen et al., 1998; Mitsopoulos-Rubens and Lenné, 2012) and car drivers' visual attention towards motorcycles (Crundall et al., 2008a, 2012; Lee et al., 2015).

A framework used to understand car-motorcycle interactions was developed by Crundall et al. (2008b). This framework suggests that a top-down influence of car drivers' attitudes will determine how they will behave in a given situation. Road users' attitudes can include attitudes that concern themselves, other road users, or the environment. These attitudes can therefore guide car drivers' actions during car-motorcycle interactions on the road, and are thought to subsequently influence measurable cognitive strategies such as drivers' visual attention allocation. It must be noted that attitudes, opinions and values all have an interconnectedness, and are all powerfully shaped by our past history, group memberships, and by our context-dependent experience of the given moment (Bergman, 1998).

The majority of research focusing on attitudes has been used as an attempt to understand human behaviour (Ajzen and Fishbein, 1975) by investigating whether a person responds favourably or unfavourably to a given object. However, attitudes can be very variable and dependent on many aspects such as whether the object of thought is specific or intangible (Augoustinos and Walker, 1995). Attitudes have also been found to be very susceptible to the influence of context effects (Turner, 1985).

One of the classic biases found in human attitudes is that of in-group bias. More than 40 years of research has shown that people favour members of their own group in their opinions, attitudes, and behaviours (Ratner et al., 2014). In a road safety context, it may be that car drivers have more negative attitudes towards an outgroup, in this case motorcyclists, compared to their in-group, which would be fellow car drivers. A common example of this might be 'motorcyclists are risk takers' which is a misconception which many car drivers hold (Crundall et al., 2008b). Although such an attitude might be widely held among car drivers, motorcyclists are likely to have a much more finely nuanced understanding of their behaviour in risky situations. Of course, it is possible that if car drivers thought more specifically about the contexts in which motorcyclists accept risk, they might modify their attitudes. In many areas of social psychology, social judgements have been deemed to be context-dependent as they depend on the frame of reference in which they are made (Haslam et al., 1992), with in-group bias also being shown to be dependent on the context (Jost and Major, 2001).

Despite car drivers being solely at fault in many motorcycle accidents (ACEM, 2009), many previous studies have focussed on understanding motorcyclists' attitudes towards their own safety (Clarke et al., 2004; Musselwhite et al., 2012). Wong et al. (2010) conducted a large motorcycle study with 623 motorcyclists, with the aim to understand why young motorcyclists may be involved in a high number of collisions. They concluded that there were three important personality characteristics in young motorcyclists which were sensation seeking, amiability and impatience. The amiable riders were relatively mature and safe riders, whereas the sensation-seeking riders were more comfortable with unsafe riding, and interested in the utility gained from it.

Conversely, a research study by Crundall et al. (2008c) looked to identify potential gaps in car drivers' schemata in relation to motorcyclists that may account for their increased probability of being involved in a crash with a motorcycle. Drivers filled in a questionnaire which comprised of 26 general and motorcycle-related items and the 24 items of the reduced Driver Behaviour Questionnaire (Parker et al., 1995). It was found that when car drivers were compared to a dual driver group (drivers who also hold a motorcycle licence), they showed more negative attitudes towards motorcyclists and also self-reported more driving violations. This study is unusual in directly comparing car drivers' and motorcyclists' attitudes, although the motorcyclists in this study were also car drivers. The majority of comparison studies have focussed on comparing the two road users' behavioural responses in simulation tests (Horswill and Helman, 2003; Shahar et al., 2011) and natural on-road driving/riding (Walker et al. (2011).

Shahar et al. (2011) is the only study to have compared car drivers' and motorcyclists' opinions towards general hazardous situations as well as comparing them in a behavioural simulation task. Car drivers and motorcyclists were compared on the degree to which 9 vignettes of various hazardous road situations were reported to be realistic and dangerous. Half of the car drivers and half of the motorcyclists were told to imagine they were driving a car through the scenario and the other half were told to imagine they were riding a motorcycle. It was found that while the participants who were told to imagine riding a motorcycle rated the vignettes to be more realistic, the real-life motorcycle riders rated the scenarios more dangerous, suggesting that their specific motorcycle experience influenced their criterion for danger. Although this was one of the first studies to compare drivers' and motorcyclists' opinions, only one of the vignettes was specifically concerned with car-motorcycle junction crashes. In addition, in some instances, participants may have been asked to imagine situations which were very unrealistic, for example, asking a car driver to imagine riding a motorcycle. If the car driver had never ridden a motorcycle before, their opinions in this condition may not be useful as the participant has no previous relevant information to draw from. A previous meta-analysis has revealed that attitudes predict behaviour better when they rely on information relevant to a behavioural decision (Glasman and Albarracín, 2006).

The use of an online questionnaire which includes both quantitative and qualitative aspects can be beneficial in providing in-depth information on road users' opinions which may guide these behaviours. Therefore, the current study's main purpose was to compare the opinions of car drivers and motorcyclists towards crashes at junctions, in particular, crashes that specifically occur with a car driver and a motorcyclist. This is the first research study to ask both car drivers and motorcyclists their opinions on the most common accidents that occur between these two road users, therefore although it may be assumed that, in general, road users blame the other road user for the crash, this has not been directly tested. By identifying and comparing the opinions of car drivers and motorcyclists, this may clarify the beliefs about nature and blameworthiness of these crashes, and therefore have important implications for road safety in terms of guiding researchers and policy makers to suggest new practical applications and interventions. Car drivers' and motorcyclists' opinions are important in regards to the framing and acceptability of road safety interventions, with these opinions influencing their engagement in such interventions.

In light of the previous research, we would expect to find evidence for in-group biases for abstract questions such as "what road user is most likely to cause a motorcyclist to have a road accident", or "what road user is most likely to be to blame for car-motorcycle junction accidents". In contrast, we would predict that if more scenario-specific information is provided for an example of a crash in a particular context, the degree of in-group bias should be reduced and car drivers' opinions about motorcyclists should be found to be more balanced.

1.1. The selection of scenarios

The specific scenarios which were presented to car drivers and motorcyclists in the online questionnaire were chosen from a

Table 1
Shows the for main types of motorcycle crash and their frequencies found in a review conducted in the U.K. by Clarke et al. (2004).

Type of Crash	Percentage of Motorcycle crashes in Sample (n = 1790)
Right of Way Crashes (ROW)	38% (n = 681)
Losing control on Bends	15% (n = 268)
Motorcycle Manoeuvrability Accidents (MMA)	17% (n = 304)
Other motorcycle crashes	30% (n = 537)

motorcycle review conducted in the U.K. by Clarke at al. (2004). The review involved the analysis of over a thousand real world crash cases, and questionnaire responses from over 100 experienced motorcyclists. Motorcycle crashes were divided into 4 categories which can been seen in Table 1 along with their frequencies.

The four categories of motorcycle crash, as found by Clarke et al., (2004), are explained below. Right of way (ROW) crashes are by far the most common motorcycle crash in the UK, being three times more likely to occur at junctions than any other road situation (Hole and Langham, 1997). Clarke et al. (2004) found that in over 65% of ROW crashes, these were typical 'look but fail to see' instances as described above where the driver reports failing to see an oncoming motorcycle and pulls out into its path (Brown, 2002). This review also reported that such crashes are more likely to be considered as the car driver's fault. In contrast, when a motorcyclist loses control on a bend, previous studies have found that this crash is usually a result of over braking, speeding or cutting the corner, with most road users accepting that such crashes are the fault of the motorcyclist (Hurt et al., 1981). According to Clarke et al. (2004), this crash is believed to be related to inexperience in riding a motorcycle, with the main emphasis on the loss of vehicle control rather than a cognitive error. The third category, Motorcycle Manoeuvrability Accidents (MMA) provides a more mixed picture. This can include many types of crash which have in common the fact that motorcyclists can manoeuvre their bikes in ways which are not available to larger vehicles. In the majority of these crashes, motorcyclists overtake another vehicle, which subsequently causes a crash. In these instances, the other driver is more than twice as likely to be considered at fault for the crash compared to the motorcyclist involved, though there is also evidence for an increased proportion of 'combined fault' accidents in this category (Clarke et al., 2004). The road user considered to be at fault for each crash type in Clarke et al. (2004) was based upon police accident files, which included a brief accident story as interpreted by the attending police officer. For the current study, we were particularly interested in exploring car drivers' opinions in cases where they are likely to be at fault (e.g. ROW Accidents) and situations where blame is harder to define, but where there is a high likelihood that the car driver was at least partly at fault (MMA).

ROW crashes have also been seen to be the most prevalent motorcycle crash in the U.S., with an analysis of 900 motorcycle crashes revealing that 75% involved another vehicle violating the ROW of the motorcycle at an intersection, usually by turning left in front of the oncoming motorcycle (Hurt et al., 1981). A comparison of motorcycle crashes from Malaysia, Taiwan and Vietnam also found that non-signalised intersections were one of the most hazardous locations for motorcycle crashes as well as crashes involving a motorcycle overtaking or filtering other traffic (Hsu et al., 2003).

In light of this, the scenarios given in our questionnaire reflect the most common junction crashes that occur with cars and motorcycles. Two scenarios which represent typical ROW crashes were given, with the blame commonly given to the car driver in these instances. Both of these scenarios included a car driver waiting at a junction to turn right, with a motorcycle approaching from the right in the first instance and the left on the second instance. Since our participants were U.K. drivers/riders all scenarios have driving/riding taking place on the left-hand side of the road. The next two scenarios were chosen to represent MMA and included two common crashes which involve motorcyclists overtaking other vehicles near a junction. The first common MMA occurs when a driver is waiting to pull out of a junction however, the visibility of an oncoming motorcycle is reduced due to them overtaking a slower vehicle approaching the junction. The second MMA is when a driver is waiting to turn right into a junction while a motorcycle is overtaking them. These 4 scenarios were selected as they are the most common crashes involving both a car driver and motorcyclist at an intersection and provide the opportunity for debate on who is at fault in these situations (Clarke et al., 2004).

2. Methods

2.1. The questionnaires

Our goal in the current study was to recruit motorcyclists and car drivers in similar ways, with them both being recruited through UK driving/riding forums and online. Respondents recruited via forums, both motorcyclists and car drivers, are likely to have an affinity towards that mode of transport, therefore respondents could be directly compared. In order to obtain a sufficient sample size, we chose to use a web-based questionnaire. We advertised these questionnaires on car driving forums which included the RAC Driving Forum, Advanced Driving Forum and The Car Expert Forum, and on motorcycle forums which included the RAC Motorcycle Forum, Advanced Motorcycle Forum and The Motorbike Forum. To increase the sample size, we additionally advertised the questionnaires on social media.

There were two linked questionnaires, one for car drivers and one for motorcyclists. Both of the questionnaires consisted of seven main sections, which in general had an identical format with the exception of slight changes in the wording to make it more comprehensible and relevant to the audience.

The first two sections asked participants for personal details such as age, gender and recruitment details, as well as details about their driving/riding experience in terms of training, mileage and main purpose of transport. These two sections were mainly included for respondent demographic purposes.

This was then followed by three on-road safety sections, with the first concerned with respondents' opinions about vulnerable road users in general, and any personal or family member road accidents. Family/friend road accidents were investigated, as previous research shows that road users who have family or close friends that ride motorcycles are less likely to collide with motorcyclists (Brooks and Guppy, 1990). The second on-road safety section was more specifically concerned with motorcycle crashes, asking respondents who they believe who is more likely to cause a motorcyclist to have a crash, what people believe to be the most common motorcycle crash, and whether the road is seen to be a shared or competitive space. The last on-road safety section was specifically concerned with who they believe is most to blame for junction crashes that involve a car and a motorcycle.

The next two sections contained four scenarios which reflect the most common car-motorcycle junction crashes as reviewed in Clarke et al. (2004). These four common motorcycle junction crashes were displayed to participants in the form of a diagram, where they had to choose what road user would be most at fault in the situation if a crash was to occur and explain why, see Fig. 1.

The final section included two optional open questions, giving respondents an opportunity to express any other opinions regarding junction crashes involving motorcycles. The main questions of interest and the possible responses for both the questionnaires are reported in Table 2.

2.2. The Linguistic Inquiry and Word Count (LIWC)

A quantitative analysis of the data was conducted, with the addition of the Linguistic Inquiry and Word Count (LIWC) to analyse the

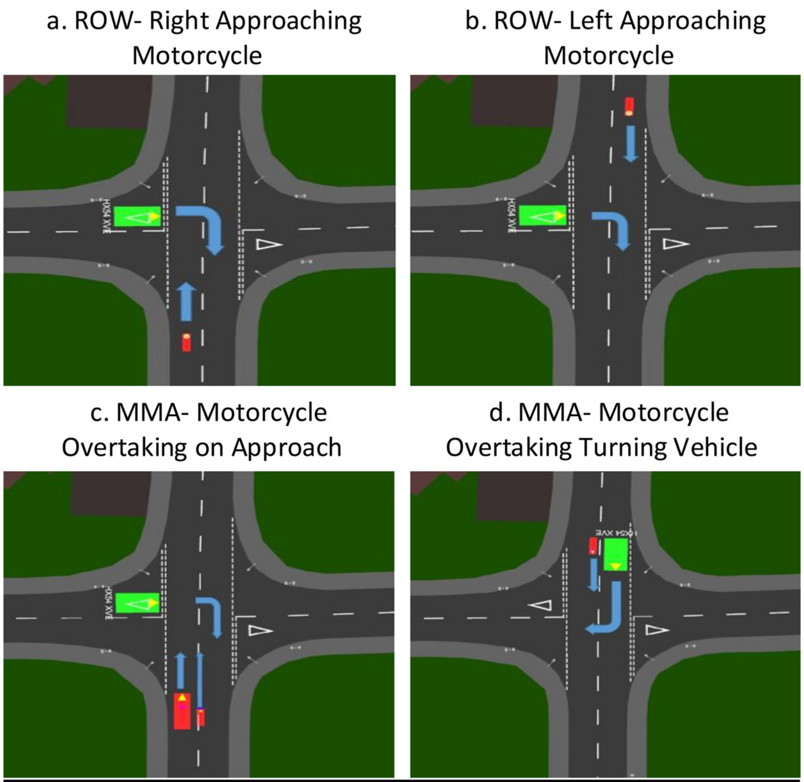

Fig. 1. The four situations shown to participants in the questionnaire. Respondents had to decide whether the green car or the red motorcycle would be at fault in these situations, if a crash were to occur. 1a and 1b were intended to represent standard situations typical of ROW (Right of Way) crash with a motorcycle approaching from the left and right, while 1c and 1d represent MMA (Motorcycle Manoeuvrability Accidents) involving a motorcycle overtaking another vehicle at the junction. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

qualitative responses the respondents gave. The LIWC was used as a formal way of presenting data, to extend the previous qualitative presentation of motorcyclists' motivations and opinions in the literature (Christmas et al., 2009).

The LIWC analyses the contents of text files and calculates the percentage of words that fall within a series of dictionary dimensions and linguistic categories (Tausczik and Pennebaker, 2010). The program has different dimensions such as summary language variables and psychological constructs (Pennebaker et al., 2015). The LIWC has been used in a large body of research with psychological constructs, for example, being established as a valid measure of understanding behaviour (Cohn et al., 2004). This indicates that quantitative methods can be effective in analysing the linguistic and emotional contents of text.

2.3. Analysis

All quantitative questionnaire responses for both car drivers and motorcyclists were subject to a non-parametric chi-square test of goodness-of-fit. This analysis was conducted to determine whether there was a relationship between group (car drivers vs. motorcyclists) and the response given to the question. Chi-squared tests were performed on questions with forced choice responses, where the respondent could only choose one answer. The possible responses that could have been given by car drivers and motorcyclists were identical on both questionnaires. In order to ensure that the assumptions for Chi-squared analyses were met, response options with very low frequencies were removed from the analysis. In addition, for selected questions, only certain responses were analysed. The responses marked with a (*) in Table 2 show responses to each question that were not analysed due to making the analysis more focussed, with the main hypotheses investigating whether car drivers and motorcyclists are more likely to blame their in-group or out-group depending on the situation presented. The responses marked with a (**) in Table 2 show the responses that were not included in the subsequent analysis due to low frequencies.

The chi-squared tests compared the primary identification of the respondents (car drivers vs. motorcyclists), by which questionnaire they chose to fill out. It was noted however, that some respondents may also be dual road users (drive a car and ride a motorcycle). Multinomial logistic regressions were performed to model the relationship between five key predictors and attribution of blame for abstract questions and four specific scenarios questions, with one of the predictors dividing the respondents down further into car drivers, motorcyclists and dual road users (drive a car and ride a motorcycle). The five predictors were gender, age, road user type (car drivers, dual road users and motorcyclists), personal accident and family/friend accident, and the attribution of blame was either car driver, motorcyclist or both. No violations of goodness of fit were found in overall Pearson chi-square statistics. As there are three possible values of the outcome variable, the reference group for all models was blaming the car driver. Although we did not correct for multiple comparisons, we report the statistics in Tables 3–5, indicating significance at $p < 0.5$, $p < 0.01$ and $p < 0.001$ and the test statistics.

All qualitative questionnaire responses were processed using the LIWC. Any linguistic dimensions or psychological categories where less than half of the participants had produced a response were removed from analysis. Although LIWC can calculate more than 90 separate linguistic variables from text, for the purposes of our research only summary language variables and words associated with psychological processes believed to be relevant to driving were selected, which included words related to affective, cognitive, perceptual and motivational (drive) processes. These psychological constructs were selected as they have been previously established as valid in understanding behaviour, with emotional language changing according to situational valence (Eid et al., 2005), and cognitive language related to traumatic events (Cohn et al., 2004), all of which are relevant to driving. Although it is possible within LIWC to break down the data further, the sub-categories within these psychological processes did not have over half of the participants producing a response. For example, cognitive processes could not be broken down into the sub-categories of 'insight', 'causation', 'discrepancy', 'tentative', 'certainty' and 'differentiation' and therefore had to be analysed under overall cognitive processes. In

Table 2
Shows the questions used in both questionnaires and the possible responses the respondents could have given to each question. Responses marked with a (*) indicate the responses that were not included in the subsequent analysis due to making the analysis more focussed, and responses marked with a (**) indicate responses that were not included in the subsequent analysis due to low frequencies- See Section 2.3 for the analysis.

Question	Possible Responses				
Transport Purpose- What is your main reason for using a car/motorcycle?	Commuting	As part of your job	Leisure	Personal	Other
Vulnerable Road User- What mode of transport do you consider to be most vulnerable on the road?	Car**	Motorcycle	Large Vehicle**	Bicycle	
Personal Accident- Have you ever been involved in an accident with another road user that has resulted in injury?	Yes	No			
Family/Friend Own Motorcycle- Does anyone in your immediate family/close friends own a motorcycle?	Yes	No			
Family/Friend Accident- Have any of your immediate family members/close friends been involved in a motorcycle accident that has resulted in injury?	Yes	No			
Cause- What road user do you think would most likely cause a motorcyclist to have a road accident?	Motorcyclists themselves	Car Drivers	Large Commercial Vehicles**	Cyclists* *	Other**
Accident Type- What do you think is the most common accident type for a motorcyclist to be involved in?	Collision while overtaking road users	Being hit from behind	Collisions with right turning vehicles	Collisions with left turning vehicles	Loss of control by a motorcyclist
Shared/Competitive - Do you believe the road to be a shared or competitive space with motorcycles?	Shared	Competitive			
Blame- The majority of accidents involving motorcycles occur at junctions. Who do you think is mostly to blame for car-motorcycle junction accidents?	Motorcyclists	Car Drivers	Both Car Driver and Motorcyclist*	Neither*	
ROW- Right Approaching Motorcycle- Who do you think would be most at fault in this situation, if an accident was to occur?	Car Drivers	Motorcyclists	Both Car Driver and Motorcyclist*	Neither*	
ROW- Left Approaching Motorcycle- Who do you think would be most at fault in this situation, if an accident was to occur?	Car Drivers	Motorcyclists	Both Car Driver and Motorcyclist*	Neither*	
MMA- Motorcycle Overtaking on Approach - Who do you think would be most at fault in this situation, if an accident was to occur?	Car Drivers	Motorcyclists	Both Car Driver and Motorcyclist*	Neither*	
MMA- Motorcycle Overtaking Turning Vehicle - Who do you think would be most at fault in this situation, if an accident was to occur?	Car Drivers	Motorcyclists	Both Car Driver and Motorcyclist*	Neither*	

Table 3
Shows the results for the Chi Squared conducted for the Cause and Blame questions as well as the ROW and MMA scenarios. The first Chi-square conducted for each question was the main analysis comparing car drivers' and motorcyclists' responses. The following Chi-squares show the gender split. Each Chi-square shows the percentage for each group, and whether there was a group difference. Below each Chi-square is the probability associated with the test.

		Car Drivers	Motorcyclists		Male Car Drivers	Female Car Drivers		Male Motorcyclists	Female Motorcyclists		Male Car Drivers vs Male Motorcyclists	Female Car Drivers vs Female Motorcyclists
	Full n	102	579		55	47		505	74			
Cause- What road user do you think would most likely cause a motorcyclist to have a road accident?	**n for question**	83	557	640	46	37	83	483	74	557	529	111
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Car Drivers	57.8	74.5	**10.04**	60.9	54.1	.39	73.9	78.4	.67	3.61	**6.99**
	Motorcyclists	42.1	25.5	**.01****	39.1	45.9	.53	26.1	21.6	.41	.06	**.01****
Blame- The majority of accidents involving motorcycles occur at junctions. Who do you think is mostly to blame for car-motorcycle junction accidents?	**n for question**	45	304	346	26	19	45	270	34	304	296	53
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Car Drivers	97.8	95.7	.43	100	94.7	1.4	95.6	97.1	.17	1.2	.18
	Motorcyclists	2.2	4.3	.51	0.0	5.3	.24	4.4	2.9	.68	.27	.67
ROW- Right Approaching Motorcycle- Who do you think would be most at fault in this situation, if an accident was to occur?	**n for question**	98	521	619	52	46	98	457	64	521	509	110
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Car Drivers	98.9	98.8	.01	98.1	100	.89	98.7	100	.85	.13	–
	Motorcyclists	1.1	1.2	.91	1.9	0.0	.34	1.3	0.0	.36	.72	–
ROW- Left Approaching Motorcycle- Who do you think would be most at fault in this situation, if an accident was to occur?	**n for question**	95	506	601	52	43	95	445	61	506	497	104
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Car Drivers	92.6	96.4	2.91	90.4	95.3	.85	96.4	93.4	1.82	**5.3**	2.71
	Motorcyclists	7.4	3.6	.08	9.6	4.7	.36	3.1	6.6	.18	**.05***	.1
MMA- Motorcycle Overtaking on Approach - Who do you think would be most at fault in this situation, if an accident was to occur?	**n for question**	61	376	437	30	31	61	333	43	376	363	74
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Car Drivers	37.7	22.6	**6.43**	33.3	41.9	.48	23.4	16.3	1.11	1.47	**6.01**
	Motorcyclists	62.3	77.4	**.01****	66.7	58.1	.49	76.6	83.7	.29	.23	**.05***
MMA- Motorcycle Overtaking Turning Vehicle - Who do you think would be most at fault in this situation, if an accident was to occur?	**n for question**	78	454	532	42	36	78	393	61	454	435	97
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Car Drivers	10.3	4.4	**4.57**	7.1	13.9	.96	4.6	3.3	.21	.54	**3.81**
	Motorcyclists	89.7	95.6	**.05***	92.9	86.1	.33	95.4	95.6	.65	.46	**.05***

$^{*}p < .05$; $^{**}p < .01$.

Table 4
Shows the results for the Multinomial logistic regression for Cause and Blame questions as well as the ROW and MMA scenarios. The first table indicates the contribution each predictor had to the overall model. χ^2 = amount by which -2 log likelihood increases when predictor is removed from full model. *df* = degrees of freedom. The second table compares the reference category outcome response (car driver), with the other two outcome responses (motorcyclist and both) for each predictor variable. B = unstandardized coefficients. OR = Odds ratio associated with the effect of a one standard deviation increase in the predictor.

Model Contributions	Cause			Blame			ROW- Right Approaching Motorcycle			ROW- Left Approaching Motorcycle			MMA- Motorcycle Overtaking on Approach			MMA-Motorcycle Overtaking Turning Vehicle		
Predictor	χ^2	*df*	*p*	χ^2	*df*	*p*	χ^2	*df*	*p*	$^2\chi$	*df*	*p*	χ^2	*df*	*p*	χ^2	*df*	*p*
Age	1.66	2	.44	5.81	2	.06	9.33	2	.01**	5.57	2	.06	20.69	2	.00***	1.12	2	.57
Gender	.49	2	.78	2.39	2	.30	.41	2	.82	2.81	2	.25	1.25	2	.54	0.48	2	.79
Road User Type	25.96	4	.00***	2.91	4	.57	5.19	4	.27	7.43	4	.12	5.85	4	.21	9.79	4	.04*
Personal Accident	13.00	2	.00***	2.07	2	.36	6.26	2	.04*	2.26	2	.32	.53	2	.77	2.90	2	.24
Family/Friend Accident	5.48	2	.06	3.44	2	.18	.74	2	.70	4.21	2	.12	2.15	2	.34	2.69	2	.26

Parameter Estimates	Accident Blame	Cause			Blame			ROW- Right Approaching Motorcycle			ROW- Left Approaching Motorcycle			MMA- Motorcycle Overtaking on Approach			MMA-Motorcycle Overtaking Turning Vehicle		
Predictor	Car Driver vs.	B	OR	*p*	B	OR	*p*	B	OR	*p*	B	OR	*p*	B	OR	*p*	B	OR	*p*
Age	Motorcyclist	.01	1.01	.51	.03	1.03	.17	.04	1.04	.30	.03	1.03	.09	.04	1.04	.00***	.01	1.0	.87
	Both	−.01	.99	.33	.01	1.01	.03*	.03	1.03	.01**	.02	1.02	.07	.02	1.02	.08	−.01	.99	.75
Gender	Motorcyclist	−.16	.85	.53	.29	1.34	.73	.19	1.21	.88	.27	1.3	.62	.34	1.4	.29	.09	1.1	.86
	Both	−.18	.83	.67	.34	1.41	.13	.25	1.28	.53	.54	1.72	.09	.32	1.37	.33	−.10	.91	.87
Road User Type																			
Car Driver vs Motorcyclist & Dual	Motorcyclist	.59	1.8	.03*	−.68	.51	.54	.06	1.06	.96	.84	2.32	.11	−.68	.51	.05*	−1.32	.26	.01**
Car Driver vs Motorcyclist & Dual	Both	1.78	5.94	.00***	.09	1.1	.71	−.91	.14	.11	−.73	.48	.10	−.28	.75	.40	−.90	.41	.10
Motorcyclist vs. Car Driver & Dual	Motorcyclist	−.53	.59	.10	−.68	0.5	.51	18.77	.00	–	−.80	.45	.45	.15	1.17	.69	−.19	.82	.77
Motorcyclist vs. Car Driver & Dual	Both	−.49	.61	.44	−.34	.71	.18	−.30	.74	.55	−.37	.69	.18	.38	1.46	.31	.30	1.35	.68
Personal Accident	Motorcyclist	−.64	.53	.00***	.10	1.11	.86	1.42	4.15	.10	−.34	.71	.47	.165	1.18	.51	−.6	.55	.15
	Both	.40	1.49	.26	−2.4	.79	.17	−53	.59	.09	−.36	.69	.18	.18	1.2	.49	−.38	.69	.40
Family/Friend Accident	Motorcyclist	−.42	.66	.02*	−.35	.70	.53	−.06	.94	.94	−.23	.79	.59	−.21	.8	.36	−.53	.59	.21
	Both	−.26	.77	.45	−.29	.75	.07	−.24	.79	.40	−.5	.61	.06	.03	1.03	.90	−.31	.74	.49

* $p < .05$.
** $p < .01$.
*** $p < .001$.

Table 5
Shows the results for the Chi Squared conducted for the questions regarding reported accidents, vulnerable road users, accident type and purpose of transport. The first Chi-square conducted for each question was the main analysis comparing car drivers' and motorcyclists' responses. The following Chi-squares show the gender split. Each Chi-square shows the percentage for each group, and whether there was a group difference. Below each Chi-square is the probability associated with the test. (Table over 2 pages).

		Car Drivers	Motorcyclists		Male Car Drivers	Female Car Drivers		Male Motorcyclists	Female Motorcyclists		Male Car Drivers Male Motorcyclists	Female Car Drivers Female Motorcyclists
	Full n	102	579		55	47		505	74			
Personal Accident - Have you ever been involved in an accident with another road user that has resulted in injury?	n for question	102	579	681	55	47	102	505	74	579	560	121
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Yes	26.5	37.9	**4.98**	29.1	23.4	.42	40.6	20.3	**11.31**	2.74	.17
	No	73.5	62.1	**.05***	70.9	76.6	.52	59.4	79.7	**.001*****	.10	.68
Family/Friend Own Motorcycle - Does anyone in your immediate family/close friends own a motorcycle?	n for question	102	579	681	55	47	102	505	74	579	560	121
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Yes	45.1	85.9	**89.08**	54.5	34.0	**4.3**	85.7	86.5	.03	**33.71**	**35.29**
	No	54.9	14.1	**.01****	45.5	66.0	**.05***	14.3	13.5	.86	**.001*****	**.001*****
Family/Friend Accident- Have any of your immediate family members/close friends been involved in a motorcycle accident that has resulted in injury?	n for question	102	579	681	55	47	102	505	74	579	560	121
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Yes	40.2	55.9	**8.66**	45.5	34.0	1.37	54.9	63.5	1.97	1.76	**10.00**
	No	59.8	44.1	**.01****	54.5	66.0	.24	45.1	36.5	.16	.18	**.01****
Vulnerable Road User - What mode of transport do you consider to be most vulnerable on the road?	n for question	101	575	676	55	46	101	501	74	575	556	120
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Motorcycle	33.7	42.4	2.73	40.0	26.1	2.17	41.7	47.3	.82	.06	**5.36**
	Bicycle	66.3	57.6	.09	60.0	73.9	.14	58.3	52.7	.37	.81	**.05***
Shared/Competitive- Do you believe the road to be a shared or competitive space with motorcycles?	n for question	102	579	681	55	47	102	505	74	579	560	121
		%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	%	%	**χ^2 (1), *p***	**χ^2 (1), *p***	**χ^2 (1), *p***
	Shared	81.4	42.4	.21	92.7	68.1	**10.15**	81	68.9	**5.72**	**4.68**	.01
	Competitive	18.6	57.6	.65	7.3	31.9	**.001*****	19	31.1	**.05***	**.05***	.92
Accident type- What do you think is the most common accident type for a motorcyclist to be involved in?	n for question	102	579	681	55	47	102	505	74	579	560	121
		%	%	**χ^2 (4), *p***	%	%	**χ^2 (4), *p***	%	%	**χ^2 (4), *p***	**χ^2 (4), *p***	**χ^2 (4), *p***
	Collision while overtaking road users	16.7	8.5	**12.52**	12.7	21.3	6.18	7.5	14.9	**12.75**	8.08	5.11
	Being hit from behind	2.0	1.9	**.05***	0.0	4.3	.19	2.0	1.4	**.05***	.09	.28
	Collisions with right turning vehicles	55.9	58		54.5	57.4		59.2	50.0			
	Collisions with left turning vehicles	10.8	6.4		12.7	8.5		5.3	13.5			
	Loss of control by a motorcyclist	14.7	25.2		20.0	8.5		25.9	20.3			
Transport Purpose- What is your main reason for using a car/motorcycle?	n for question	98	570	668	52	46	98	496	74	570	548	120
		%	%	**χ^2 (3), *p***	%	%	**χ^2 (3), *p***	%	%	**χ^2 (3), *p***	**χ^2 (3), *p***	**χ^2 (4), *p***
	Commuting	34.7	20.7	**83.66**	38.5	30.4	5.09	20.8	20.3	**23.53**	**52.36**	**16.15**
	As part of your job	11.2	2.6	**.001*****	15.4	6.5	.17	3.0	0.0	**.001*****	**.001*****	**.001*****
	Leisure	28.6	70.9		28.8	28.3		72.2	62.2			
	Personal	25.5	5.8		17.3	34.8		4.0	17.6			

* $p < .05$.
** $p < .01$.
*** $p < .001$.

regards to the chosen psychological processes, cognitive processes reflect how much respondents are actively thinking about the given topic, affective processes refer to the detection of positive and negative emotions (e.g. anxiety, anger, sadness), perceptual processes refer to sensory processes (e.g. seeing, hearing, feeling) and motivational processes refer to the respondents drives and needs (e.g. achievement, reward, risk).

Most variables are expressed as a percentage of the amount of words used in that particular question that fall within a particular category. However, total word count and words per sentence were expressed as an exact number. In cases where there was a significant difference in the language used for motorcyclists and car drivers, the LIWC was used to select quotes from the three respondents who expressed the highest percentage of words that fell within that particular category, to give examples of the most expressive answers given.

3. Results

3.1. Respondents

In total, there were 1813 participants who viewed the questionnaire, with 681 completing the questionnaire. In regards to the analysis, only fully completed responses were included. There were 102 completed car driver responses and 579 completed motorcyclist responses. As can be seen by these figures, the majority of the overall sample were motorcyclist responses. Both of the questionnaires were available to complete for 8 months. A post hoc power analysis was conducted using the software package, G*Power 3.1 (Faul and Erdfelder, 1992). The overall sample size of 681 had more than adequate power (.95) to detect a medium effect (w = .3) with the alpha level used for analysis being $p < .05$.

In regards to the 102 car drivers, there were 47 females (46%) and 55 males (54%). The average age was 39.37 years (SD = 15.38) with an age range of 18–74 years. The sample of car drivers had held a driving licence for between 1 year and 53 + years (Mode = 4–12 years). Their annual mileage also ranged from 0 to 30,000 miles (Mode = 7000-15,000 miles). In terms of recruitment, car drivers were recruited from car driving forums (19.6%, n = 20), through friends or relatives (23.5%, n = 24) and through social media (56.9%, n = 58).

In regards to the 579 motorcyclists, there were 74 females (13%) and 505 males (87%). The average age was 44.73 years (SD = 11.95) with an age range of 17–79 years. The sample of motorcyclists had held a driving licence for between 1 year and 53 + years (Mode = 4–12 years). Their annual mileage also ranged from 0 to 30,000 miles (Mode = 5000–7000 miles). Motorcyclists were recruited from motorcyclist forums (9.3%, n = 54), through friends or relatives (4.3%, n = 24) and through social media (86.4%, n = 501).

As a large proportion of the motorcyclists were male and the car drivers had a fairly equal split of males and females, the analysis could be confounded by gender. It could be possible that any difference between car drivers' and motorcyclists' opinions are due to a gender difference. For this reason, chi-squared tests were conducted for all questions to investigate the gender differences within and between car drivers and motorcyclists, as well as gender being included as a predictor in the multinomial logistical regression models.

All responses to the qualitative questions were initially combined and analysed using the LIWC. It was found that motorcyclists had a significantly higher word count (m = 37.5) compared with car drivers (m = 23.7) (t (679) = 4.17, $p < .001$) and used a greater number of words per sentence (m = 12.56) compared to car drivers (m = 10.30) (t (677) = 2.04, $p < .05$).

3.2. Purpose of transport

As car drivers and motorcyclists were asked to indicate their annual mileage, the median mileage was 7000 miles therefore a chi-square was performed to see if there was a relationship between group and annual mileage, above and below 7000 miles. Car drivers' annual mileage was more likely to be over 7000 miles compared with motorcyclists, and motorcyclists' annual mileage was more likely to be under 7000 miles than car drivers, χ^2 (1) = 36.78, $p < .001$. This may be explained, in part, by the reasons the two groups gave for their main purpose of using a car or a motorcycle.

Car drivers and motorcyclists were asked what the main reason for using their mode of transport was. A chi-square test found a relationship between group and transport purpose, with car drivers more likely to use their car for commuting, as part of their job or personal reasons, whereas motorcyclists were more likely to use their motorcycle for leisure purposes- See Table 5 for results of statistical tests.

In regards to gender, there was a significant difference in male motorcyclists' and female motorcyclists' responses, male car drivers' and male motorcyclists' responses and female car drivers' and female motorcyclists' responses. The former group from these comparisons were more likely to use their motorcycles for commuting, as part of their job and personal reasons, whereas the latter were more likely to use their motorcycles for leisure purposes – See Table 5.

3.3. Blameworthiness of motorcycle crashes

3.3.1. Cause

Both groups were asked "what road user do you think is most likely to cause a motorcyclist to have a road accident?". It was found that car drivers and motorcyclists significantly differed in their responses such that more motorcyclists blamed car drivers. In regards to gender differences, it was found that female car drivers and female motorcyclists significantly differed in their responses- See Table 3 for results of statistical tests.

When asked to explain their choice, there was a significant difference in overall affective language use, with motorcyclists using more affective language (m = 5.5%) than car drivers (m = 3.9%) (t (679) = 2.36, $p < .05$). The three motorcyclists that expressed the most affective language all thought car drivers were likely to cause a motorcyclist to have a crash due to the following reasons, 'Bad Awareness', 'Carelessness' and 'Poor Observation'.

A multinomial logistic regression found that by adding the five key predictors of gender, age, road user type (car drivers, dual road users and motorcyclists), personal accident and family/friend accident to a model that contained only intercept, this significantly improved the fit between the model and the data, $\chi 2(12, N = 681) = 53.26$, Nagelkerke R2 = .09, $p < .001$. As shown in Table 4, significant contributions to the model were made by road user type (car drivers vs motorcyclists and dual road users) and personal accident. It was found that car drivers are more likely than motorcyclists and dual road users to blame motorcyclists for the cause of accidents compared to blaming car drivers. In addition, car drivers are more likely than motorcyclists and dual road users to blame both (car driver and motorcyclist) compared to blaming car drivers. In regards to personal accident, respondents who have been involved in a personal accident are less likely to blame motorcyclists compared to car drivers.

3.3.2. Blame

When both groups were asked "who do you think is mostly to blame for car-motorcycle junction accidents?" there was no relationship between group and blame, such that both groups blamed car drivers - See Table 3.

When asked to explain their choice, there was a significant difference in overall use of language associated with cognitive processes, with car drivers (m = 20.65%) using more cognitive language than motorcyclists (m = 16.64%) (t (679) = 2.27, $p < .05$). The three car drivers that expressed the most language associated with cognitive processes all gave different responses on who they believed was mostly to blame for car-motorcycle junction crashes: 'Not paying attention'

(Blamed Car Drivers), 'They can't see clearly' (Blamed Motorcyclists), 'Both need to consider other drivers' (Blamed both Car Drivers and Motorcyclists).

In regards to the multinomial logistic regression, by adding the predictors to a model that contained only intercept, this did not significantly improve the fit between the model and the data, $\chi2(12, N = 674) = 19.52$, Nagelkerke $R2 = .03$, $p = .07$ – See Table 4 for results of statistical tests.

3.4. Scenarios

3.4.1. ROW- right approaching motorcycle

As can be seen in Table 3, there was no relationship between group and blame for the ROW- right approaching motorcycle scenario, such that both groups blamed car drivers.

When asked to explain their choice for the ROW- right approaching motorcycle scenario, there was a significant difference in overall affective language use, with motorcyclists using more affective language ($m = 2.5\%$) than car drivers ($m = 1.5\%$) (t (679) = 2.23, $p < .05$). The three motorcyclists that expressed the most affective language all thought the car driver was to blame for this crash scenario for the following reasons, 'failure to observe', 'failing to give way' and 'fault? Car driver. Poor defensive tactics… motorcyclist'.

There was also a significant difference in overall use of motivational language, with motorcyclists using more motivational language ($m = 3.9\%$) than car drivers ($m = 2.5\%$) (t (679) = 2.62, $p < .01$). The three motorcyclists that expressed the most motivational language all thought the car driver was to blame for this crash scenario due to 'The law', 'Poor judgment' and 'lack of observation'.

The multinomial regression found that by adding the predictors to a model that contained only intercept, this significantly improved the fit between the model and the data, $\chi2(12, N = 678) = 23.65$, Nagelkerke $R2 = .06$, $p < .05$. As shown in Table 4, significant contributions were made by age and personal accident to the model. It was found that the more age increases, the more likely respondents are to attribute blame to both car driver and motorcyclists compared to just blaming the car driver.

3.4.2. ROW left approaching motorcycle

For the ROW – left approaching motorcycle scenario, there was also no relationship between group and blame, such that both groups blamed car drivers. In regards to gender differences, male car drivers and male motorcyclists differed in their responses- See Table 3.

When asked to explain their choice for the ROW- left approaching motorcycle scenario, there was a significant difference in overall use of language associated with cognitive processes, with motorcyclists ($m = 11.3\%$) using more than car drivers ($m = 8.9\%$) (t (679) = 2.26, $p < .05$). The three motorcyclists that expressed the most language associated with cognitive processes all thought the car driver was to blame for this crash scenario, for the following reasons 'probably didn't see the motorcycle', 'car driver should make sure the road is clear' and 'lack of observation or impatience'.

The multinomial logistic regression found that by adding the predictors to a model that contained only intercept, this significantly improved the fit between the model and the data, $\chi2(12, N = 679) = 21.81$, Nagelkerke $R2 = .05$, $p < .05$, however, as shown in Table 4, there were no significant individual contributions made to the model.

3.4.3. MMA- motorcycle overtaking on approach

For the MMA- motorcycle overtaking on the approach scenario, it was found that car drivers and motorcyclists significantly differed in their responses, such that more motorcyclists blamed motorcyclists. In regards to gender differences, female car drivers and female motorcyclists significantly differed in their responses- See Table 3.

When asked to explain their choice for the MMA- motorcycle overtaking on the approach scenario, there was a significant difference in overall affective language use, with motorcyclists using more affective language ($m = 4.1\%$) than car drivers ($m = 2.5\%$) (t (679) = 2.33, $p < .05$). The three motorcyclists that expressed the most affective language all thought the motorcyclist was to blame for this crash scenario due to the following reasons, 'Dangerous overtake', 'Unsafe overtake' and 'Poor defensive skills by biker, easily avoided'.

The multinomial regression found that adding the predictors to a model that contained only intercept, this significantly improved the fit between the model and the data, $\chi2(12, N = 675) = 34.91$, Nagelkerke $R2 = .06$, $p < .001$, with a significant contribution made by age to the model- See Table 4. It was found that as age increases, respondents are more likely to attribute blame to the motorcyclist compared to the car driver.

3.4.4. MMA- motorcycle overtaking turning vehicle

In the MMA- motorcycle overtaking turning vehicle scenario, car drivers and motorcyclists significantly differed in their responses, although both groups blamed motorcyclists. In regards to gender, female car drivers and female motorcyclists significantly differed in their responses- see Table 3.

The multinomial logistic regression found that by adding the predictors to a model that contained only intercept, this significantly improved the fit between the model and the data, $\chi2(12, N = 676) = 20.54$, Nagelkerke $R2 = .04$, $p < .05$, with a significant contribution made by road user type (Car driver vs Motorcyclists and Dual Road Users) to the model. It was found that car drivers are less likely than motorcyclists and dual road users to blame the motorcyclist compared to blaming the car driver.

3.5. General vs. specific

As seen previously, when both groups were asked in a general abstract sense "what road user do you think is most likely to cause a motorcyclist to have a road accident?", car drivers and motorcyclists significantly differed in their responses, with motorcyclists more likely to blame car drivers- see Fig. 2a.

Over the four specific scenarios, the amount of times each respondent blamed the car driver, motorcyclist and other ('both car driver and motorcyclist' or 'neither') was calculated. Independent samples t-tests were conducted, comparing car drivers' and motorcyclists' attribution of blame summed across all four specific scenarios. It found that car drivers were significantly more likely to blame car drivers in specific situations compared to motorcyclists (t (679) = 2.56, $p < .05$), and motorcyclists were significantly more likely to blame motorcyclists in specific situations compared to car drivers (t (679) = 1.99, $p < .05$). In regards to the 'other' responses, there was no significant difference in these responses between car drivers and motorcyclists [t (679) = .51, $p = .61$]- see Fig. 2b.

3.6. Reported accidents

As can be seen in Table 5, motorcyclists and car drivers significantly differed in their responses- in regards to whether they have been involved in an accident that has resulted in injury. In regards to gender, there was a significant difference in male motorcyclists' and female motorcyclists' responses in regards to whether they have had an accident- see Table 5.

In regards to family/friend accidents, motorcyclists were also more likely to have a family member/friend who has been involved in a motorcycle accident (55.9%) compared to car drivers (40.2%). In regards to gender, there was a significant difference in responses made by female car drivers and female motorcyclists, with female motorcyclists more likely to have a family member/friend who has been involved in a motorcycle accident (63.5%) compared to female car drivers (34%)- See Table 5.

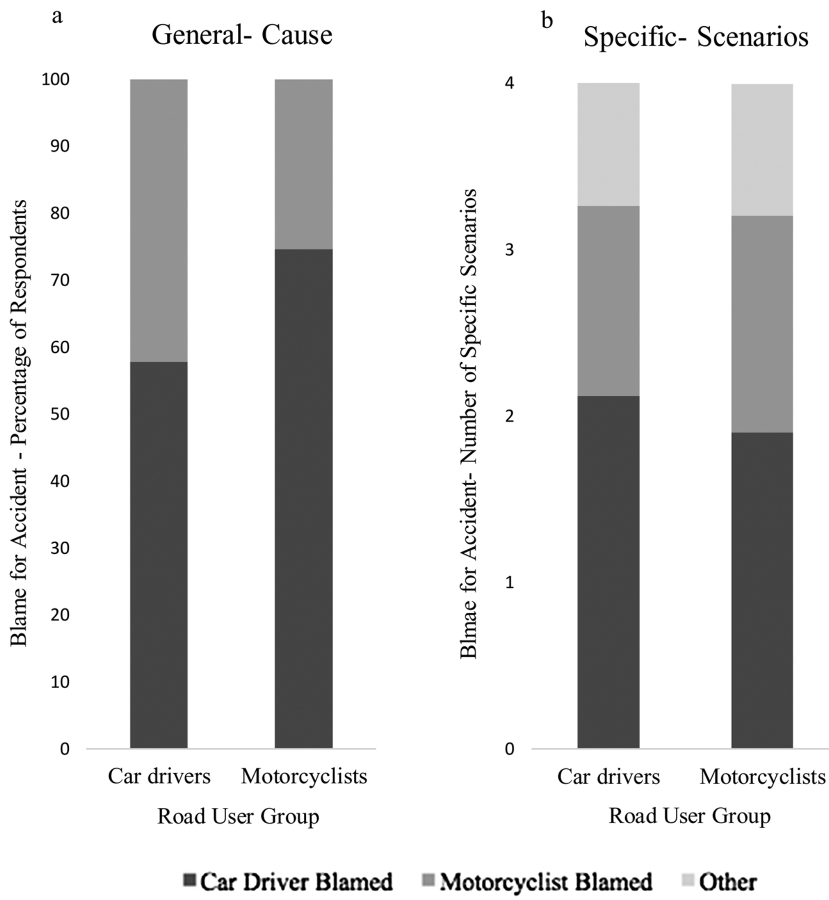

Fig. 2. Fig. 2a shows the difference in car drivers' and motorcyclists' responses when asked in a general abstract sense what road is most likely to cause a motorcycle to have an accident. Fig. 2b shows the mean number of times car drivers and motorcyclists blamed each road user type across all four specific scenarios.

3.7. *Family/friend own motorcycle*

In regards to owning a motorcycle, motorcyclists and car drivers differed significantly in their responses, with motorcyclists more likely to have immediate family/close friends who owned a motorcycle (85.9%) compared to car drivers (45.1%)- See Table 5.

In regards to gender differences, there was a significant difference in responses made by male car drivers and female car drivers, female motorcyclists and female car drivers and male car drivers and male motorcyclists. The former group from these comparisons were more likely to have immediate family/close friends who owned a motorcycle compared to the latter – See Table 5.

3.8. *Sharing the Road*

It was found that there was no relationship between group and choosing who they consider to be the most vulnerable road user, and whether the road is a shared or competitive space – See Table 5.

In regards vulnerable road users, there was a significant difference in female car drivers' and female motorcyclists' responses- see Table 5.

In regards shared/competitive space, there was a significant difference in male car drivers' and female car drivers' responses, male motorcyclists' and female motorcyclists' responses and male car drivers' and male motorcyclists' responses- see Table 5.

Respondents were asked what they think is the most common accident type for a motorcyclist to be involved in. Car drivers were more likely choose motorcyclists overtaking other vehicles or collisions with left turning vehicles, whereas motorcyclists were more likely to choose collisions with right turning vehicles or a loss of control by the motorcyclist- see Table 5. When asked to explain their choice regarding the most common accident, car drivers had a significantly higher word count (m = 14.9) compared with motorcyclists (m = 13.0) ($t(679) = 1.96$, $p < .05$).

In regards to gender, there was a significant difference in male motorcyclists' and female motorcyclists' responses- see Table 5. Female motorcyclists were more likely choose motorcyclists overtaking other vehicles or collisions with left turning vehicles, whereas male motorcyclists were more likely to choose collisions with right turning vehicles or a loss of control by the motorcyclist.

4. Discussion

The results indicate that when comparing car drivers' and motorcycles' opinions towards the same road situations, their opinions change depending on how specific the situation is. When asked in a general abstract sense which road user is most likely to cause a motorcyclist to have a road accident, car drivers' and motorcyclists' responses significantly differed, with motorcyclists particularly likely to blame car drivers, demonstrating an in-group bias. However, when asked who they believe is to blame for a specific car-motorcycle crash at a junction, this in-group bias is no longer present - both groups tend to blame the car driver and there is no evidence of car drivers tending to blame motorcyclists more. This is a striking and rather unexpected finding – particularly given that when specific details about the car-motorcycle junction crash are subsequently provided, attributions of blame become much more varied.

This reduction of in-group bias is notable in the scenario questions, where it appears repeatedly across examples, especially in the MMA scenarios, with motorcyclists more likely to blame the motorcyclist. This reduction in in-group bias was also displayed with car drivers, however, the smaller sample size means that the effect is not statistically significant. When looking at all four specific scenarios together, this reversal in in-group favouritism was also seen, with car drivers being more likely to blame the car driver and motorcyclists being more likely to blame the motorcyclist. This was also true when drivers were spilt into three road user categories for the multinomial logistic regressions, as drivers with any motorcycle experience were less likely to blame motorcyclists for the cause of general crashes compared to car drivers however, this in-group bias reduced in the specific MMA scenarios, as they were more likely than car drivers to blame motorcyclists.

These findings support the well-established finding that attitudes are variable and context-dependent (Turner, 1985). As hypothesised, specificity had an effect on road users' opinions about blame in differing situations, with specific situational detail mitigating the in-group bias which was displayed by these road users when asked generally about motorcycle accidents. In light of this, it could be the case that due to the context and frame of judgement being more specific in the scenarios in terms of the situation and location of the vehicles involved, this changes the road users' opinions compared to when asked generally about motorcycle accidents. These specific scenarios are arguably more like a real-world situation.

In regards to the ROW scenarios, there seems to be agreement from both car drivers and motorcyclists, that the car driver would be at blame in these situations. Substantial research investigating real life junction ROW accidents has found that in a high proportion of these situations, police records show the main contributory factor to be 'fail to give way (or yield)' (Lynam et al., 2001). This suggests that both road user groups were sensitive to the fact that motorcyclists, by law, have right of way in this instance and have answered in agreement to this. In addition, given that motorcyclists believed these crashes occur due to perceptual reasons, in terms of the car driver failing to observe or see the approaching motorcycle, this suggests that motorcyclists are also sensitive to the notion of 'Look But Fail To See' (LBFTS) errors, inferring that this crash could be caused by the lack of observation by the car driver. Although these scenarios only included a single motorcycle, perceptual errors have been seen to be apparent when both single vehicles and multiple vehicles are approaching the junction (Labbett and Langham, 2006; Crundall et al., 2012).

These findings therefore suggest that as the situation surrounding the junction crash becomes more specific, this elicits a fairer evaluation of blame from both road user types, reducing their in-group favouritism compared to when asked about the cause of motorcycle accidents in an abstract sense. Due to the reduction in in-group bias in specific situations, it could be the case that negative attitudes towards the other road user are no longer influencing behavioural decisions made at a junction. This suggests that these crashes may not be a result of a violation, as negative attitudes have been seen to heavily contribute to violations (Mesken et al., 2002), but possibly due to an error that is less influenced by attitudes. Although these specific scenarios were more comparable to real life situations compared to previous questions, it must be highlighted that in reality, it may nonetheless be the case that a poor attitude may affect drivers' visual attention at a junction, as gap acceptance is a quick and dynamic behaviour, therefore all situational information may not be taken into account.

In both the right turn and overtaking scenarios, a lack of motorcyclist defensive skills was highlighted in both cases by motorcyclist respondents. Motorcyclists' defensive skills are those that allow the rider to behave quickly and efficiently in difficult circumstances. It seems to be the case that in situations where the car driver or motorcyclist is seen to be at fault, motorcyclists expect to use defensive techniques, whether this be to anticipate the mistake of the car driver in order to protect themselves, or use these skills in order to make a decision about safe overtakes. Although defensive skill training has been seen to reduce motorcycle accidents (McDavid et al., 1989), it should not be the case that motorcyclists alone have to anticipate the behaviour of another road user in order to feel safe on the road or make themselves known. As the LIWC highlighted in both road user groups' responses throughout the questionnaire, the visual attention of both road users at intersections is extremely important and should be a target of investigation, in particular car drivers' visual attention. Previous research has found that drivers' visual attention at intersections towards oncoming motorcycles is not always sufficient (Crundall et al., 2008a, 2012; Lee et al., 2015), which may be partly due to a difficulty in judging motorcyclists' speeds (Horswill and Helman, 2003), particularity as motorcycles spend a much greater proportion of time travelling at higher speeds (DfT, 2015b).

When respondents were asked about the most common accident type, car drivers were more likely to choose motorcyclists overtaking other vehicles, and motorcyclists were more likely to choose motorcyclists losing control. These choices are understandable given that cars are usually the vehicles which are being overtaken by motorcycles, therefore this crash would be more noticeable to this road user group. Similarly, when motorcyclists lose control of their bike, this situation only involves a motorcyclist, therefore car drivers will not be aware of how common these crashes are. Motorcyclists were also more likely to choose vehicles turning right - given that accident statistics show that right turns are responsible for around 70% of all crashes at junctions in the U.K. (Transport Department, 1994), it may be the case that motorcyclists have encountered more unsafe experiences with car drivers turning right, compared to car drivers turning left at junctions.

When investigating the purpose of transport, the differences in car drivers' and motorcyclists' responses suggest that our car driver respondents used their vehicle for more practical purposes such as commuting, whereas the motorcyclists use their motorcycle more for leisure purposes. This, in part, may explain why the car drivers had a generally higher annual mileage compared to motorcyclists. Previous studies which have investigated the key determinants of motorcyclists' riding behaviour, indicated that motorcycle riding is predominately a social activity, often occurring within groups (Watson et al., 2007). Motorcyclists reasons for why and how they ride have also been seen to be related to the social context of riding including self-identity (Tunnicliff et al., 2011). Findings from car driver interviews, however, have found that drivers mainly use a car for reasons of flexibility and freedom, minimising the amount of time and effort needed to reach a destination (Kent, 2014).

In regards to the responses made to the questionnaires, there were notably more motorcyclist responses compared to car driver responses. As the recruitment strategy was similar for both questionnaires, the large difference in responses is striking. It seems to reflect the fact that motorcyclists are far more likely to want to express their opinions on car-motorcycle crashes, than car drivers are. In addition, when actually completing the questionnaire motorcyclists also had an overall higher word count and greater number of words per sentence compared to car drivers, which has been seen to reflect an increase in cognitive complexity (Arguello et al., 2006). This may suggest that motorcyclists have stronger opinions about junction crashes and are more engaged in the given questionnaire. It also must be noted that the recruitment strategy may have had an effect on the responses required, as forum users may be more passionate about their motorcycle/car, or road safety. That said, forum users only made up a small percentage of the overall respondent sample, and there is no reason to believe that these findings would not be true for other road users (Delbosc and Currie, 2014).

In addition, although there were roughly equal male and female car driver respondents, there were significantly more males (87%) than females (13%) in the motorcyclist sample, suggesting that vehicle use is confounded with gender. However, these gender splits accord well with previous research which has found that men are seven times more likely to make a motorcycle trip than women (Clarke et al., 2004) and car driver estimates show there were 53% male and 47% female car drivers in the U.K. in 2016 (DfT, 2017). Therefore, although there may be gender confounds in the opinions reported by car drivers and motorcyclists, separating these effects out will never be completely satisfactory.

The fact that motorcyclists reported being involved in more injury related crashes compared to car drivers is consistent with the crash statistics described previously (DfT, 2015a,b). This may also partially explain their higher engagement in the questionnaire compared with car drivers, as more direct behavioural experiences have been seen to increase the strength and accessibility of attitudes towards a given situation (Fazio et al., 1982). It is also expected that as motorcyclists are vulnerable road users, they have a heightened awareness of the dangers associated with intersections compared to car drivers, and therefore may have more to discuss when asked about this given topic. In addition, the fact that drivers who had reported a personal accident were less likely to blame motorcyclists than car drivers, again suggests that as ROW accidents account for 70% of all crashes at junctions in the U.K., respondents may be drawing upon their direct behavioural experiences when attributing blame.

The primary road safety implications of these research findings are around the framing and acceptability of road interventions. Previous research studies have found that both car drivers (39.48%) and motorcyclists (40.42%) are equally likely to have undertaken advanced driver/rider training (Horswill and Helman, 2003), which is reflected in the current sample (Car drivers– 29.41%, Motorcyclists– 29.36%). This suggests that both road users are willing to improve their safety related skills and defensive skills on the road. Given that car drivers' and motorcyclists' opinions were collected in regards to accident blame, these opinions are important in the engagement of safety interventions. An example of this could be exposing new car drivers to more on-road motorcycle interactions where car drivers are likely to accept blame, i.e. ROW crashes, touching upon existing educational campaigns such as 'Think! Bike', as it is more likely these road users will engage in safety related interventions in these specific situations. Conversely, by exposing motorcyclists to situations where motorcyclists are likely to accept blame, i.e. MMA crashes, this may increase their willingness to expand their knowledge and skills when manoeuvring around other vehicles on the approach to a junction.

Future research should consider investigating car drivers' and motorcyclists' crash history in more depth, by distinguishing how recent the crash was and under what circumstances it happened, as this additional information may provide new insights on blame attribution. In addition, a qualitative thematic analysis of car drivers' and motorcyclists' responses could also be considered, to see if additional themes emerge beyond those seen in the current study.

5. Conclusions

In summary, when comparing the opinions of car drivers and motorcyclists towards junction crashes, their responses in relation to who they believe is blameworthy is dependent on how specific the situation is which is presented. When respondents were asked, who is the main cause of motorcycle crashes in an abstract sense, motorcyclists were more likely to blame car drivers, demonstrating an in-group bias. However, when presented with specific scenarios, this in-group favouritism is reduced or reversed. In typical ROW crashes, the law is taken into account, as well as a large emphasis on the lack of observation given around junctions, especially from car drivers. We conclude that road users may show in-group biases when their general opinions are measured, but that their attribution of blame in crashes is very much dependent on the precise nature of the crash. Providing road users with details of very specific crash situations is likely to elicit a fairer evaluation of blame in both motorcyclists and car drivers and could represent a useful strategy for future road safety interventions. Future road safety interventions should focus on the framing and acceptability of interventions, as road users' opinions on blame attribution will largely influence their engagement in such interventions.

Conflicts of interest

None.

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Paper 2

How Does Drivers' Visual Search Change as a Function of Experience?
A Systematic Review and Meta-Analysis

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How does drivers' visual search change as a function of experience? A systematic review and meta-analysis

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ABSTRACT

Novice drivers are statistically over-represented in reported road crashes, with recent evidence suggesting that some of this increased crash involvement may be a result of limitations in their cognitive processing. Such processing has typically been measured by recording drivers' patterns of eye movements, however, the exact ways in which eye movements are reported and interpreted varies substantially between different studies in the literature. Therefore, the objective of this systematic review was to investigate whether novice drivers and experienced drivers do differ in clear and reproducible ways in their visual search.

Studies were identified through searches of Web of Science, Medline, TRID Database, and the TRB Research in Progress Database, with no restrictions on publication status. Studies were included if they compared the visual search of a novice driver group (< 3 years driving experience) and an experienced driver group (> 3 years driving experience) using an eye tracking method and reported at least one of the following four visual search outcomes: fixation durations, horizontal spread of search, vertical spread of search and number of fixations. Two reviewers independently screened searches and assessed the full texts of potentially included studies.

Of the 235 studies initially identified 18 were included in the review, with 13 studies reporting sufficient data to be included in the meta-analysis for at least one outcome measure. Given that the included studies deployed a range of method types, additional sub-group analyses were conducted using this factor. Sensitivity analyses were also conducted by temporarily removing extreme experience groups (e.g. driving instructors and learner drivers) in order to test the effect of different levels of experience and training.

The meta-analyses, along with support from results discussed narratively, revealed that novice drivers have a narrower horizontal spread of search compared to experienced drivers, however, there were no overall differences in fixation durations, vertical spread of search or number of fixations when the studies were pooled together. These findings have important primary implications for the development of novice training interventions, with novice drivers needing to develop a broader horizontal spread of visual search, but not to necessarily learn to fixate further down the road. Subgroup analyses also provided considerations for future research studies in terms of the experience of the driver groups, and the method type used.

1. Introduction

Driving on public roads is a highly complex and responsible task, with mistakes or risk-taking having potentially fatal consequences (Drews et al., 2008). It is widely agreed that it takes time and experience to become a fully safe and competent driver (Mayhew et al., 2003). Given the importance of visual information when driving, it is unsurprising that there have been studies investigating drivers' visual search with a particular focus on experience, dating back more than 40 years (e.g. Mourant and Rockwell, 1972; Renge, 1980). However, although there are many studies investigating this topic, it is often difficult to compare these due to the variety of methodologies deployed (Crundall and Underwood, 1998).

1.1. Age and experience

Driving statistics for many years have found that driver age and experience both make independent contributions to high crash rates (McCartt et al., 2009). Young car drivers in the UK between the ages of 17 and 25 are statistically over-represented in reported road accidents compared to older drivers aged 25 and above (DfT, 2015). In the UK, young car drivers have been found to make up 18% of all reported road crashes, which is considerably higher than the 5% of miles they account for (DfT, 2015). In the US, young drivers which include drivers between

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the ages of 15–20 years made up 9% of all fatal crashes in 2016, despite accounting for only 5.4% of all licensed drivers (National Highway Traffic Safety Administration, 2016). Globally, it has been found that road injuries sustained from driving are the leading cause of death for people between the ages of 15–29 years (World Health Organization, 2018).

Driver inexperience is also one of the most frequently reported contributory factors towards traffic crashes in the UK literature (Chapman and Underwood, 1998a) and therefore novice drivers are particularity at risk (Clarke et al., 2006). However, methodologically, it has always been difficult to separate the effects of age from those of experience on accident frequencies, as they are typically closely interrelated (McCartt et al., 2009). Nonetheless, in reviews conducted in the US and Canada, it has been found that increased driving experience has a protective effect on crash risk, with increases in driving experience being associated with reductions in crash rates for drivers of all ages (Mayhew et al., 2003; McCartt et al., 2003). This evidence has helped shape countermeasures, for example, the graduated driver licensing (GDL) scheme, with these programs applying to all new drivers regardless of age (McCartt et al., 2009).

While some studies have used the distance driven since passing a driving test as a measure of experience, many drivers find this information difficult to report accurately. Moreover, raw measures of experience based on distance driven can lead to confusing positive relationships between experience and crash involvement because of basic exposure effects, with individuals who drive more frequently being more likely to be involved in a crash (Peck, 1993). Therefore, the most common independent variable relating to driving experience in published research tends to be length of licensure. Because time since licensure is easy to calculate as a measure of driving experience and can be related directly to crash statistics, the observation has been made in the UK that drivers with less than 3 years driving experience are statistically over-represented in reported crashes compared to drivers with more than 3 years driving experience (Crundall et al., 2003; Clarke et al., 2006).

1.2. ‘A failure to look properly’

In the UK, contributory factors associated with traffic crashes are routinely assessed by the completion of a STATS 19 form by police officers at the scene (Haigney, 1995). The police officer is required to provide factors that are thought to have contributed to the crash, with the most common category titled ‘Driver Error’. This category includes various types of perceptual errors such as a ‘failure to look properly’ and ‘failure to judge the other person’s path or speed’ (Sabey and Staughton, 1975). Since 2005, ‘failed to look properly’ has continued to be the most frequently reported contributory factor for reported road crashes, with 39% of crashes described using this contributory factor in 2017 (DfT, 2018). For this reason, drivers’ visual search on the road has been under intensive investigation, with researchers particularly interested in what affects drivers’ eye movements on the road (Crundall and Underwood, 1998).

1.3. Previous literature

When a new driver becomes qualified, it is relatively easy to confirm that they possess adequate motor skills to control the vehicle (steering, braking) however, there is evidence to suggest that their higher order cognitions are not fully developed (Isler et al., 2011). Cognitive processing demands are reflected by several aspects of eye movement behaviour, therefore measuring this behaviour is a strong indication of cognitive difficulty on the road (Chapman and Underwood, 1998b; Underwood, 2007). Studies investigating drivers’ visual search typically use eye tracking technology, allowing for moment-by-moment tracking of the driver’s eye movements over the visual scene (Bremmer et al., 2009). It is typical for drivers’ general visual search to be measured over the visual scene in terms of fixation durations (how long each fixation lasts before the next saccade), the number of fixations made in a given time period, and horizontal and vertical spread of search (in terms of the variance in fixation locations across the visual field).

A previous information processing model for the control of eye movements proposed by Findlay and Walker (1999) provides a theory for deriving predictions about the distribution of fixations in a given scene, by identifying two competing pathways known as the “when” and “where” pathways. The decision to move the eyes is based on the competing demands of a “fixate” centre (which attempts to process information currently available at the point of gaze) and a “move” centre (which identifies potential locations within a broad saliency map to redirect gaze towards). The decision about when to make a new saccade is thus both related to the information that is being processed foveally (with fixation durations often regarded as an indicator of processing load - Cohen, 1981) and the information potentially available from other areas of the visual field. Within this model activation in both pathways is dependent on a mixture of both top down and bottom up factors.

In the context of driving, the model allows us to predict that experienced drivers might be able to process items at the point of gaze faster than novices, and that they would thus show shorter fixation durations overall. Such shorter fixation durations could allow additional visual search to take place that might be reflected in them achieving more fixations overall, or a broader spread of search over the visual field. Top down factors based on driver experience may also influence the “where” pathway, suggesting areas of the visual field for new fixations. Thus, an experienced driver may choose to fixate areas of low visual salience because of the knowledge that they are sources of potential future hazard-related information. The potential interaction between processing at the point of fixation and the processing of peripheral information in a driving context has been demonstrated by Crundall et al. (2002), who found that both experienced drivers’ and novice drivers’ ability to spot peripheral targets was reduced when a hazard was present at the point of fixation.

The effect of experience on drivers’ visual search has been extended by investigating extreme levels of experience and training. Advanced driver groups such as driving instructors and police drivers are of specific interest as they are among the most skilful drivers on the road. Their training heavily relies on improving observation on the road, with both the Road Craft Manual for police drivers (Coyne et al., 2007) and the Driver Instructor Handbook (Miller and Stacey, 2013) stressing the importance of improving scanning of the environment and peripheral vision. On the other hand, learner drivers are also of interest, as this minimal driving experience provides further insight into the role of driving experience on drivers’ search on the road (Konstantopoulos et al., 2012).

1.4. The effect of method type on drivers’ visual search

Studies investigating this topic have deployed a variety of method types including both simple methodology such as static images and video clips of driving scenes (e.g. Huestegge et al., 2010; Yeung and Wong, 2015), and immersive methodology such as driving simulators and on-road studies (e.g. Bos et al., 2015; Jiang et al., 2012). While images and video clips have been used in many studies due to the practical ease of the method and the ability to expose drivers to multiple driving clips in a short time, there are also some important limitations. Firstly, these methods fail to provide the driver with any element of vehicle control. Although novice drivers are believed to have adequate motor control skills (Deery, 1999), the elimination of this element may free up extra resources, which are usually needed for basic motor control, in order for drivers to scan the environment (Crundall et al., 2012).

In addition, it has also been seen that the visual field which drivers have access to during the driving task can cause differences in drivers’ visual search strategies (Di Stasi et al., 2011; Alberti et al., 2012). When comparing novice and experienced drivers' visual search under a narrow and wide field of view in a driving simulator, it was found that only experienced drivers made use of the wider eccentricities when identifying a hazard, demonstrating a larger difference in horizontal spread of search (Alberti et al., 2014). This finding suggests that the immersiveness of the driving environment may have different effects on novice drivers' and experienced drivers' visual search.

1.5. Place for the systematic review and rationale

Although there has been more than 40 years of studies into visual search and driving expertise, minimal reviews of the literature have been conducted. Green (2007) assessed eye movements while driving, by focusing on the effects of the road environment, driver characteristics and in-vehicle devices on drivers' eye movements. This review highlighted that in an era of driver distraction (e.g. driver information systems) and automated driving (e.g. adaptive cruise control), where these systems have the potential to cause visual interference (Chisholm et al., 2008), reviews of drivers' visual search on the road could provide insights into how these systems might affect driving. In a more recent review, Fisher et al. (2016) narratively summarised a proportion of the existing literature regarding eye movements and driving, focussing on how novice drivers' eye movements differed from experienced drivers on the road.

While both Green (2007) and Fisher et al. (2016) both stressed the importance of reviewing the driving literature regarding the changes in eye movements as a function of experience, there is yet to be a systematic review that seeks to gather all evidence that fits a pre-specified eligibility criterion in order to address the specific question of whether drivers' visual search is related to their level of driving experience. Therefore, this systematic review is the first to assess the relationship between driving experience and drivers' general visual search, synthesising non-randomised controlled studies which compare the visual search of novice and experienced drivers. By using a systematic method and meta-analysis, this is thought to reduce bias and produce reliable findings from which conclusions can be drawn (Antman et al., 1992), as results of independent studies can be statistically summarised (Glass, 1976). Systematic reviews are also extremely important in regards to informing policy decisions, particularly given that both researchers and policy makers are concerned with driver safety.

This systematic review has important primary implications for road safety, particularly in regards to visual search strategy interventions for novice drivers. These interventions include road commentary training for improving search allocation (Crundall et al., 2010; Cantwell et al., 2013; Castro et al., 2016), hazard perception training for anticipating and detecting hazards (Chapman et al., 2002; Horswill et al., 2013) and graduated driver licensing (GDL) schemes in Australia, New Zealand and Canada (Hartling et al., 2004), where specific training to maximise visual search across the driving scene is given. The current systematic review allows for a better understanding of how novice and experienced drivers distribute their visual search across the roadway, and therefore can help inform such interventions.

1.6. Objectives

This systematic review and meta-analysis have been undertaken to investigate whether driving experience relates to drivers' general visual search, by comparing novice drivers' and experienced drivers' fixation durations, spread of search (horizontal spread of search and vertical spread of search) and number of fixations over the driving scene.

Given that studies investigating this topic have deployed a variety of method types, additional sub-group analyses will be conducted by categorising the included studies by method type (simple methodology or immersive methodology). This allows for all studies, irrelevant of choice of method, to be included in the overall meta-analysis of each outcome measure, as well as investigating the effects of this factor on drivers' visual search.

2. Methods

2.1. Criteria for considering studies for this review

The 27-item PRISMA checklist was used when conducting and reporting this systematic review and meta-analysis (Moher et al., 2009). This systematic review identified all studies which investigated whether driving experience related to drivers' visual search by comparing the visual search of novice and experienced drivers. Since this is a between subject comparison of novice and experienced driver groups from the population, the studies feature no formal randomisation as it is not possible to randomly assign drivers to one of the two groups. The included studies used various methods to investigate potential differences in visual search including on-road studies, driving simulator studies, video recordings and static images of driving scenes.

2.1.1. Inclusion criteria

This review considered all studies that met the inclusion criteria. As there is no single objective defined measure of a novice and experienced driver, we used a practically important distinction based on crash statistics. It is clear that drivers with less than 3 years driving experience are statistically over-represented in reported road crashes compared to drivers with more than 3 years' experience (Clarke et al., 2006), with the reduction in reported road crashes over the first 3 years commonly including those where the driver is primarily at fault (rear end stunts, turns across traffic). Although 3 years is a rather arbitrary cut-off, and may not conform with some literature which suggests that crash risk drops most dramatically during the first 6 months (Mayhew et al., 2003) or first year of driving (Bingham and Shope, 2004), it does provide a clearly defined point around which there is an undeniable reduction in the disproportionate crash involvement associated with novice drivers, and allows for more studies to be considered for inclusion in the systematic review. So, for the current review a novice driver was defined as a driver who had no more than 3 years driving experience after passing the practical test and additionally included learner drivers. In contrast, experienced drivers were defined as those who had 3 or more years driving experience after passing the practical test. Studies that investigated groups of drivers with advanced training such as driving instructors, taxi drivers and police pursuit drivers were included. Only studies that examined the visual search of drivers with normal and corrected normal vision (glasses and contact lenses) were included. Participants in the studies could be of any age or gender. All included studies were published in the English language, though we made no country, date or publication restriction to the search.

2.1.2. Exclusion criteria

The systematic review criterion therefore excluded studies which investigated the visual search of non-drivers. We additionally excluded studies which had passengers present in the car or simulator during the experiment (except the researcher) to eliminate any distraction effects. Studies that only investigated differences in novice and experienced drivers' visual behaviour under the influence of alcohol, drugs, fatigue or in-car distractions such as a mobile phone were also excluded.

2.1.3. Outcome measures

The review considered studies that investigated novices' and experienced drivers' visual search using an eye tracking method and measured at least one of the following outcome measures: fixation durations, spread of search and number of fixations. Fixation durations reflect the length of time drivers generally hold their eyes in each location before moving on. In driving data smooth pursuits on moving objects are typically included as fixations. Spread of search is divided into two measures: horizontal spread of search and vertical spread of search. These measures show the variance of fixations over the horizontal and vertical axis. Finally, the number of fixations is simply how many fixations a driver made over the driving scene and provides a measure of sampling rate. Although we would generally expect the number of fixations to be inversely proportional to the fixation duration, the ways in which these measures are recorded and reported in individual studies means that this is not always the case. Although some studies provide additional details (e.g. fixations on specific aspects of the road environment), these are not universally provided and there is great variety in the way such details are categorised making them hard to use in a systematic review. Therefore, only studies that reported at least one of these four measures over the whole driving scene, and not in areas of specific interest were included. These general visual search measures were chosen as outcomes measures as they are less sensitive to heterogeneity in the methods and tasks used as opposed to capturing the sequences of fixations for hazard anticipation.

2.2. Search methods for identification of studies

The search strategy used was developed to find peer reviewed full journal articles and abstracts (subject to enough information), grey literature including conference proceedings and current ongoing unpublished research.

Electronic searches included Web of science (May, 1900- Jan, 2019), Medline OVID (1946- Jan, 2019) and TRID, the TRIS and ITRD (1990- Jan, 2019) Database. The TRID database is an integrated database that combines the records from TRB's Transportation Research Information Services (TRIS) Database and the International Transport Research Documentation (ITRD) Database, and therefore is a key database of the review. In addition, current ongoing research was also searched electronically using the TRB Research in Progress (RiP) Database (1990- Jan, 2019). These databases were chosen as they are key transport databases and it was unlikely that new studies could have been found elsewhere.

A search strategy was developed to include all relevant keywords relating to drivers, experience, and visual search in each resource. In order for a record to be included in the initial search, the study must have included at least one word or phrase from each of the three categories. See Supplementary File 1 for the search strategy and list of the specific keywords used.

2.3. Data collection and analysis

Following the electronic searches, all citations were downloaded into Mendeley and all duplicates were removed. In regards to the selection of studies, this involved a two-step process. Firstly, the initial search results from the electronic databases were screened against the inclusion criteria by two reviewers who read the titles, abstracts and keywords to identify the studies with potential relevance. Secondly, the full text of the selected citations were obtained and assessed. Two independent reviewers decided on the study's inclusion using the predetermined inclusion criteria. The studies that were not included can be seen in Supplementary File 2, with the reasons for exclusion provided.

The results of the study selection are reported using a PRISMA flow diagram (Moher et al., 2009) in Fig. 1. Qualitative synthesis refers to the number of studies that met the inclusion criteria and therefore could be discussed narratively, and quantitative synthesis refers to the amount of studies that provided the necessary values to be included in the meta-analyses.

2.4. Critical appraisal and data extraction

All studies were critically appraised by two independent reviewers at the study level for methodological quality using the standardised critical appraisal tool, McMaster Critical Appraisal Tool for Quantitative Studies (Law et al., 1998). This tool was chosen due to its relevance for quantitative, non-randomised controlled studies, therefore had the most fitting criteria for studies included in this review. All papers, regardless of the results of their methodological quality, underwent data extraction and synthesis where possible. The critical appraisal process allowed for full engagement with all of the included papers. The results of the critical appraisal are reported in Tables 1 and 2.

2.4.1. Dealing with missing data

Where data were missing, the authors were contacted and the additional data was requested. If an included study did not report a particular outcome, this study was not included in the analysis of that outcome.

2.5. Data synthesis

2.5.1. Quantitative synthesis

The data from the included studies was synthesised using a meta-analysis where possible, using Review Manager 5 (version 5.1 Nordic Cochrane Centre, the Cochrane Collaboration). There were 13 studies with sufficient data details to calculate the standardised mean difference with 95% confidence intervals for at least one outcome measure, See Table 1.

Standardised mean differences were used as the summary statistic due to the included studies measuring horizontal spread of search, vertical spread of search and number of fixations in a variety of ways. Horizontal and vertical spread of search were measured by the standard deviation of x and y locations in degrees or pixels, however, the available field of view and calibration range of the eye-trackers differed dramatically between studies meaning that raw values could not be directly compared. Number of fixations were measured by the mean number, or total number of fixations during the driving clip, however, these values differed considerably due to the varying length of the driving scenes. Fixation durations were always measured in milliseconds. See Table 1 for each individual studies unit of measurement for each outcome. Given that the remaining measures differed in detail between studies it was necessary to standardise these results to a uniform scale before combining them (Higgins and Green, 2011).

Statistical testing was used (Z, Chi-Square) to investigate the significance of the overall effect for each outcome measure, and for overall subgroup differences (Polanin and Pigott, 2015). As previous reviews have acknowledged a need for consistency in reporting meta-analysis results, these statistical tests will have their corresponding 95% confidence intervals and measure of heterogeneity (I^2).

Heterogeneity was assessed statistically using the standard I^2 test, looking at similarities of studies. While it is acknowledged that determining what constitutes a large I^2 value is subjective, the following rule has been previously suggested (Schünemann et al., 2013). If the heterogeneity is between 0% and 40%, then a fixed effects model should be used whereas if the heterogeneity is between 40% and 85% then a random effects model should be used.

2.5.1.1. Coding of outcome measures. In regards to the coding of outcome measures for each study, values were averaged on occasions where the measure had been separately calculated for different environmental demands (e.g. rural, suburban and dual carriageway; high, medium and low hazardous clips; daytime and night time clips). This approach was taken in order to resolve dependence of the effect sizes in the meta-analysis when multiple measures were available for a single construct (Scammacca et al., 2014). This method is in accordance to Cooper's (1998) shifting-unit-of-analysis approach.

On occasions where a study had both an advanced group of drivers (i.e. police pursuit drivers) and an experienced group of drivers with no additional training, these two groups were integrated into a single experienced group for the overall meta-analysis of each outcome measure, by averaging the values for these drivers. The combining of these driver

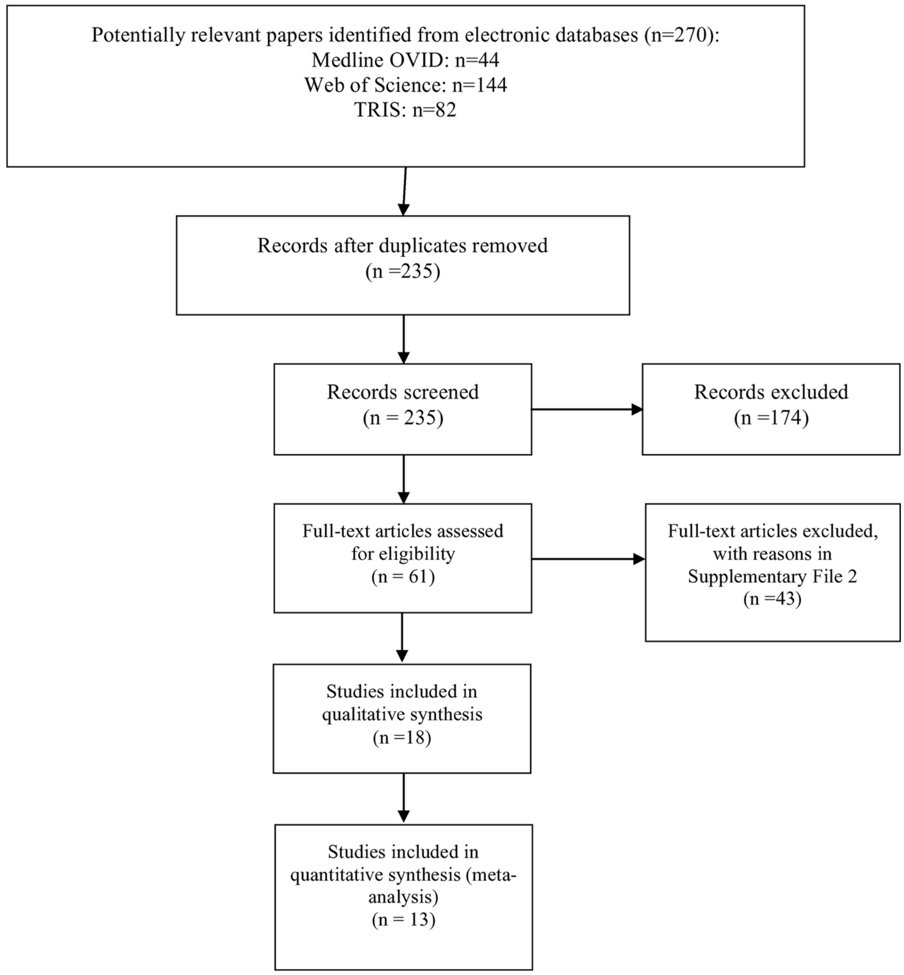

Fig. 1. A PRISMA flow diagram for the number of records included in each stage of the review.

groups meant that all drivers included in the experienced driver group still met the inclusion criteria of more than 3 years driving experience. The inclusion of these advanced driver groups also allowed for the sensitivity analysis detailed below.

2.5.2. *Qualitative synthesis*

Five studies did not report sufficient data to calculate a mean difference and 95% confidence intervals (Bos et al., 2015; Crundall et al., 1999; Laya, 1992; Lehtonen et al., 2014; Mourant and Rockwell, 1972) and therefore given that statistical pooling was not possible, these findings will be discussed narratively. This qualitative synthesis allows for the findings of these studies to still be integrated in the review as they met the pre-defined inclusion criteria (Ryan, 2013), See Table 2.

2.5.3. *Subgroup analysis*

Due to the variety of method types used to compare experienced and novice drivers' visual search, subgroup analyses were conducted as there was sufficient data to determine whether outcome measures vary according to method type (Fu et al., 2011), which was either simple methodology or immersive methodology. Simple methodology is defined as a method that presents the visual driving scene on a screen that subtends less than 90 degrees of visual angle, and where the participant has to merely observe the driving scene, requiring no form of vehicle control. These methods usually involve drivers watching static images or video clips. Immersive methodology is defined as a method that presents the visual driving scene on a screen that subtends at least 90 degrees of visual angle, and requires the participant to control a vehicle throughout the driving task. The most common forms of method are driving simulators (both medium and high fidelity) and on-road studies. Each included study fell clearly into one of the categories as defined above (simple vs. immersive). The coding of these outcomes as a function of method was the same as those previously stated, by averaging across the different road demands in each study.

2.5.4. *Sensitivity analysis*

To examine the effect of removing studies with the greatest potential risk of bias, a sensitivity analysis was conducted where necessary to test decisions made regarding the inclusion of learner drivers and experienced driver groups who have additional driver training. The main overall analysis for each outcome measure was repeated with these studies temporarily removed.

In addition, given that the definitions of a novice and experienced driver varies considerably across studies, the definition of novice drivers as those with less than 3 years of licensure, and experienced drivers being those with more experience than this is a potentially controversial one. Other studies have defined novice drivers as having held a licence for less than a year (Bingham and Shope, 2004) and experienced drivers as having held a licence for at least 5 years (Chapman and Underwood, 1998a, 1998b). Therefore, the main analysis for each outcome measure was also repeated by removing the studies that included novice drivers with more than 1-year's experience, and experienced drivers with less than 5-years' experience, making the eligibility criteria for novice and experienced drivers more restrictive. The removal of these studies reduced the number of studies that were included in the meta-analysis for each measure but did not change the overall effect for each outcome measure, see S3 for the full restricted

Table 1
Shows the 13 studies that were included in the meta-analysis for at least one measure, as well as the information collected for each of these studies during the critical appraisal.

Studies Included in Meta-Analysis

Study	Method	Task Type	No of Exp	Average Experience (m)	Extra Experienced Group	No of Nov	Average Experience (m)	Learner Drivers	Outcome Reported in Meta-Analysis	Units of Outcome Measures	Outcomes Reported not in Meta-analysis
Alberti et al. (2014)	Simulator	Hazardous Situations	20	126	none	20	19	none	Horizontal Spread of Search	Degrees	None
Borowsky and Oron-Gilad (2013)	Video Clips	Hazardous Situations	27	91.1	Includes 10 taxi drivers	17	1.5	none	Vertical Spread of Search	Degrees	No of Fixations and Horizontal Spread of Search
Chapman and Underwood (1998a)	Video Clips	Rural, Suburban, Urban	26	84	none	51	3	none	Mean Fixation Duration, Vertical Spread of Search	Milliseconds, Degrees	Horizontal Spread of search
Crundall and Underwood (1998)	On-road	Rural, Suburban, Urban	16	108	none	16	2	none	Mean Fixation Duration, No of Fixations, Horizontal/ Vertical Spread of Search	Milliseconds, Total Number, Degrees	None
Crundall et al. (2003)	Video Clips	Hazardous Situations	32	226.79	Includes 16 Police pursuit drivers	16	34.8	none	Mean Fixation Duration, Horizontal Spread of Search	Milliseconds, Pixels	Vertical Spread of Search
Hills et al. (2018)	Static Images	Hazardous Situations	20	99	none	36	12	none	Horizontal/ Vertical Spread of Search	Proportion of Eye Movements	None
Huestegge et al. (2010)	Static Images	Hazardous Situations	20	60	none	20	9	Includes learner drivers	Mean Fixation Duration, No of Fixations	Milliseconds, Mean Number	None
Jiang et al. (2012)	On-road	Rural, Urban, Dual Carriageway	5	139.19	none	5	36	none	Mean Fixation Duration, Horizontal/Vertical Spread of Search	Milliseconds, Degrees	None
Kahana-Levy et al. (2019)	Video Clips	Hazardous Situations	35	102.95	none	23	6.45	none	Horizontal/Vertical Spread of Search, No of Fixations	Degrees	None
Konstantopoulos et al. (2010)	Simulator	Differing Visibility	10	408	All driving instructors	11	0	All leaner drivers	Mean Fixation Duration, No of Fixations, Horizontal/ Vertical Spread of Search	Milliseconds, Total Number, Degrees	None
Underwood et al. (2002a)	Video Clips	Rural, Urban, Dual Carriageway	16	55.07	none	16	1	none	Mean Fixation Duration, Horizontal/Vertical Spread of Search	Milliseconds, Degrees	None
Underwood et al. (2003)	On-road	Rural, Urban, Dual Carriageway	16	108	none	20	2.4	none	No of Fixations	Mean Number	None
Yeung and Wong (2015)	Video Clips	Hazardous Situations	28	99.4	none	14	24	none	Mean Fixation Duration	Milliseconds	Horizontal Spread of Search

Table 2
Shows the 5 studies that were not included in the meta-analysis, as well as the information collected for each of these studies during the critical appraisal.

Studies not Included in Meta-Analysis

Study	Method	Task Type	No of Exp	Average Experience (m)	Extra Experienced Group	No of Nov	Average Experience (m)	Learner Drivers	Outcome/s Measured	Reason for exclusion in Meta-analysis
Bos et al. (2015)	Simulator	Hazardous Situations	8	162	none	10	30	none	No of Fixations, Horizontal/ Vertical Spread of Search	Means and SD of experienced and novice drivers not reported
Crundall et al. (1999)	Video Clips	Hazardous Situations	20	60	none	20	2.5	none	Mean Fixation Duration, Horizontal/Vertical Spread of Search	Means and SD of experienced and novice drivers not reported
Laya (1992)	Simulator/On-road	Driving around curves	8	60	none	8	12	none	Mean Fixation Duration	Means and SD of experienced and novice drivers not reported
Lehtonen et al. (2014)	On-road	Driving around curves	9	120	none	9	18	none	Horizontal/Vertical Spread of Search	Means and SD of experienced and novice drivers not reported
Mourant and Rockwell (1972)	On-road	Differing Road Types	4	60	none	6	0	All learner drivers	Horizontal/Vertical Spread of Search	Means and SD of experienced and novice drivers not reported

analysis.

It must also be noted that a large proportion of the studies included in the meta-analyses were conducted at the University of Nottingham, with many of the same researchers present. Due to this, the participants that took part in the on-road study by Crundall and Underwood (1998) were a subset of the participants used in the hazard perception clip study by Chapman and Underwood (1998a). The second author of the current paper is also a co-author on a substantial proportion of the included studies, therefore for this reason, the inclusion and appraisal of studies in the review was conducted solely by the first author and a second independent reviewer. An additional sensitivity analysis was conducted to remove any studies that have the same co-author as the current paper. Again, the removal of these studies did not change the overall effect for each outcome measure, see S4 for this analysis.

3. Results

The search strategy found 18 papers fitting the inclusion criteria. These studies included 320 experienced drivers with driving experience ranging from 5 years to 34 years, and 318 novice drivers with driving experience ranging from 0 years to 3 years. These studies were published between 1992 and 2019, with two studies using static images of road scenes, seven studies using video clips, three driving simulator studies, five on-road studies and one study conducted on-road and in a driving simulator.

3.1. Mean fixation duration

There were ten studies that reported fixation durations as a function of experience (Chapman and Underwood, 1998a; Crundall and Underwood, 1998; Crundall et al., 1999, 2003; Huestegge et al., 2010; Jiang et al., 2012; Konstantopoulos et al., 2010; Laya, 1992; Underwood et al., 2002a; Yeung and Wong, 2015).

Two studies could not be included in the meta-analysis and therefore will be discussed narratively. One study investigated differences in experienced drivers' and novice drivers' fixation durations when displaying hazardous, high demand situations (Crundall et al., 1999) and the other investigated fixation durations around curves (Laya, 1992). These studies had a total of 28 experienced drivers and 28 novice drivers. Both studies concluded that novice drivers have significantly longer fixation durations compared to experienced drivers.

For the other eight studies, these were pooled in a meta-analysis, inputting the mean and standard deviation for both novice and experienced driver groups for each study. Although all of the included studies measured fixation durations in milliseconds, the means and standard deviations varied considerably between studies. Therefore, for this reason, and for consistency in reporting, fixation durations are firstly reported with standardised mean differences, See Fig. 2, and then with mean differences, along with an effect size (Cohen's d). Cohen's d has been calculated using the standard deviation from Chapman and Underwood (1998a) which has been chosen to be most representative due to its large and justified sample size (Higgins and Green, 2011).

Firstly, in regards to the standardised mean difference, the overall effect of driving experience on fixation durations did not produce a significant difference, $Z = 1.69$, $p = .09$, (95% CI −0.44, 0.03), See Fig. 2.

Given that two studies included advanced drivers in the experienced group, with Crundall et al. (2003) using police pursuit drivers and Konstantopoulos et al. (2010) using driving instructors, as well as Konstantopoulos et al. (2010) and Huestegge et al. (2010) using learner drivers, a sensitivity analysis was conducted which removed these studies. When these studies were removed, there was still no overall effect of driving experience on drivers' fixation durations, $Z = 0.63$, $p = .53$ (95% CI -0.40, 0.20), with this null result being much more evident.

Secondly, in regards to mean difference, the overall effect of driving

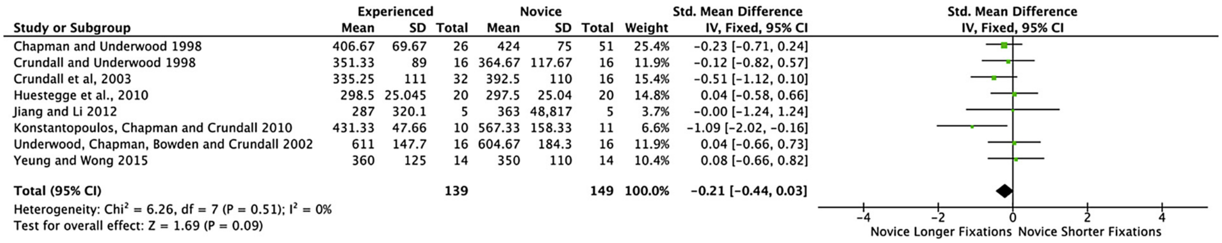

Fig. 2. A forest plot to show the standardised mean difference and overall effect of driving experience on novice' and experienced drivers' fixation durations.

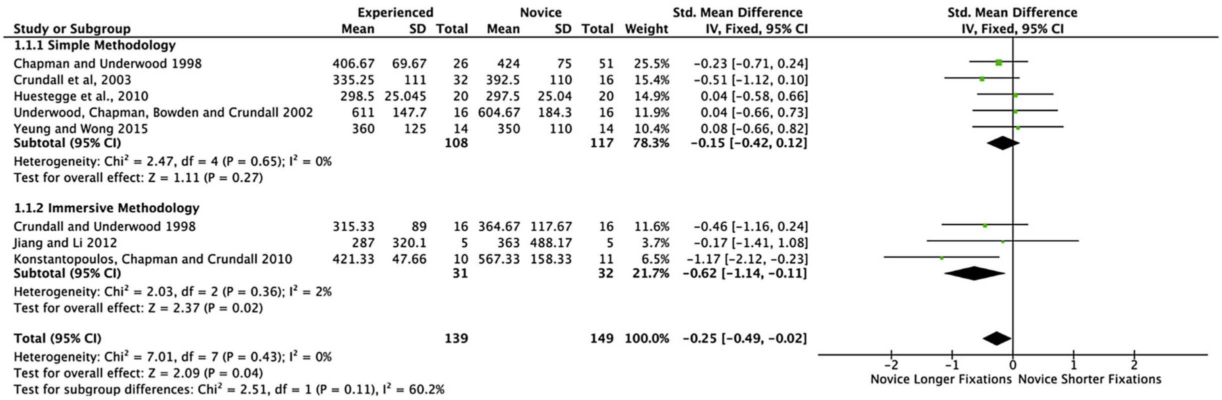

Fig. 3. A forest plot to show the subgroup analysis of how driving method (simple methodology and immersive methodology) changes the effect of experience on drivers' fixation durations.

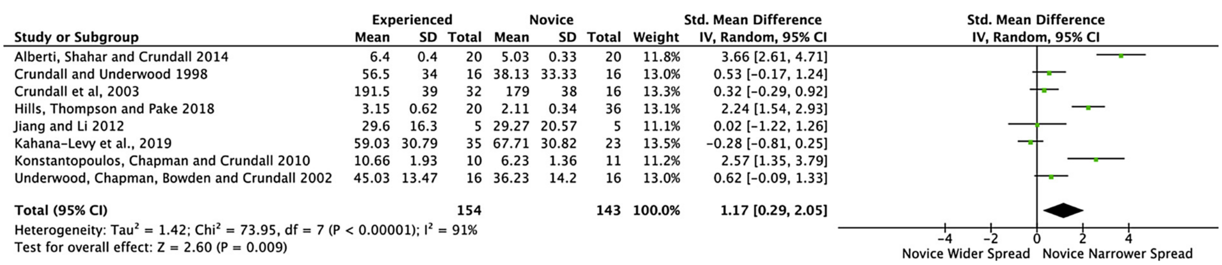

Fig. 4. A forest plot to show the overall effect of driving experience on novice' and experienced drivers' mean horizontal spread of search.

experience on fixation durations did not produce a significant difference, Z = 1.03, p = .30, (95% CI -20.09, 6.24), *d* = .29.

In addition, a subgroup analysis was conducted to determine whether fixation durations vary according to the method type used. The overall effect of method type did not significantly change the effect of experience on drivers' fixation durations (Chi^2 = 2.51, p = .11). The effect of simple methodology alone was not significant (Z = 1.11, p = .27 (95% CI -0.42, 0.12)), whereas the effect of immersive methodology alone was significant (Z = 2.37, p = .02 (95% CI −1.14, -0.11)), See Fig. 3.

3.2. Horizontal spread of search

There were fifteen studies that reported horizontal spread of search as a function of experience (Alberti et al., 2014; Borowsky and Oron-Gilad, 2013; Bos et al., 2015; Chapman and Underwood, 1998a; Crundall and Underwood, 1998; Crundall et al., 1999, 2003; Hills et al., 2018; Jiang et al., 2012; Kahana-Levy et al., 2019; Konstantopoulos et al., 2010; Lehtonen et al., 2014; Mourant and Rockwell, 1972; Underwood et al., 2002a; Yeung and Wong, 2015).

Seven studies could not be included in the meta-analyses and therefore will be discussed narratively. Six of these studies, which included 121 novice drivers and 118 (incl. 10 taxi drivers) experienced drivers (Borowsky and Oron-Gilad, 2013; Bos et al., 2015; Chapman and Underwood, 1998a; Crundall et al., 1999; Lehtonen et al., 2014; Yeung and Wong, 2015), found that there was no significant difference in novice drivers' and experienced drivers' horizontal visual search over a range of low, medium and high driving demand situations, which were conducted using a range of methods including video clips, simulators and on-road. In contrast, Mourant and Rockwell (1972) found that experienced drivers had significantly wider horizontal spread of search compared to novice drivers however, this was the only one of these seven studies to use learner drivers for the novice driver group.

For the other eight studies, these were pooled in a meta-analysis. The overall effect of driving experience on horizontal spread of search produced a significant standardised mean difference, Z = 2.60, p = .009 (95% CI 0.29, 2.05), with experienced drivers having a wider horizontal spread of search compared to novice drivers, See Fig. 4.

As before, a sensitivity analysis was conducted by removing the two studies that included an advanced experienced group and learner drivers (Crundall et al., 2003; Konstantopoulos et al., 2010). When these studies are removed, there was still an overall effect of driving experience on drivers' horizontal spread of search, Z = 1.98, p < .05 (95% CI 0.01, 2.22), however, this difference had reduced.

In addition, a subgroup analysis was conducted to determine whether horizontal spread of search varies according to the method type used. The overall effect of method type did not significantly change the effect of experience on drivers' horizontal spread of search (Chi^2 = 1.16, p = .28). The effect of simple methodology alone was not significant (Z = 1.39, p = .16 (95% CI -0.26, 1.55)), whereas the effect

Study or Subgroup	Experienced Mean	Experienced SD	Experienced Total	Novice Mean	Novice SD	Novice Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.2.1 Simple Methodology								
Crundall et al, 2003	191.5	39	32	179	38	16	13.4%	0.32 [−0.29, 0.92]
Hills, Thompson and Pake 2018	3.15	0.62	20	2.11	0.34	20	12.8%	2.04 [1.26, 2.82]
Kahana–Levy et al., 2019	59.03	30.79	35	67.71	30.82	23	13.6%	−0.28 [−0.81, 0.25]
Underwood, Chapman, Bowden and Crundall 2002	45.03	13.47	16	36.23	14.2	16	13.1%	0.62 [−0.09, 1.33]
Subtotal (95% CI)			**103**			**75**	**52.9%**	**0.64 [−0.26, 1.55]**
Heterogeneity: Tau² = 0.74; Chi² = 23.70, df = 3 (P < 0.0001); I² = 87%								
Test for overall effect: Z = 1.39 (P = 0.16)								
1.2.2 Immersive Methodology								
Alberti, Shahar and Crundall 2014	6.4	0.4	20	5.03	0.33	20	11.8%	3.66 [2.61, 4.71]
Crundall and Underwood 1998	56.5	34	16	38.13	33.33	16	13.1%	0.53 [−0.17, 1.24]
Jiang and Li 2012	29.6	16.3	5	29.27	20.57	5	11.0%	0.02 [−1.22, 1.26]
Konstantopoulos, Chapman and Crundall 2010	10.66	1.93	10	6.23	1.36	11	11.1%	2.57 [1.35, 3.79]
Subtotal (95% CI)			**51**			**52**	**47.1%**	**1.69 [0.02, 3.36]**
Heterogeneity: Tau² = 2.61; Chi² = 32.00, df = 3 (P < 0.00001); I² = 91%								
Test for overall effect: Z = 1.98 (P = 0.05)								
Total (95% CI)			**154**			**127**	**100.0%**	**1.14 [0.28, 1.99]**
Heterogeneity: Tau² = 1.32; Chi² = 67.14, df = 7 (P < 0.00001); I² = 90%								
Test for overall effect: Z = 2.61 (P = 0.009)								
Test for subgroup differences: Chi² = 1.16, df = 1 (P = 0.28), I² = 13.5%								

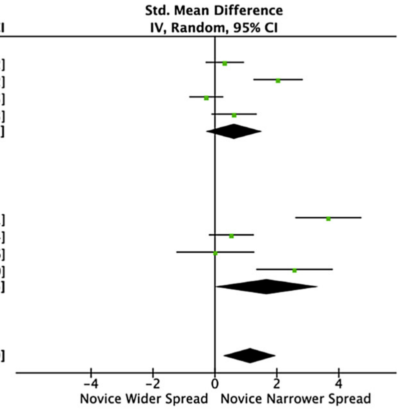

Fig. 5. A forest plot to show the subgroup analysis of how driving method (simple methodology and immersive methodology) changes the effect of experience on drivers' horizontal spread of search.

of immersive methodology alone was significant (Z = 1.98, $p < .05$ (95% CI 0.02, 3.36)), See Fig. 5.

3.3. Vertical spread of search

There were thirteen studies that reported vertical spread of search as a function of experience (Borowsky and Oron-Gilad, 2013; Bos et al., 2015; Chapman and Underwood, 1998a; Crundall and Underwood, 1998; Crundall et al., 1999, 2003; Jiang et al., 2012; Hills et al., 2018; Kahana-Levy et al., 2019; Konstantopoulos et al., 2010; Lehtonen et al., 2014; Mourant and Rockwell, 1972; Underwood et al., 2002a).

Five studies could not be included in the meta-analyses and therefore will be discussed narratively. Three of these studies, which included 39 novice drivers and 37 experienced drivers (Bos et al., 2015; Crundall et al., 1999; Lehtonen et al., 2014), found that there were no significant differences in novice' and experienced drivers' vertical visual search. In contrast, Mourant and Rockwell (1972) and Crundall et al. (2003) found that novice drivers had significantly wider vertical spread of search compared to experienced drivers however, these studies were the only two to use extreme driver groups in their sample in terms of police pursuit drivers and learner drivers.

For the other eight studies, these were pooled in a meta-analysis. The overall effect of driving experience on vertical spread of search did not produce a significant standardised mean difference, Z = 1.38, p = .17 (95% CI −0.68, 0.12), See Fig. 6.

Given that two of the studies included in the meta-analysis also used an advanced driver experienced group, with Borowsky and Oron-Gilad (2013) using taxi drivers and Konstantopoulos et al. (2010) using driving instructors as well as leaner drivers, these studies were removed from the analysis. Again, there was no overall effect of driving experience on drivers' vertical spread of search, Z = .80, p = .42 (95% CI −0.69, 0.29).

In addition, a subgroup analysis was conducted to determine whether vertical spread of search varies according to the method type used. The overall effect of method type did not significantly change the effect of experience on drivers' vertical spread of search ($Chi^2 = 0.09$, p = .76), with both simple methodology alone (Z = 1.21, p = .23 (95% CI −0.90, 0.21) and immersive methodology alone (Z = 0.88, p = .38 (95% CI −0.73, 0.27)) not being significant.

3.4. Number of fixations

There were seven studies that reported number of fixations as a function of experience (Borowsky and Oron-Gilad, 2013; Bos et al., 2015; Crundall and Underwood, 1998; Huestegge et al., 2010; Kahana-Levy et al., 2019; Konstantopoulos et al., 2010; Underwood et al., 2003).

Two studies could not be included in the meta-analyses and therefore will be discussed narratively. These two studies, which include 27 novice drivers and 35 experienced drivers (incl. 10 taxi drivers) (Borowsky and Oron-Gilad, 2013; Bos et al., 2015), found that there was no significant difference between the number of fixations made by experienced drivers and novice drivers.

For the other five studies, these were pooled in a meta-analysis. The overall effect of driving experience for number of fixations did not produce a significant standardised mean difference, Z = 1.10, p = .27 (95% CI −0.13, 0.46).

A sensitivity analysis was conducted by removing the two studies that included learner drivers, with one of these studies also including driving instructors (Huestegge et al., 2010; Konstantopoulos et al., 2010). By removing these studies, the heterogeneity involved in this meta- analysis was reduced from 13% to 0%. The removal of these studies did not change the overall effect dramatically, still failing to produce a significant difference, Z = .96, p = .34 (95% CI −0.18, 0.54).

In addition, a subgroup analysis was conducted to determine whether the number of fixations varies according to the method type used. The overall effect of the method type used in the study did not significantly change the effect of experience on drivers' number of fixations ($Chi^2 = .21$, p = .64), with the effect of simple methodology alone

Study or Subgroup	Experienced Mean	Experienced SD	Experienced Total	Novice Mean	Novice SD	Novice Total	Weight	Std. Mean Difference IV, Random, 95% CI
Bowowsky and Oron-Gilad 2013	35.92	8.05	27	42.64	8.04	17	13.4%	−0.82 [−1.45, −0.19]
Chapman and Underwood 1998	0.4	0.28	26	0.44	0.36	51	15.7%	−0.12 [−0.59, 0.35]
Crundall and Underwood 1998	16.13	11.43	16	22.5	14.23	16	12.4%	−0.48 [−1.19, 0.22]
Hills, Thompson and Pake 2018	1.95	0.23	20	2.4	0.44	36	14.0%	−1.17 [−1.76, −0.58]
Jiang and Li 2012	33.67	17.53	5	24.7	16.93	5	6.7%	0.47 [−0.80, 1.74]
Kahana–Levy et al., 2019	23.34	15.75	35	17.56	14.24	23	14.9%	0.38 [−0.16, 0.91]
Konstantopoulos, Chapman and Crundall 2010	3.2	0.56	10	3.3	0.6	11	10.5%	−0.17 [−1.02, 0.69]
Underwood, Chapman, Bowden and Crundall 2002	4.37	2.66	16	4.37	2.64	16	12.5%	0.00 [−0.69, 0.69]
Total (95% CI)			**155**			**175**	**100.0%**	**−0.28 [−0.68, 0.12]**
Heterogeneity: Tau² = 0.21; Chi² = 20.16, df = 7 (P = 0.005); I² = 65%								
Test for overall effect: Z = 1.38 (P = 0.17)								

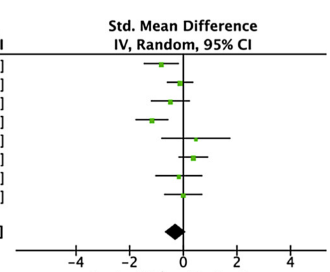

Fig. 6. A forest plot to show the overall effect of driving experience on novice' and experienced drivers' vertical spread of search.

(Z = .32, p = .75 (95% CI −0.49, 0.69) and immersive methodology alone (Z = .91, p = .36 (95% CI −0.35, 0.96)) not being significant.

4. Discussion

4.1. Summary of results

Despite claims for the past 40 years that novice drivers' visual search differs from experienced drivers' visual search on the road, the current findings suggest that these differences are not so apparent when all available studies are pooled together. While it was clear that there was a difference in drivers' horizontal spread of search, with novice drivers having a narrower horizontal spread of search compared to experienced drivers, there were no reliable differences found in fixation durations, vertical spread of search and number of fixations. While horizontal spread of search continues to support the general conclusions from previous literature, there are some factors that need to be considered when identifying the differences between novice drivers' and experienced drivers' eye movements such as the experience level of the two groups of drivers, and the effect of method type.

4.2. Differences in novice drivers' and experienced drivers' visual search

The only measure to show a clear overall difference in the meta-analysis between novice and experienced drivers was horizontal spread of search, with novice drivers displaying a narrower spread of search compared to experienced drivers. This difference has been widely interpreted as novice drivers having limited experience in scanning and anticipating the location of potential hazards in the peripheral (e.g. Mourant and Rockwell, 1972; Kahana-Levy et al., 2019).

In addition, the sensitivity analysis which temporarily removed studies that investigated extreme experience groups showed a reduction in the difference between novice and experienced drivers, suggesting that the inclusion of these drivers may have accounted for a substantial proportion of the overall effect. The inclusion of these groups may have also accounted for the differences in the results of the studies described narratively (Mourant and Rockwell, 1972). However, without the inclusion of these groups, the difference between novice and experienced drivers still remained.

When the studies were sub-grouped by method type, this factor was not seen to change the effect of experience on drivers' horizontal spread of search, with both simple and immersive sub-groups displaying a trend towards novice drivers having a narrower spread of search than experienced drivers. However, when focussing on the subgroups individually, the studies conducted in an immersive environment produced a significant difference between novice' and experienced drivers' horizontal spread of search whereas, simple methodology did not. This finding is supported by previous research which indicates that only experienced drivers make use of a more immersive, wider field of view to detect oncoming hazards, with novice drivers failing to look for potential hazards in the peripheral (Alberti et al., 2014).

4.3. Absence of differences in novice drivers' and experienced drivers' visual search

In regards to fixation durations, the pooling of relevant studies in the meta-analysis showed no overall difference between novice drivers and experienced drivers, refuting the widely used claim that novice drivers have generally longer fixation durations over the visual scene compared to experienced drivers (e.g. Rayner, 1998; Green, 2007). Although there were no overall differences, this result should be interpreted with caution as it is not as conclusive as other measures. The overall effect size (Cohen's *d* of 0.29), which can be calculated for this measure given the compatibility of units between studies, can be seen to be between small and medium in Cohen's terms (Cohen, 1988).

When temporarily removing the studies that included drivers with extreme experience, the absence of an overall difference became much more pronounced for fixation durations compared to the removal of these studies for all other measures. This suggests that extreme experience groups may be driving the tendency towards a difference between novice and experienced drivers' fixation durations, which could have important practical implications for interventions.

In addition, while the subgrouping of studies by method type did not produce a significant overall difference, the studies conducted in an immersive environment produced a significant difference between novice and experienced drivers' fixation durations, whereas simple methodology did not. These findings suggest that when further studies are conducted that involve driving on real roads it is possible that a reliable difference in fixation durations between novice and experienced drivers may yet emerge. The absence of an overall difference in the current meta-analysis may be driven by the majority of studies being conducted using simple methodology, so it remains possible that drivers' fixation durations in immersive driving situations may still be relevant in predicting and reducing accident involvement for novice drivers on real roads.

In regards to vertical spread of search, the pooling of all relevant studies revealed no overall difference between novice and experienced drivers, refuting previous research which has found that newly qualified drivers favour vertical search due to different information needs, i.e. helping maintain lane position (Land and Horwood, 1995). This lack of difference between the two groups is perhaps understandable, as vertical spread of search is arguably less important compared to horizontal search in a driver's ability to detect hazards, and therefore neither experienced, nor novice drivers are searching wider then deemed necessary (Chapman and Underwood, 1998a). In addition, as there was no effect of method type, these findings suggest that the measure of vertical spread of search in all contexts in not sensitive enough to demonstrate differences between the two groups, and therefore is not a reliable measure to include in visual search training interventions.

The sensitivity analysis, which removed the studies that included learner drivers and advanced driver groups, was seen to further confirm that there were no differences between the two groups. The most influential study which indicated differences in vertical spread of search (Mourant and Rockwell, 1972) has also been previously criticised for the minimal experience their learner drivers had on the road, and therefore an alternative interpretation for the increase in vertical spread of search demonstrated by novice drivers could be due difficulties in controlling the vehicle. This finding suggests that previous reports of differences in novice and experienced drivers' vertical spread of search may not be representative of typical changes in visual search over the first years of unsupervised driving.

Finally, it was found that there was no overall difference in novice drivers' and experienced drivers' number of fixations over the driving scene. This pooling of data is in contrast to previous claims which report that novice drivers make fewer fixations compared to experienced drivers in order to limit the amount of visual information being processed (Crundall and Underwood, 1998). When these data were subgrouped by method type, this was not seen to change the effect of experience. This increases the reliability of this finding, with this absence of a difference not being sensitive to the immersiveness of the environment.

In light of the 'where' and 'when' pathways (Findlay and Walker, 1999), the absence of an overall effect for number of fixations is compatible with the absence of an effect for fixation durations. That said, this systematic review only focuses on the number of fixations drivers make generally over the visual scene while completing a task, and not on specific areas of interest such as the number of fixations drivers make on their external mirrors or at wide eccentricities, due to the limited number of studies that have directly investigated this (Underwood et al., 2002b; Konstantopoulos et al., 2010). It is these areas of interest that may be related to driving experience, particularly as novice and experienced drivers' horizontal spread of search significantly differed over the visual scene.

4.4. Implications of results

The findings from the current systematic review have a number of implications for road user safety. Firstly, these findings help to understand the high accident liability of novice drivers, by highlighting the potential problems in their cognitive processing, reflected by their eye movements. Secondly, these visual search differences help with the development of interventions, with results suggesting that horizontal spread of search should be the immediate focus when developing training interventions for novice drivers. For example, by encouraging novice drivers to have a wider visual search in order to scan for potential hazards, as well as repeated exposure to hazards that could develop in the periphery, this could help improve novice drivers' knowledge and understanding in such situations (Chapman et al., 2002).

While previous authors have cautioned against a wholesale encouragement of a broader spread of search, in case this results in incomplete processing of the objects or locations being currently fixated (Chapman et al., 2002), the current results suggest that differences in processing times between novice drivers and experienced ones may be relatively small compared to differences in horizontal spread of search. This does highlight the importance of top down influences on the "where" pathway and suggests that interventions can safely encourage new drivers to devote their search to a wider range of horizontal locations in the visual scene.

In contrast, visual training interventions should have less emphasis on improving vertical spread of search, for example increasing drivers' ability to look further down the road. This would require the changing of current practical training interventions, such as the Road Craft manual for police drivers (Coyne et al., 2007) that indicates that drivers should 'increase the length and breadth of their vision' and 'The Roadcraft Education Strategy' to educate non-drivers or learner drivers, encouraging 'forward observation and peripheral vision awareness' (The Roadcraft Model, 2018).

Finally, these findings also highlight some factors that should be carefully considered when conducting future research studies. Both the experience and training of the recruited driver groups should be an important consideration when predicting and interpreting results based on previous literature. In addition, studies which use simple methodology to compare visual search strategies, particularly when measuring drivers' fixation durations and horizontal spread of search, should be mindful of the fact that the absence of differences found between groups may not be representative of drivers' behaviour in more immersive driving environments and on real roads.

4.5. Limitations of the studies

When critically apprising the included studies, this process highlighted limitations in the field that could be addressed when conducting further research. Firstly, in terms of driver recruitment there are often problems generalising from academic research using student samples on to the broader population. In this case, although we have included some studies involving participants from a student population, many of the studies have recruited novice drivers direct from Test Centres, and experienced drivers from Newspaper advertisements. Secondly, the majority of included studies did not report any drop outs during the study. This is particularly surprising for driving simulator studies, as there is a high likelihood that some participants would have dropped out due to simulator sickness (Brooks et al., 2010). Future research studies should clearly report participant dropout rates in order to give an accurate representation of the included sample.

In addition, all of the studies, with the exception of Chapman and Underwood (1998a), gave no justification of sample size. This lack of justification allows for underpowered experiments to be conducted, with the danger that null results from these relatively small studies cannot be published. The associated implication is publication bias, with the literature being over-represented by studies with positive results. Although publication bias is a potential source of bias, formal tests could not be performed due to the number of studies included for each outcome measure. The guidelines for the use of funnel plots and asymmetry tests vary from at least 10 studies to an ideal number of 75 studies for high power (Higgins & Green; Begg and Mazumdar, 1994). However, to help minimise publication bias, the current search strategy had no restrictions on publication status by including research in progress databases. In addition, this is an area in which studies with relatively small sample sizes may still be published in some form given the effort required to obtain the data. In fact, the study with the smallest sample size (Jiang et al., 2012) is one with the smallest effect sizes for any of the key variables. Moreover, given that the only study to justify the sample size was not seen as an outlier in any of the outcome measures, there is no direct evidence of effect-size inflation in the current data.

Finally, it was noted at the start of the review that although there any many studies investigating this topic, it is difficult to compare these due to potential forms of heterogeneity in term of design, outcomes measures and participants. In terms of the design, the demands of the driving task varied dramatically between the included studies, with the use of many different road types (e.g. rural, dual carriageway and curved roads) which could not be operationally defined in order to pool the studies. A second form of potential heterogeneity was the measurement of outcomes. Even though fixation duration was the only outcome to be measured in consistent units, the values still varied substantially across studies. It is possible that these differences are due to factors such as authors adopting different eye tracker dispersion algorithms, with this criterion not always being documented in research outputs. While these forms of heterogeneity cannot be avoided in such a review, this stresses the importance of using standardised mean differences and random effects models to account for this. In regards to participants, it has previously been highlighted that there is no consistent definition of a novice or experienced driver in the literature, and therefore a distinction was made based on UK crash statistics (Clarke et al., 2006). However, the sensitivity analyses did confirm that none of our overall conclusions would have been different even if a more restrictive definition of novice and experienced drivers had been adopted.

4.6. Conclusion

In summary, the pooling of studies in this systematic review provides reliable conclusions regarding the difference between novice drivers' and experienced drivers' visual search, with novice drivers displaying a narrower spread of horizontal search compared to more experienced drivers, suggesting that novice drivers do not anticipate and scan for potential hazards to either side of them. In contrast, no reliable experience differences were found for fixation durations, vertical spread of search and number of fixations. A key implication for the development of training interventions is that novice drivers need to develop a broader horizontal spread of visual search but do not necessarily need to learn to "look further down the road". Limitations in novice drivers' fixation durations, and to some extent horizontal search, are most notable for learner drivers and in immersive testing environments, therefore we recommend that this should be the focus for future research, training, and evaluation.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.aap.2019.105266.

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Supplementary Material

Content:

S1: Search Strategy Keywords

S2: The excluded studies based on the inclusion criteria

S3: The results of the sensitivity analysis performed on a more restrictive eligibility criteria for novice (<1 year) and experienced (> 5 years) drivers.

S4: The results of the sensitivity analysis when removing the studies that have the same co-author as the current paper

S1: The search strategy that was developed to include all the following keywords in each resource.

“Experienced Drivers” OR “Advanced Drivers” OR “Skilled Drivers” OR “Police Pursuit Drivers” OR “Expert Drivers” OR “Novice Drivers” OR “Young Novice” OR “Novice Teen”

AND

“Experience” OR “Exposure” OR “Skill” OR “Driving Experience” OR “Driving Exposure” OR “Driving Skill”

AND

“Visual Attention” OR “Visual Search” OR “Eye Movements” OR “Spread of Search” OR “Fixation Duration” OR “Fixations” OR “Number of Fixations” OR “Sampling Rate” OR “Attention” OR “Search Patterns” OR “Visual Exploration” OR “Attention Allocation” OR “Visual Measures”

S2: The studies that were not included using the pre-determined inclusion criteria are given, with the reasons of inclusion provided.

	Excluded Studies with Titles	**Reasons for Exclusion**
1	**Albright et al., (2018)** Comparison of younger and older drivers on driving habits: The role of perceived experience and executive function.	The experience of the novice and experienced driver groups were not given in years of licensure, with drivers indicating experience on a Likert scale. An eye tracker was not used, therefore there were no relevant outcome measures.
2	**Abele et al., (2018)** Consistency between subjectively and objectively measured hazard perception skills among young male drivers.	Only one group of drivers were used with their experience ranging from 0.5-6 years. Fixations were also specific to an area of interest (hazard).
3	**Borowsky et al., (2008)** The relation between driving experience and recognition of road signs relative to their locations.	The study did not measure relevant visual search measures, with the only eye movement variable consisting of a binary variable of fixating on a specific hazard or not.
4	**Borowsky et al., (2012)** Drivers’ perception of vulnerable road users: A hazard perception approach.	The study did not measure relevant visual search measures as fixation durations and number of fixations were measured on a particular hazard (pedestrian).
5	**Chan et al., (2010)** Are driving simulators effective tools for evaluating novice drivers’ hazard anticipation, speed management, and attention maintenance skills?	The study did not measure relevant visual search measures as the eye movement variables were the amount of time the driver looked off road.
6	**Chapman, King and Underwood (2002)** The role of experience in searching road scenes.	The study used non-drivers for the novice group.
7	**Cox et al., (2017)** Risk and safety perception on urban and rural roads: Effects of environmental features, driver age and risk sensitivity.	The study had no clearly defined novice and experienced driver group, and it did not use an eye tracer therefore eye movement measures were not recorded. The study was concerned with ratings of the perceived hazards.
8	**Crundall (2009)** The deceleration detection flicker test: A measure of experience?	The study did not use an eye tracker and therefore eye movements over the visual scene were not measured.
9	**Crundall et al., (2012)** Why do car drivers fail to give way to motorcycles at T-junctions?	The aim of the study was to investigate the effect of motorcycle experience on visual search therefore the novice and experienced groups could not be easily distinguished.
10	**Crundall (2016)** Hazard prediction discriminates between novice and experienced drivers.	The study did not use an eye tracker and therefore eye movements over the visual scene were not measured. The study was concerned with hazard detection, by asking participants a series of questions.

10	**Delhomme (1998)** Control motivation and young drivers' decision making.	The study did not use an eye tracker and therefore eye movements over the visual scene were not measured. The study was concerned with speed regulation.
12	**Divekar et al., (2012)** Effect of external distractions: Behavior and vehicle control of novice and experienced drivers evaluated.	The study did not measure relevant visual search measures as the eye movement variables were the amount of time the driver looked at external distractions.
13	**Falkmer et al., (2005)** A comparison of eye movement behavior of inexperienced and experienced drivers in real traffic environments.	The paper did not provide enough details regarding experience for the experienced group.
14	**Fei and Kuan (2010)** Study on Eyes Movement of Drivers with Different Driving Experience on Perception of Traffic Signs	Some of the novice drivers included in the study were too experienced, with their criteria being less than 5 years driving experience.
15	**Fisher et al., (2008)** *Evaluation of PC-based novice driver risk awareness*	The study did not have a novice and experienced driver group, recruiting only learner drivers.
16	**Fu et al., (2011)** Research on heart rate and eye movement as indicators of drivers' mental workload.	The novice and experienced group of drivers were not determined by years of licensure but by whether they had drove over 50,000km.
17	**Garay- Vaga and Fisher (2005)** Can novice drivers recognize foreshadowing risks as easily as experienced drivers?	The study did not measure relevant visual search measures as the eye movement measure were whether the driver fixated on specific areas of risk.
18	**Garay- Vaga et al., (2007)** Hazard anticipation of novice and experienced drivers: empirical evaluation on a driving simulator in daytime and nighttime conditions.	The study did not measure relevant visual search measures as the eye movement measure were whether the driver fixated on specific areas of risk.
19	**Gotardi et al., (2019)** Adverse effects of anxiety on attentional control differ as a function of experience: A simulated driving study.	The study did not mention the years of licensure for the novice and experienced driver groups, with these groups being determined by answers to a questionnaire concerning the amount of city driving.
20	**Kim et al., (2017)** Comparing aging and automaticity: A study on the effects of secondary tasks on driving ability.	The study's main aim was to investigate the effect of mobile phone use and navigational devices while driving.
21	**Lee et al., (2006)** Eyeglance behavior of novice teen and experienced adult drivers.	The study did not use an eye tracker, with a video of the driver's face being used for eye glance behaviors.
22	**Liao et al.., (2018)** Understanding Driver Response Patterns to Mental Workload Increase in Typical Driving Scenarios.	The novice (20-35 years) and experienced driver (45+ years) groups are categorised by age, and the study did not measure relevant visual search measures.

23	**Muttart et al., (2013)** Comparison of anticipatory glancing and risk mitigation of novice drivers and exemplary drivers when approaching curves.	The study did not measure relevant visual search measures as the glance behaviour variables were glances towards the focus of expansion during navigation around curves.
24	**Nabatilan et al., (2012)** Effect of driving experience on visual behavior and driving performance under different driving conditions.	The study did not have a novice and experienced driver group, and its main aim was to look at mobile phone use while driving.
25	**Pammer et al., (2018)** Expert drivers are better than non-expert drivers at rejecting unimportant information in static driving scenes.	The study compared expert (paramedic training) and non-expert drivers however, all drivers had more than 22 years driving experience therefore there was no novice group.
26	**Pammer and Blink (2018)** Visual processing in expert drivers: What makes expert drivers expert?	The study used non-driving visual and cognitive tasks, and no eye tracker was used therefore the study did not measure relevant visual search measures.
27	**Pollatsek et al., (2006)** Identifying and remedying failures of selective attention in younger drivers.	This paper reviewed previous research e.g. Pradhan et al., 2005 and discussed the effectiveness of training interventions.
28	**Pradhan et al. (2010)** Training attention maintenance: A first step.	The novice (16-18 years) and experienced driver (35-55 years) groups are categorised by age, and the study did not measure relevant visual search measures.
29	**Scott et al., (2013)** Visual information search in simulated junction negotiation: Gaze transitions of young novice, young experienced and older experienced drivers.	The study did not measure relevant visual search measures as the scene was divided up into seven areas of interest and gaze frequency in these areas was measured.
30	**Taylor et al., (2013)** The view from the road: The contribution of on-road glance-monitoring technologies to understanding driver behavior.	This paper was a review of how glance-monitoring technologies have been used in the field to identify the skill deficiencies of novice and older drivers.
31	**Underwood et al., (2002)** Selective searching while driving: the role of experience in hazard detection and general surveillance.	This research contains data that is not independent, as it has already been used in the meta-analysis in Crundall & Underwood (1998a).
32	**Underwood (2007)** Visual attention and the transition from novice to advanced driver.	This paper was a review of the literature regarding visual attention and experience, with no experimental work conducted.
33	**Underwood (2013)** On-road behaviour of younger and older novices during the first six months of driving.	The study did not use an eye tracker and therefore eye movements were not measured, with the study concerned with on-road behaviour (i.e. speed).

34	**Underwood et al., (2003)** Driving experience, attentional focusing, and the recall of recently inspected events.	The study did not measure relevant visual search measures as the main eye movement measure was whether a number of target objects had been fixated.
35	**Underwood et al., (2011)** Driving simulator validation with hazard perception.	This paper was a review of the literature, focusing on the use of different methods (simulator and on-road) to assess drivers' visual attention.
36	**Underwood et al., (2013)** Driving experience and situation awareness in hazard detection.	The criterion for the experienced driver group was not experienced enough (>2 years), and the study did not use an eye tracker and therefore eye movements were not recorded.
37	**Wetton et al., (2010)** The development and validation of two complementary measures of drivers' hazard perception ability.	The study did not use an eye tracker and therefore eye movements were not measured, with the study concerned with reaction time to detect hazards.
38	**Whelan et al., (2002)** Alternative methods of measuring hazard perception: Sensitivity to driving experience.	The study recruited non-drivers and did not use an eye tracker therefore eye movements were not measured. The study was concerned with reaction time to detect hazards.
39	**Wikman et al., (1998)** Driving experience and time-sharing during in-car tasks on roads of different width.	The novice (400-15000km) and experienced driver (50000-2000000km) groups are categorised by distance driven, and the study did use an eye tracker therefore no eye movement measures were recorded.
40	**Young et al., (2015)** Where do novice and experienced drivers direct their attention on approach to urban rail level crossings?	The study did not use an eye tracker, with a video of the driver's face being used for eye glance behaviors.
41	**Young et al., (2017)** Commentary driver training: Effects of commentary exposure, practice and production on hazard perception and eye movements.	The study did not have separate novice and experienced driver group, with the study concerned with investigating the effectiveness of commentary training.
42	**Yuan et al., (2011)** Analysis of Visual Fixation Areas and Visual Transition Characteristics During the Driving Process.	The novice (<50000km) and experienced driver (>50000km) groups are categorised by distance driven.
43	**Zhang et al., (2015)** A classification method between novice and experienced drivers using eye tracking data and Gaussian process classifier.	The experienced driver group had not been driving for more than 3 years (>2 years) and the study did not measure relevant visual search measures.

S3: The results of the sensitivity analysis when removing studies that included novice drivers that have held a licence for over 1-year and experienced drivers that have held a licence for under 5 years.

Firstly, in regards to mean fixation durations, five studies were pooled for analysis (Chapman & Underwood, 1998a; Crundall & Underwood, 1998; Huestegge et al., 2010; Konstantopoulos et al., 2010; Underwood, Chapman, Bowden and Crundall, 2002), with three studies being removed (Crundall et al., 2003; Jaing & Li, 2012; Yeung & Wong, 2015). When these studies were removed, there was still no overall effect of driving experience on drivers' fixation durations, Z=1.33, p=.18, (95% CI -0.48, 0.09).

In regards to horizontal spread of search, five studies were pooled for analysis (Crundall & Underwood, 1998; Hills, Thompson & Pake, 2018; Kahana-Levy et al., 2019; Konstantopoulos et al., 2010; Underwood, Chapman, Bowden & Crundall, 2002), with three studies being removed (Alberti et al., 2014; Crundall et al., 2003; Jiang et al., 2012). When these studies were removed, there was still an overall effect of driving experience on horizontal spread of search, Z=2.04, p=.04, (95% CI 0.04, 2.11).

In regards to vertical spread of search, seven studies were pooled for analysis (Borowsky & Oron-Gilad, 2013; Chapman & Underwood, 1998a; Crundall & Underwood, 1998; Hills, Thompson & Pake, 2018; Kahana-Levy et al., 2019; Konstantopoulos et al., 2010; Underwood, Chapman, Bowden & Crundall, 2002), with one study being removed (Jiang et al., 2012). When these studies were removed, there was still no overall effect of driving experience on drivers' vertical spread of search, Z=1.58, p=.11, (95% CI -0.75, 0.08).

Finally, for number of fixations, all of the studies in the original meta-analysis met this inclusion criteria and therefore a sensitivity analysis could not be performed.

S4: The results of the sensitivity analysis when removing the studies that have the same co-author as the current paper

Firstly, in regards to mean fixation durations, four studies were pooled for analysis (Crundall & Underwood, 1998; Huestegge et al., 2010; Jaing & Li, 2012; Yeung & Wong, 2015), with four studies removed (Chapman & Underwood, 1998a; Crundall et al., 2003; Konstantopoulos et al., 2010; Underwood, Chapman, Bowden & Crundall, 2002). When these studies were removed, there was still no overall effect of driving experience on drivers' fixation durations, Z=0.01, p>.99, (95% CI -0.38, 0.37), with this null result being much more evident.

In regards to horizontal spread of search, five studies were pooled for analysis (Alberti et al., 2014; Crundall & Underwood, 1998; Hills, Thompson & Pake, 2018; Kahana-Levy et al., 2019; Konstantopoulos et al., 2010), with three studies being removed (Crundall et al., 2003; Konstantopoulos et al., 2010; Underwood, Chapman, Bowden & Crundall, 2002). When these studies were removed, there was still an overall effect of driving experience on horizontal spread of search, Z=1.94, p=.05, (95% CI 0.01, 2.22).

In regards to vertical spread of search, five studies were pooled for analysis (Borowsky & Oron-Gilad, 2013; Crundall & Underwood, 1998; Hills, Thompson & Pake, 2018; Jiang et al., 2012; Kahana-Levy et al., 2019), with three studies being removed (Chapman & Underwood, 1998; Konstantopoulos et al., 2010; Underwood, Chapman, Bowden & Crundall, 2002). When these studies were removed, there was still no overall effect of driving experience on drivers' vertical spread of search, Z=1.44, p=.25, (95% CI -1.04, 0.27).

Finally, in regards to number of fixations, three studies were pooled for analysis (Crundall & Underwood, 1998; Huestegge et al., 2010; Kahana-Levy et al., 2019), with two studies being removed (Konstantopoulos et al., 2010; Underwood, Chapman, Bowden & Crundall, 2002).

When these studies were removed, there was still no overall effect of driving experience on drivers' number of fixations, Z=0.33, p=.74, (95% CI -0.29, 0.41).

Paper 3

Drivers' Visual Search Behaviour towards Vulnerable Road Users at Junctions as a Function of Cycling Experience

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Drivers' Visual Search Behavior Toward Vulnerable Road Users at Junctions as a Function of Cycling Experience

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Objectives: The current study investigated the behavior and visual attention of two groups of drivers with differing pedal cycling experience (pedal cyclists and nonpedal cyclists) towards vulnerable road users at junctions in a driving simulator.

Background: Pedal cyclists and motorcyclists are involved in a disproportionate number of crashes given the distance they travel, with a high proportion of these crashes occurring at junctions. Many studies have found that car drivers who also hold a motorcycle license have increased awareness towards motorcycles.

Methods: The task involved approaching a T-junction and turning right when it was deemed to be safe. In Study 1, the junction was controlled by a give way sign, and in Study 2, the junction was controlled by a stop sign. Each T-junction contained a target vehicle (car, motorcycle, or pedal cycle), approaching from a near, medium, or far distance from the junction.

Results: Participants did not look at pedal cycles approaching from a far distance for as long as they looked at approaching motorcycles and cars, despite all vehicles travelling at identical speeds. No differences were found between pedal cyclists and nonpedal cyclists on any visual attention measures, indicating that pedal cycling experience was not associated with differences in drivers' attention toward pedal cycles.

Conclusions: Findings have implications for road safety, demonstrating subtle differences in drivers' everyday visual attention toward differing vehicle types.

Applications: This research has the potential to inform the development of in-car technical assistive systems, improving the safety of vulnerable road users at junctions.

Keywords: attentional processes, visual search, simulation, bicycle safety, eye tracking

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INTRODUCTION

Motorcyclists and pedal cyclists are vulnerable road users, involved in a large number of road crashes. There has been a great increase in seriously injured motorcyclists and pedal cyclists in the United Kingdom over the last 7 years, with an estimated rise of 5% for motorcycles and 7% for pedal cycles at the end of 2016 compared with the 2010–2014 average (Department of Transport, 2016). This rise can be explained, in part, by the increasing motorcycle and pedal cycle traffic on the road; however, these road users are nonetheless involved in a disproportionate number of crashes given the distance they travel.

Motorcycle crashes have been studied in more depth than pedal cycle crashes. The most frequent type of motorcycle crash in the United Kingdom has been identified as ROW (right of way) crashes, whereby another road user pulls out of a side junction into the path of a motorcycle on a main carriageway (Clarke, Ward, Bartle, & Truman, 2007), also commonly termed the "look but fail to see" (LBFTS) error (Brown, 2002). It is typical in these crashes that drivers report being careful and attentive with their visual checks, but nonetheless they fail to see an oncoming road user. The majority of these crashes occur at "uncontrolled" (i.e., no stop light or sign with only give way markings and/or sign) T-junctions in urban environments (Hole, Tyrrell, & Langham, 1996).

In a more recent U.K. study, Pai and Saleh (2008) explored motorcycle injuries at T-junctions. It was found that injuries were the greatest when approaching motorcycles collided with a vehicle turning right, and injuries worsened when that junction was controlled by a stop or give way sign. Similarly, in regards to pedal cycles, Stone and Broughton (2003) extracted over 30,000 standardized reports from serious injury cycling crashes in the United Kingdom and found that one of the most frequent pedal cycle crashes at T-junctions occurs when the pedal cycle is travelling on a main road from the right and another vehicle is turning right onto the main road.

One of a few studies investigating drivers' visual search towards pedal cycles investigated drivers' selective attention at on-road intersections, using hidden video cameras to measure drivers' head movements (Summala, Pasanen, Räsänen, & Sievänen, 1996; see also Räsänen & Summala, 1998). This was conducted on roads in Finland on which traffic drives on the right-hand side. It was found that the most prevalent pedal cycle crash occurs when the cyclist is coming from the right and a driver is pulling out of a side road and turning right. This was seen to be caused by inappropriate visual search strategies, with the driver scanning the right side of the intersection less frequently than the left side, presumably because drivers failed to give sufficient importance to traffic in the cycle lanes. This seems to be a different crash type to the one described earlier (Stone & Broughton, 2003); however, in this Finnish study, cyclists were travelling on a dedicated two-way cycle lane that the approaching vehicle had to cross before joining the main road. Such cycle lanes are rare on British roads, where most cyclists have to travel with the rest of the traffic. Crashes on British roads are thus more likely to be related to failures in attention towards cyclists when they are using the same road infrastructure as other vehicles.

The previous studies that examined drivers' behavior and visual attention toward pedal cycles at junctions have investigated naturalistic events and accidents in order to capture drivers' everyday on-road behavior. These studies used video validations and reconstructions in order to estimate the speed and distance of approaching vehicles in these instances, as these factors cannot be controlled. This makes it difficult to determine whether differences in visual search are because an approaching vehicle is a cyclist or are simply related to the speeds at which the vehicle is coming. By investigating drivers' behavior and visual attention toward different road users in a simulated environment, it becomes possible to match the speeds and distances of different vehicle types, allowing for the investigation of drivers' visual search toward differing vehicle types when they are approaching a junction at identical speeds.

In regards to experience, there have been studies showing that drivers who also ride a motorcycle have increased detection of motorcycles compared with drivers with no motorcycle experience. Magazzù, Comelli, and Marinoni (2006) conducted a case control study to investigate how motorcycle experience can affect crash risk. It was found that drivers who have a motorcycle license are less prone to be involved in car-motorcycle collisions compared with drivers with no motorcycle license. This suggests that the riding ability and the increased awareness of the dangers associated with motorcycles at junctions may help with the detection of oncoming motorcycles and the prediction of their maneuvers. Brooks and Guppy (1990) found that car drivers who have family members or close friends that ride motorcycles are also less likely to collide with motorcyclists and showed better observation toward motorcycles than drivers who did not.

Crundall, Crundall, Clarke, and Shahar (2012) investigated visual attention toward motorcycles by comparing experienced and novice drivers with "dual drivers" (car drivers with considerable experience of both car driving and motorcycle riding). Participants were presented with video clips, which displayed a car approaching and stopping at a junction. Participants were asked to imagine they were driving the car and had to press a button when they believed it was safe to pull out. Some clips contained an oncoming car, motorcycle, or no vehicles. It was found that experienced drivers' fixation durations toward motorcycles were much shorter than those of "dual drivers" and novice drivers. Crundall et al. (2012) proposed that experienced drivers do not realize they are looking at a motorcycle and therefore terminate their gaze prematurely. This was attributed to overlearned visual search strategies and decreased expectations of approaching motorcycles. Dual drivers were seen as "gold standard" performers on all measures, suggesting that this group has an increased understanding that motorcycles require special attention. Whether or not the authors' interpretation is correct, the findings clearly indicate that car drivers' attentional allocation is strongly affected by motorcycle experience.

In a more recent study, Beanland and Hansen (2017) explored the influence of nondriving experiences on attentional allocation by comparing drivers with and without cycling experience. Twenty drivers and 22 cyclist-drivers were recruited to perform a change detection flicker task, with participants needing to determine whether two alternating images are identical or differ in one detail. Participants were instructed to imagine they were driving when viewing each road scene. The changed object was either a road sign, car, pedestrian, or bicycle. Cyclist-drivers were significantly faster at identifying changes, in particular to the road sign and bicycle. It was concluded that drivers with cycling experience have more efficient attentional processing of some aspects of road scenes.

In light of previous research, the two current studies investigate drivers' visual search behavior toward pedal cycles and motorcycles in a high-fidelity driving simulator. We wanted to discover whether differences found in change-detection and video-based tasks could also be observed when drivers are freely controlling the vehicle. Critically we wanted drivers to make real decisions where they actually had to pull out at a junction to be sure that visual search strategies are representative of those used in real driving situations. In order to manipulate the likelihood of the driver actually pulling out in front of an oncoming vehicle, we added a naturalistic manipulation to the junction. This was added whether it was controlled by a "Give Way" sign (Study 1) or a "Stop Sign" (Study 2). It was our expectation that drivers would be more likely to wait for oncoming vehicles to pass if they knew that they had to actually stop at the junction; thus, Study 1 would provide details of visual search in situations where drivers generally pull out ahead of oncoming vehicles, while Study 2 would provide information about visual search in cases where the driver generally waits for an oncoming vehicle. These studies additionally investigate the effect pedal cycling experience has on drivers' visual search at junctions, comparing pedal cyclist drivers to nonpedal cyclist drivers. Most previous research investigating drivers' visual search toward pedal cycles have focused on either real on-road data or used static images of road scenes. The current studies thus have important implications for road safety, providing a better understanding of drivers' different visual search toward oncoming vehicles approaching at identical speeds, focusing on road users with differing pedal cycling experience.

METHODS

Participants

This research complied with the American Psychological Association Code of Ethics and was approved by the Institutional Review Board at The University of Nottingham. Informed consent was obtained from each participant.

Data were collected from 80 participants who received a £5 inconvenience allowance for their time. Forty participants took part in Study 1, which included a "Give Way" sign at the junction, and 40 participants took part in Study 2, which included a "Stop" sign at the junction.

Participants were recruited based on how often they used a pedal cycle. In Study 1, 20 pedal cyclists who held a driving license and cycled frequently (mean age = 24 years, SD = 6.8, range = 20–45; male = 11, female = 9) and 20 nonpedal cyclists who did not cycle frequently (mean age = 22, SD = 2.1, range = 20–28; male = 6, female = 14) were recruited. Pedal cyclists reported having held a driving license for between 1 and 264 months (M = 53.95), with a reported annual mileage between 60 and 15,000 miles (M = 3,668) and reported cycling for between 7 and 240 months (M = 78.12), with an average annual mileage of 624 miles. Nonpedal cyclists reported having held a driving license for between 8 and 120 months (M = 53.7), with a reported annual mileage between 50 and 10,000 miles (M = 2,699).

In Study 2, 20 pedal cyclists (mean age = 25 years, SD = 7.3, range = 20–45; male = 11, female = 9) and 20 nonpedal cyclists (mean age = 22, SD = 7.3, range = 19–45; male = 5, female = 15) were recruited. Pedal cyclists reported having held a driving license for between 3 and 252 months (M = 83.40), with a reported annual mileage between 50 and 10,000 miles (M = 3,460) and reported cycling for between 12 and 360 months (M = 162.13), with an average annual mileage of 680 miles. Nonpedal cyclists reported having held a driving license for between 10 and 120 months (M = 45.9), with a reported annual mileage between 50 and 10,000 miles (M = 3,327).

Design

Although the two studies were conducted separately, to aid brevity in reporting, they are combined for analysis purposes. The two studies differed by the sign that was displayed at the entrance to the junction, in order to understand drivers' behavior and visual search at "Give Way" and "Stop" controlled junctions. The experiments did not differ in any other way. A 2 × 2 × 3 × 3 mixed design formed the core of the combined analysis, with two between-subjects factors, which were Road Sign (Give Way vs. Stop) and Group (pedal cyclists and nonpedal cyclists), and two within-subjects factors relating to the oncoming target vehicles, which were Vehicle Type (pedal cycle, motorcycle, and car) and Distance (near, medium, and far).

Each scenario started with the participant placed 135 m from the junction entry line; therefore, as participants were instructed to approach the junction at 20 mph, it took approximately 15 seconds to drive from the start position to the junction entry line. On the approach to the junction, participants drove over a trigger box, which was a point that triggered the target vehicle to start moving. The trigger box was 50 m from the junction entry line; therefore, it took approximately 5 seconds to drive from the trigger box to the junction entry line. At this point, no target vehicle was yet visible to the driver (see Figure 1). Once the participant had reached the junction entry line, the near, medium, and far distance target vehicles had always come into sight but differed in the amount of time it would still take them to reach the center of the junction, travelling at a speed of 15 mph (typically, near = 3 seconds, medium = 6 seconds, far = 9 seconds). This meant that the starting points of the target vehicles were 20 m, 40 m, and 60 m, respectively. It must be noted that these timings may differ slightly, as these depend on the exact approach and stopping behavior of the participant. Although it was technically possible to pass in front of the oncoming vehicle, attempting to do so when the vehicle was at a near distance did not normally make it possible to come to a complete halt at the junction before pulling out.

On the approach to the junction, the full junction and the target vehicles became visible approximately 20 m from the junction entry line, known as the start of the "approach zone"; therefore, it took approximately 2 seconds to reach the junction entry line. Before this point, the junction was occluded by houses on either side of the road (see Figure 1). In regards to the dynamics of the junction, more of the right-hand side of the junction was visible earlier on; however, as the right-hand side vehicles were approaching in the closer lane, they were initially less visible compared with the vehicles approaching from the left-hand side of the junction, in the further lane. As this is a naturalistic junction, whereby the right- and left-hand side of the junction are slightly different and therefore are imitating a real-life situation, any differences in drivers' visual attention between left and right may be due to the specific parameters of the junction. For this reason, right and left traffic were not analyzed separately.

Each target vehicle (pedal cycle, motorcycle, and car) was placed at all three distances (near, medium, and far) and appeared from the left and right with equal frequency, all traveling at 15 mph. These scenarios only contained the target vehicle, with no other traffic. There were 18 experimental trials. As the target vehicle's movement was trigged before the start of the "approach zone," the participants always saw the vehicles moving.

A further 12 general traffic scenarios that had no target vehicles but included general traffic were included to ensure that participants did not always expect a target vehicle and were scanning for traffic on the left and right side of the junction. Each scenario terminated the moment the driver pulled out into the junction (irrespective of whether this was before or after the approaching vehicle crossed the junction). This scenario termination point was positioned after the participant had committed to the right-hand turn maneuver, still allowing for a crash to occur if he or she had pulled out unsafely.

All trials were fully counterbalanced, with six orders (A, B, C, D, E, and F), containing all 30

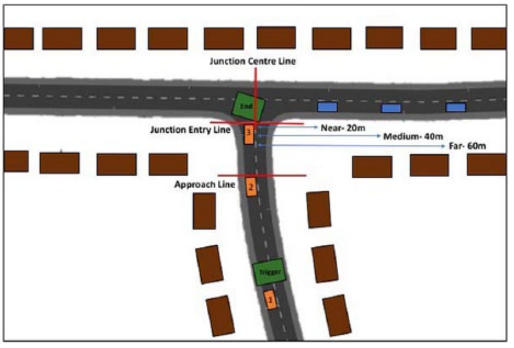

Figure 1. Parameters of the junction used in the experiment. The road and houses are to scale; however, the vehicles have been made larger to make them more visible. The participant's vehicle in Position 1 shows the driver approaching the junction, just before entering the trigger box. This trigger box initiates the movement of the target vehicle. Position 2 indicates the point where the participant enters the approach zone. This is the point where the houses no longer occlude the junction, with the left- and right-hand side of the junction and the approaching traffic becoming clearly visible. Position 3 is the point where the driver has reached the junction entry line. Once the participant initiates a right turn maneuver and enters the "end" box, this terminates the trial. The junction center line is the line used to indicate a right or left fixation and determine whether this was toward or away from the approaching vehicle. The three vehicles positioned on the right-hand side of the junction indicate the typical near, medium, and far distance vehicles at the point where the driver has reached the junction entry line (Position 3). The green boxes represent trigger points programmed in the simulator, and the red lines were points defined by the experimenters in order to analyze results.

trials in a random order. Both studies included the same randomized orders, with seven participants in each study completing Orders A, B, C, and D and six participants completing Orders E and F.

Stimuli and Apparatus

The experiment took place in the Nottingham Integrated Transport and Environment Simulation (NITES) facility's high-fidelity driving simulator. This simulator comprises a full BMW Mini, housed within a projection dome and mounted on a six-degree motion platform with a 360-degree projection screen (see Figure 2). For the current studies, the motion base was turned off because the short trial lengths and abrupt terminations of each trial made the motion cues confusing. The scenarios were formed on the screens using six projectors. The simulator was equipped with two linked FaceLAB 5.0 eye-tracking systems (four cameras and two infrared sources), which allowed participants' eye movements to be tracked continuously over a range of approximately 120 degrees in front of the driver.

XPI (XPI Simulation, London, UK) driving simulation software was used to create 30 scenarios. All scenarios took place at the same T-junction. As the experiment was conducted in the United Kingdom, all driving was conducted on the left-hand side of the roads. Figure 3 shows an example of all three vehicles used in the experiment (car, motorcycle, and pedal cycle) from the view of the driver, approaching from the right. These vehicles are placed at the near distance, from the point where the driver had reached the junction entry line. In regards to the pedal cycle, the simulated rider had a pedaling motion when moving.

Procedure

Following a 5-minute practice drive, which was purposely more demanding than the experimental drive, participants completed a short "Driving & Cycling Experience" questionnaire with a main purpose of understanding how often the participant drove and cycled. The primary task was explained to every participant by the experimenter reading out the following systematic instructions:

> In this experiment, you will encounter a T-junction 30 times. Your task is to drive up to the T-junction at a speed of 20 mph and perform a maneuver at the end of the junction when it is deemed to be safe. An audio message will instruct you to turn right prior to stopping at the junction. Once you start to pull out of the junction, the scenario will immediately end and the next one will begin shortly after. You must try and drive as naturally as possible throughout the experiment.

Figure 2. The NITES facility's high-fidelity driving simulator. The simulator consists of a full BMW Mini, housed within a projection dome and mounted on a six-degree of freedom motion platform.

Figure 3. The three vehicle types used in the experiment (car, motorcycle, and pedal cycle). These are taken from the view of the driver, with the vehicles approaching from the right. These vehicles are approaching from a near distance.

For Study 2, which included a Stop sign, there was a slight change in the instructions: "An audio message will instruct you to turn right when approaching the junction."

For all junctions, the audio clip contained the instruction "at the junction, go right." A right turn was used as this was a more difficult and balanced task, compared with the alternative left turn. In order to make a right turn, drivers had to scan for oncoming traffic from both the left- and right-hand side of the junction.

Participants' eye movements were recorded throughout each scenario. Each scenario was around 20 seconds long, and the whole experimental procedure lasted around 40 minutes.

RESULTS

Driving Experience and Age

Drivers' reported experience and ages were subject to a 2 × 2 between-groups ANOVA with factors of Road Sign (Give Way vs. Stop) and Group (pedal cyclists vs. nonpedal cyclists). Drivers' licensure (in months), annual mileage, and age range were subject to a log transformation due to positive skew. These analyses confirmed that there were no significant differences in drivers' licensure between groups, $F(1, 76) = .34$, MSE = .14, $p > .05$, $n^2_p = .004$) or experiments, $F(1, 76) = .05$, MSE = .14, $p > .05$, $n^2_p = .001$; in drivers' annual mileage between groups, $F(1, 76) = .03$, MSE = .57, $p > .05$, $n^2_p = .001$, or experiments, $F(1, 76) = 1.26$, MSE = .57, $p > .05$, $n^2_p = .02$; and in age between groups, $F(1, 76) = 4.00$, MSE = .01, $p > .05$, $n^2_p = .04$, or experiments, $F(1, 76) = .02$, MSE = .01, $p > .05$, $n^2_p = .001$.

Data Analysis

Most behavioral and eye movement measures were subject to a 2 × 2 × 3 × 3 mixed design

ANOVA with factors of Road Sign (Give Way vs. Stop), Group (pedal cyclists vs. nonpedal cyclists), Vehicle Type (pedal cycle, motorcycle, and car), and Distance (near, medium, and far). For the factor of Target Vehicle, two a priori orthogonal contrasts were specified. The first contrast compared data from pedal cycle trials with that of motorcycle and car trials together to assess any overall effect of cycling experience toward pedal cycles. The second contrast compared motorcycle trials with car trials to assess any overall effect between these two motor vehicles. For the factor of Distance, contrasts were specified that tested for linear trends in the data. Each target vehicle approached at each distance from the left and right of the junction at equal frequency; however, for the purpose of analysis, the vehicle direction was aggregated to increase the number of trials contributing to each cell.

Behavioral Measures

Driver behavior was measured by looking at Approach Behavior. Approach Behavior was obtained by calculating how long it took drivers to travel through the "approach zone." The "approach zone" started 20 m from the junction entry line and finished at the moment where the front of the drivers' car had entered the junction by crossing the junction entry line. The "approach zone" thus started when the left and right side of the junction first became visible, the target vehicles were visible, and at the point where approaching traffic may start to alter the approach behavior of the driver.

Approach behavior: In regards to drivers' approach behavior, a main effect of Vehicle Type was found, $F(2, 152) = 3.54$, MSE = 18.06, $p < .05$, $n^2_p = .05$, with contrasts revealing a significant difference between pedal cycles compared with cars and motorcycles, $F(1, 76) = 5.67$, MSE = 31.23, $p < .05$, $n^2_p = .07$. Participants approached the junction faster when a pedal cycle was approaching compared with a car or motorcycle. There was also a main effect of Distance, $F(2, 152) = 12.25$, MSE = 19.74, $p < .001$, $n^2_p = .14$, with contrasts revealing a linear trend, $F(1, 76) = 17.19$, MSE = 7.85, $p < .001$, $n^2_p = .18$. Participants approached the junction faster when vehicles were approaching from a closer distance—for cars (near = 10.32 seconds, medium = 10.39 seconds, far = 10.87 seconds), for motorcycles (near = 9.52 seconds, medium = 10.47 seconds, far = 10.64 seconds), and for pedal cycles (near = 7.32 seconds, medium = 9.93 seconds, far = 11.23 seconds).

There was also an interaction between Vehicle Type and Distance, $F(4, 304) = 2.89$, MSE = 36.37, $p < .05$, $n^2_p = .04$, with contrasts revealing a linear difference between pedal cycles compared with cars and motorcycles, $F(1, 76) = 13.18$, MSE = 29.43, $p < .01$, $n^2_p = .15$. Participants approached the junction faster when vehicles are approaching from a nearer distance. The combination of these two main effects and the interaction highlights the finding that drivers approached the junction fastest when there was a pedal cyclist approaching from a near distance.

Eye Movement Measures

With drivers making big rapid head movements and fixations at wide eccentricities, it was difficult to always be sure of the quality of the eye tracking. This was particularly problematic at wide eccentricities where fixations were often made toward the target vehicle, but because of calibration difficulties, we could not be sure that the target vehicle was actually fixated. If we had chosen to adopt a very strict criterion for determining whether a vehicle was fixated, there is a danger that we would falsely conclude that far vehicles were rarely fixated simply because calibration was poorer at wide eccentricities. Because of this, we adopted a very conservative approach, focusing on the broad direction of fixation (toward or away from the target vehicle, rather than requiring an unambiguous fixation on the vehicle) and choosing dependent variables that would not be systematically affected by differences in calibration quality between individuals. This approach has the additional advantage that the visual angle subtended by the target vehicle has no direct effect on whether a fixation is regarded as being on the vehicle. Choosing to aggregate between left and right approach directions also ensures that none of the reported differences can be influenced by differences in calibration quality for extreme left and right angles.

In regards to drivers' visual attention at the junction, we calculated three main variables of interest: Proportion of Fixations, Proportion of Gaze, and Mean Fixation Duration. A custom-built MatLab script was used to automatically analyze drivers' eye movements, with a fixation dispersion threshold of 0.1 of a radian for 100 ms, to regard a fixation to be in progress. The Proportion of Fixations was calculated by measuring the number of fixations toward and away from the target vehicle side of the junction. The tolerance for fixations toward the target vehicle was any fixation made to the side of the junction center line where the target vehicle was approaching (see Figure 1), after the participant had crossed the approach line, and the target vehicle was still approaching the junction. This did not include any fixations toward the target vehicle when the vehicle had crossed the junction center line. Fixations away from the target vehicle were any fixations made to the side of the junction center line where the target vehicle was not approaching. The proportion of all these fixations toward the target vehicle side of the junction was then calculated. The Proportion of Gaze was calculated in the same way as the previous measure with total gaze duration rather than number of fixations. Total gaze duration is the total time spent on fixations to the target vehicle side of the junction, so Proportion of Gaze gives a general measure of how much visual attention was biased toward the oncoming vehicle. The Mean Fixation Duration was calculated by the total gaze duration toward the target vehicle side of the junction, divided by the number of fixations made toward the target vehicle side of the junction.

Proportion of Fixations and Proportion of Gaze were subject to an arcsine transformation due to a leptokurtic distribution. Mean Fixation Duration was subject to a log transformation due to a positive skew in the data. The reported statistics for these measures are from the transformed data. However, Figure 4 shows the untransformed data in order to present proportion units between 0 and 1.

Proportion of fixations. A main effect of Vehicle Type was found, $F(2, 152) = 3.39$, MSE = .05, $p < .05$, $n^2_p = .04$, with contrasts revealing a significant difference between pedal cycles compared with cars and motorcycles, $F(1, 76) = 3.27$, MSE = .05, $p < .05$, $n^2_p = .05$. Participants had a higher proportion of fixations on the target side of the junction when the approaching vehicle was a pedal cycle compared with a car or a motorcycle.

There was an interaction between Vehicle Type and Distance, $F(4, 304) = 2.54$, MSE = .04, $p < .05$, $n^2_p = .03$, with contrasts indicating a linear difference between pedal cycles compared with cars and motorcycles, $F(1, 76) = 7.35$, MSE = .06, $p < .01$, $n^2_p = .09$. Participants' proportion of fixations toward the target vehicle was greater when cars and motorcycles were approaching from a far distance compared with pedal cycles but greater when pedal cycles approached from a medium or near distance compared with cars and motorcycles (see Figure 4a).

There was also a main effect of Road Sign, $F(1, 76) = 10.55$, MSE = .01, $p < .01$, $n^2_p = .12$, with participants having a higher proportion of fixations toward the target vehicle when a Stop Sign was present compared with a Give Way Sign. There was no main effect of Group, $F(1, 76) = .19$, MSE = .01, $p = .66$, $n^2_p = .01$.

Proportion of gaze. An interaction between Vehicle Type and Distance was found, $F(4, 304) = 2.57$, MSE = .05, $p < .05$, $n^2_p = .03$, with contrasts indicating a linear difference between pedal cycles compared with cars and motorcycles, $F(1, 76) = 7.66$, MSE = .08, $p < .01$, $n^2_p = .09$. Again, participants' proportion of gaze toward the target vehicle was greater when cars and motorcycles were approaching from a far distance compared with pedal cycles; however, it was greater when pedal cycles approached from a medium or near distance compared with cars and motorcycles (see Figure 4b).

There was also a main effect of Road Sign, $F(1, 76) = 9.79$, MSE = .02, $p < .01$, $n^2_p = .11$, with participants having a higher proportion of gaze toward the target with a Stop Sign compared with a Give Way Sign. There was no main effect of Group, $F(1, 76) = .59$, MSE = .02, $p = .45$, $n^2_p = .01$.

Mean fixation durations. A main effect of Distance was found, $F(2, 152) = 4.29$, MSE = .05, $p < .05$, $n^2_p = .05$, with contrasts revealing a significant linear trend, $F(1, 76) = 3.27$, MSE = .05, $p < .05$, $n^2_p = .12$. Participants had higher mean fixation durations on the target side of the junction when the vehicle was approaching from a closer distance.

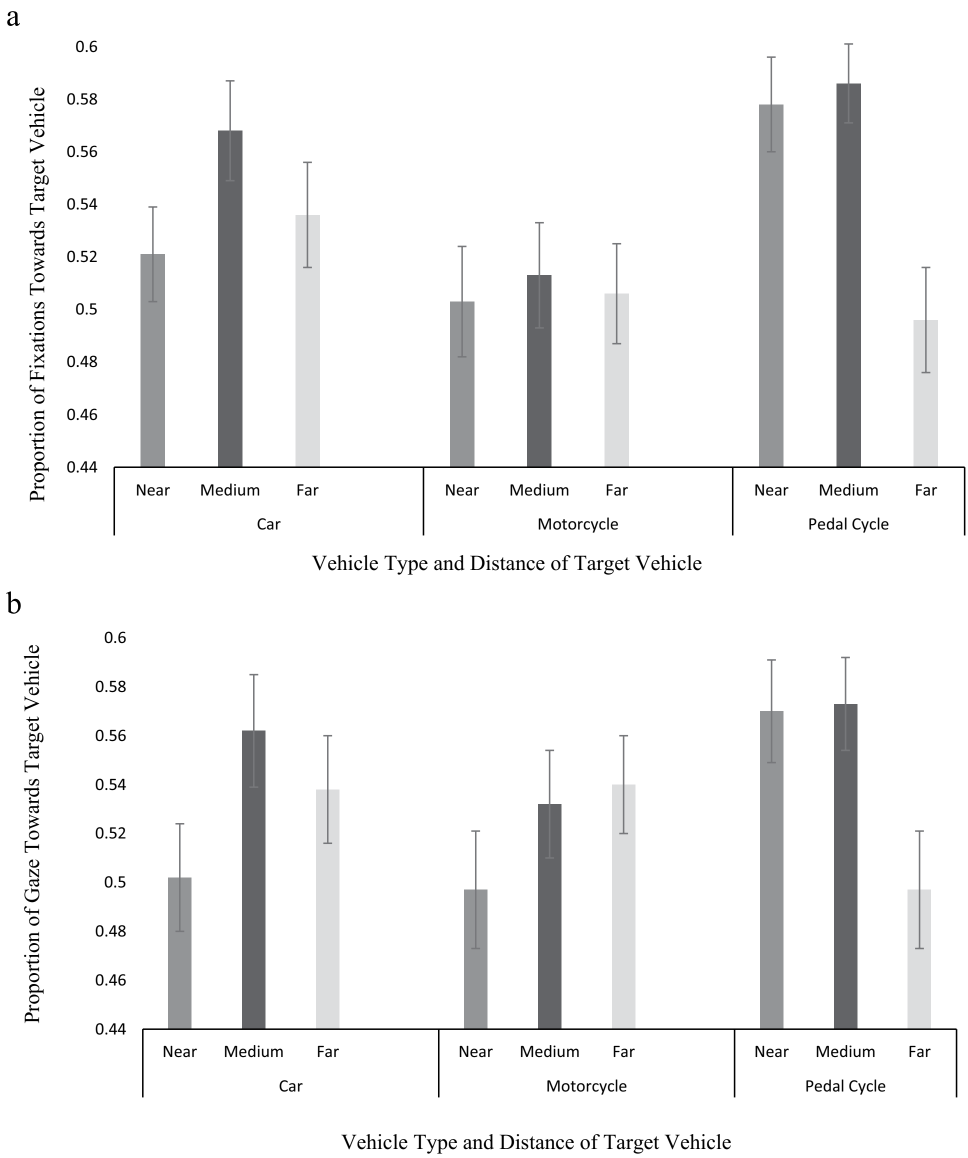

Figure 4. Figure 4a shows the drivers' proportion of fixations to the target vehicle side of the junction as a function of Vehicle Type and Distance, and Figure 4b shows the drivers' proportion of gaze as a function of Vehicle Type and Distance. These means are untransformed. Error bars display one standard error above and below the mean.

There was a main effect of Road Sign, $F(1, 76) = 11.23$, MSE = .15, $p < .01$, $n^2_p = .13$, with drivers fixating toward the approaching vehicle for longer with a Stop Sign present than a Give Way Sign. There was no main effect of Group, $F(1, 76) = 1.14$, MSE = .15, $p = .29$, $n^2_p = .02$.

DISCUSSION

The first immediate finding from the study is that drivers' attention was not associated with pedal cycling experience at junctions. Despite previous research suggesting that experience with a certain vehicle may change drivers' visual attention toward this vehicle (Crundall et al., 2012), this does not seem to be the case for pedal cyclists when pulling out of a junction as a driver. The second immediate finding is that, in general, drivers do not look toward pedal cycles approaching from a far distance as much as they look toward motorcycles and cars. In contrast, at closer distances, they may actually look more toward pedal cycles than either motorcycles or cars. Both of these results occurred irrespective of the sign present at the junction, implying that the differences in visual search are present in cases both where the driver generally pulls out in front of the target vehicle and where they wait for it. The manipulation of the change in road sign was conformed to by participants, with drivers pulling out in front of the target vehicle on significantly more occasions with a Give Way Sign present compared with a Stop Sign. It should be noted that these differences have been observed despite the fact that speed of travel for target pedal cycles was identical to that of motorcycles and cars.

In regards to the first finding, although previous literature has established findings indicating that drivers with specific motorcycle experience (Crundall at al., 2012) and pedal cycling experience (Beanland & Hansen, 2017) have more efficient visual attention toward motorcycles and pedal cycles compared with drivers only, this does not seem to be the case when scanning a junction in order to complete a maneuver. This contradictory finding may be explained by the difference in task requirements between our study and previous ones performed by driver-cyclists—passively watching video clips does not require additional demands such as vehicle control and does not require participants to complete a maneuver.

These contradictory results may be a result of the difference between the factors that promote motorcycle and pedal cycle use. Motorcyclists' views about why and how they ride have been seen to be related to the social context of riding, including social- and identity-related influences relating to the group, as well as self-identity (Tunnicliff, Watson, White, Lewis, & Wishart, 2011). In contrast, cycling may not play such an important role in the self-identity of a cyclist, using a pedal cycle for reasons such as efficiency, flexibility, cost, economy, and health (Levulytė, Baranyai, Török, & Sokolovskij, 2016).

In addition, it may be possible that pedal cyclists are not as aware as motorcyclists about the dangers surrounding junctions. Crash statistics show that motorcyclists are much more likely to be involved in crashes, with motorcycles accounting for 21% of UK road deaths and pedal cyclists accounting for 6% in 2015 (Department of Transport, 2015). Current educational campaigns such as the UK Department for Transport's Think! Bike are also heavily associated with motorcyclists' rather than pedal cyclists' safety. For this reason, it may be the case that pedal cyclists do not have a heightened awareness of the dangers associated with cycling on road compared with that of motorcyclists, which in turn may result in cyclists not having an increased detection of oncoming pedal cyclists compared with that of nonpedal cyclists.

In the absence of differences between pedal cyclists and nonpedal cyclists on all eye movement measures, we conclude that the specific pedal cycling experience of the pedal cyclist group is not associated with changes in drivers' visual attention toward oncoming pedal cycles or motorcycles at controlled simulated junctions. Given that our sample size provided enough power to detect the effect (medium effect size for within-between interaction, Cohen's $f = 0.25$, $1\text{-}\beta = 0.80$) if it was present, this suggests that pedal cycling experience does not make drivers' visual attention strategy safer at junctions.

In regards to the second finding, the visual attention measures suggest that drivers do not distribute as much visual attention toward pedal cyclists approaching from far distance compared with motorcycles and cars. It may be the case that drivers do not deem pedal cycles approaching from a far distance to be as dangerous as approaching motor vehicles due to the usual difference in speed and mass and therefore are happy to focus their attention elsewhere in the visual scene for potential danger. It also may be the case that pedal cycles manifest different looming behaviors compared with larger motor vehicles, as faster moving vehicles are thought to loom less than slower vehicles (Wann, Poulter, & Purcell, 2011), and a driver's ability to detect the motion of an object decreases, the smaller the object is. Although this behavior seems plausible, it is surprising given that the visual parameters of the approaching pedal cycles in this simulation environment, in terms of distance and speed, were identical to the far-approaching motorcycles and cars. This may suggest that drivers are terminating their gaze away from far-approaching pedal cycles too early, not fully forming a representation of the pedal cycle's speed and distance. It must also be noted that although drivers' eye movements were aggregated across left- and right-approaching vehicles, drivers' proportion of fixations (left = .54, right = .51) and proportion of gaze (left = .48, right = .56) did not significantly differ whether the far pedal cycle was approaching from the left or the right.

In addition, drivers approached the junction faster when a pedal cycle was approaching from a near or medium distance compared with a motorcycle or car. These different approach dynamics again suggest that the appraisal of threat from the pedal cyclist may be different, with less time needed to make a decision at the junction. Conversely, drivers' approach behavior for far-approaching pedal cycles was slower compared with a motorcycle and car, suggesting that drivers took more time to make a decision, possibly due to the perceived low threat of a far-approaching pedal cycle compared with a motor vehicle. Previous research has found that when countermeasures are in place to reduce drivers' speed on the approach to a junction, this changed drivers' visual search toward pedal cycles for the better, simply providing more time to look at the approaching vehicle (Summala et al., 1996).

Although pedal cyclists will often be travelling slower than cars or motorcyclists, in urban environments there are plenty of occasions where recreational cyclists can achieve the local speed limit. The current research suggests that such situations may present a particular problem, with drivers failing to pay sufficient attention to distant but relatively fast-moving pedal cyclists. With previous studies demonstrating that drivers are poor at determining the speed of other vehicles, particularly when travelling at high speed (Dommes, Cavallo, Vienne, & Aillerie, 2012), this is particularly relevant to the increase in the use of E-bikes (pedal cycles that provide electrical support). These bikes have been seen to reach higher speeds than conventional pedal cycles; therefore, drivers may misjudge their approaching speed (Schleinitz, Petzoldt, Krems, & Gehlert, 2016).

The subtle differences found in drivers' everyday visual attention can be used in the development of in-car technologies. As a starting point, this study demonstrates how much visual attention drivers distribute to vulnerable road users dependent on vehicle type and distance at a junction. These eye movement measures can help in the understanding of drivers' cognitive mechanisms involving the distribution of visual search at a junction in simulated driving environments. The visual information that drivers obtain at junctions, which inevitability informs their behavior, is important for the development of in-car technical assistive systems for drivers, making drivers safer. One particular source of information that may be important for such systems to provide would be warnings related to distant pedal cycles that are nonetheless approaching the driver at relatively high speeds. In regards to road safety, this in turn could help prevent the high proportion of crashes at junctions involving these road users.

Finally, it must be noted that no crashes occurred during the experiment. Although many crashes between cars and either pedal cycles or motorcycles do occur at real junctions, it is important to remember that these crashes are nonetheless rare events—the vast majority of real junction crossings are conducted safely. Even though we observed 1,440 experimental trials in the course of this study, this is still relatively little driving compared with the expected frequency of crashes on real British roads (less than one crash per 10,000 miles of driving; Department of Transport, 2016). We did explore safety margins by measuring the shortest time to contact with an oncoming vehicle on occasions where the driver chose to pull out, but we found that this did not differ overall as a function of the oncoming vehicle type. In terms of specific "near crash" events, defined by a time to contact of below 2 seconds (e.g., Matsui, Takahashi, Imaizumi, & Ando, 2011), it was found that there were marginal, Cochran's Q(2) = 5.20, p = .074, n = 80, differences in the frequency of "near crashes" as a function of oncoming vehicle type—pedal cycle (4 participants), motorcycle (1 participant), and car (0 participants). This tendency, combined with the relatively high approach speeds for near and medium pedal cycles, provides support for the idea that drivers may be more likely to "take a chance" in front of a pedal cyclist than an oncoming motorcycle or car, even though the approach speeds are matched.

In conclusion, this study provides important and novel information, indicating that drivers who pedal cycle frequently do not show any differences in their visual attention toward pedal cycles on the road compared with nonpedal cyclists, despite previous research finding this in other settings. We found that drivers do not distribute as much visual attention toward pedal cycles approaching from a far distance despite them approaching at identical speeds to motorcycles and cars. These subtle differences in drivers' visual attention shed light on drivers' everyday visual search at junctions as a function of vehicle type, which can have important implications for vulnerable road users' safety.

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KEY POINTS

- Previous studies have found that specific motorcycle experience enhances drivers' visual attention toward motorcycles at junctions; however, no previous research has investigated the effect pedal cycling experience has on drivers' visual attention toward pedal cycles at junctions, despite the increase in pedal cycle use on public roads.
- Drivers' visual attention at junctions was not associated with pedal cycling experience in a simulation environment.
- Drivers, in general, do not distribute as much attention toward pedal cycles approaching from far distances, despite them approaching at identical speeds to cars and motorcycles.
- Subtle differences in drivers' visual attention toward vulnerable road users at junctions are important for the future safety of these road users.

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Paper 4

Comparing Drivers' Gap Acceptance for Cars and Motorcycles at Junctions using an Adaptive Staircase Methodology

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Comparing drivers' gap acceptance for cars and motorcycles at junctions using an adaptive staircase methodology

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A B S T R A C T

A disproportionate number of road deaths occur at intersections where one vehicle is a motorcycle. Previous research has not systematically varied the type of vehicles presented in a controlled environment.

We compared drivers' (n = 54) gap acceptance when either a car or motorcycle was approaching a junction. We used a QUEST adaptive staircase to estimate gap acceptance thresholds for cars and motorcycles separately. On each trial, drivers saw a car approaching from the left and a vehicle (car or motorcycle) approaching from the right. The driver had to stop for the car from the left, but could choose whether to pull out in front of the vehicle from the right, or to wait for it to pass. Participants completed the task in either a medium-fidelity simulator (steering wheel and pedals, 180-degree screen) or a high-fidelity simulator (fully instrumented car, 360-degree screen).

Participants accepted significantly smaller (riskier) gaps in front of motorcycles than in front of cars, particularly in the high-fidelity simulator. The speed of crossing the junction did not differ between vehicle types, meaning that drivers were closer to the motorcycle than the car during the manoeuvre. There was one instance that appeared to replicate a 'Look But Fail To See' error, where a participant pulled out in front of an oncoming motorcycle resulting in a crash. This suggests that drivers accept riskier gaps around motorcycles than cars, which may be due to a difference in attitude towards different vehicles or differences in optic flow properties. These results help to explain the disproportionate involvement of motorcycles in real junction crashes.

1. Introduction

1.1. The problem

Intersection safety is a major problem worldwide, with crash data suggesting that there are higher risks in these segments of the road compared with other road segments. Many accidents at intersections can be attributed to inappropriate gap selection by drivers who are pulling out of a side road and entering a carriageway with approaching vehicles (Hoareau, Candappa, & Corben, 2011). This suggests that there is a need to better understand drivers' gap acceptance behaviour to develop strategies that can support drivers' decision making at intersections.

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When inspecting intersection crash data, a large number of intersection crashes involve motorcycles. Data from the UK show that motorcycles are involved in a disproportionate amount of road crashes given the distance travelled, with 122.3 motorcycle fatalities compared with 1.8 car driver fatalities per billion miles (DfT, 2015). In many road crashes involving motorcyclists, car drivers are solely at fault, with the main cause of motorcycle crashes in the UK consisting of right of way violations (ACEM, 2009). These crashes occur when another road user, usually a car, pulls out of a side junction into the path of a motorcycle on a main carriageway (Clarke, Ward, Bartle, & Truman, 2007). These crashes in the previous literature are commonly known as 'Look But Fail To See' errors, with it being typical in these accidents that a driver reports being careful and attentive with their visual checks but nonetheless fails to see an oncoming motorcyclist (Brown, 2002). However, there are many reasons why a driver may report afterwards that they failed to see an oncoming motorcycle. The driver may not want to admit to a driving error, for example, accepting a risky gap between traffic.

1.2. Gap acceptance literature

There is a growing literature investigating drivers' behaviour at intersections in regards to their response to different gaps in traffic. Gap acceptance tasks ask the driver to decide between acceptable and unacceptable gaps to move into. These methods produce rich sources of data, compare gaps which are accepted or rejected by drivers, and estimate the 'critical gap'. This 'critical gap' has been defined as 'the minimum time gap a driver is ready to accept' (Brilon, Koenig, & Troutbeck, 1999, p. 2).

Previous research has used both naturalistic observations and experimental studies (Beanland, Lenné, Candappa, & Corben, 2013; Keskinen, Ota, & Katila, 1998; Scott, Hall, Litchfield, & Westwood, 2013; Yan, Radwan, & Guo, 2007). In most experimental studies the researchers have presented approaching vehicles at a limited and predetermined set of distances. This method allows for vehicles at selected distances to be repeatedly presented to participants. For example, Scott et al. (2013) investigated the effect of driving experience on visual attention at junctions, using a gap acceptance design which included a series of gaps between vehicles which increased in 1.5 s increments. It was found that young experienced drivers distribute their gaze more evenly across the junction, whereas older and novice drivers made sweeping transitions. However, due to the time constrained nature of the task, the study was only able to complete a single manoeuvre with each participant, with the authors concluding that future studies need to investigate drivers' gap acceptance using a larger sample so more gaze sequences can be analysed.

In addition, Beanland et al. (2013) used time gaps which varied from 3 to 11 s to measure a driver's gap acceptance (whether the driver accepted or rejected a given gap), accepted lag (the time of arrival of the target vehicle when participants have accepted the gap in front of it) and turn time, for two different manoeuvres (turning across traffic and merging with traffic). Drivers appear to vary their gap acceptance strategy depending on the intended manoeuvre, with drivers accepting smaller gaps when turning across traffic compared to merging with traffic. As drivers can vary their behaviour dependent on manoeuvre type, this would suggest that it is possible for drivers to vary their behaviour dependent on approaching vehicle type, for example, motorcycles.

Despite the pressing need, few studies of gap acceptance have systematically varied the type of vehicles presented. A review of published articles examining drivers' gap acceptance behaviour found that there are substantial experimental research studies investigating drivers' gap acceptance when intersecting with cars however, relatively fewer research efforts have been made to investigate gap acceptance behaviour when intersecting with motorcycles, despite the high number of crashes occurring with this type of vehicle (Pai, 2011).

Gap acceptance studies when intersecting with motorcycles are also extremely important in developing countries, where the number of motorcycles can be very high (Lee & Sheppard, 2017). Serag (2015) focussed on drivers' gap acceptance in developing countries, conducting a field study in Egypt. It was found that when estimating drivers' gap acceptance (where the driver was 50% likely to accept the gap), these gaps were less than those in developed countries, suggesting riskier behaviour from drivers' in developing countries. Many of these countries have a different traffic composition which needs to be taken into account, especially the characteristics of motorcycles. Ibrahim and Sanik (2007) conducted a field study in Malaysia at T-junctions, investigating drivers' gap acceptance behaviour as a function of approaching vehicle type. The results indicated that there were significant differences in drivers' gap acceptance for cars and motorcycles, demonstrating smaller gaps for motorcycles compared to cars. These results suggest that there may be a specific problem associated with gaps accepted around motorcycles, however, without experimentally controlling the behaviour of different vehicles it is not possible to decide whether it is the vehicle type, or its behaviour that brings about the differences in gap acceptance (motorcycles may be approaching with different speeds and directions than other traffic).

One of the few simulator studies investigating gap acceptance towards motorcycles and cars was conducted by Mitsopoulos-Rubens and Lenné (2012). Three time gaps of 5.0, 7.0 and 9.0 s were used, which were associated with a 20% (i.e. low), 50% (i.e. medium) and 80% (i.e. high) rate of gap acceptance, respectively. It was found that when the time gap was short and long, participants were more likely to accept fewer trials with an approaching motorcycle than car, however, this effect was reversed with the medium time gap.

Although the method of constant stimuli used in previous studies (Beanland et al., 2013; Mitsopoulos-Rubens & Lenné, 2012; Scott et al., 2013) can be argued to be satisfactory in some circumstances (e.g. Crundall, Humphrey, & Clarke, 2008), it may lead to participants being repeatedly exposed to stimuli that may be a long way from their personal threshold. Previous gap acceptance literature highlights that drivers are neither wholly consistent (e.g. always rejecting gaps lower than the critical gap and accepting gaps higher than the critical gap) or homogeneous, with some drivers accepting smaller gaps than others (Amin & Maurya, 2015). This suggests that there is variability within and between drivers. Presenting pre-determined stimuli may lead to participants behaving unrealistically, particularly in simulator studies. Trials in a simulator are longer so participants may simply become bored, or, they may begin to be able to predict the structure of each trial. In the current study, we take advantage of the flexible nature of a driving simulator to introduce an adaptive staircase procedure for measuring critical gaps. This has the considerable advantage that the gaps used are rapidly and efficiently altered to approach the individual driver's personal critical gap so that most of the experimental trials actually require a difficult decision to be made by the driver.

The current study measures drivers' gap acceptance for cars and motorcycles at junctions, using the QUEST Bayesian adaptive staircase procedure (Watson & Pelli, 1983), which works on the basis that the stimulus values presented to participants depend critically on the preceding responses, with the posterior distributions of the psychometric-function parameters being updated on a trial-by-trial basis. We used a separate QUEST function for each driver and for cars and motorcycles separately. The QUEST adaptive staircase method for measuring drivers' gap acceptance estimates the distance where the driver was 50% likely to accept the gap. This is similar to previous studies investigating developing (Serag, 2015) and developed countries (Mitsopoulos-Rubens & Lenné, 2012) however, this method increases the efficiency of the testing procedure, by adjusting the distance of the target vehicle for each trial based on the individual's previous responses to vehicles of that type. This minimises the number of trials needed to reach each critical threshold, measuring tightly around the threshold region, therefore reducing the time and tediousness of the testing process (Kingdom & Prins, 2010).

Multiple methods have been used to assess gap acceptance. A naturalistic observation study was conducted in Japan, videoing drivers' on-road behaviour at T-junctions (Keskinen et al., 1998). Various measures of gap acceptance were measured including time gap (the time from the moment the driver entered the junction until the nearest vehicle reached the centre line of the intersection), time difference (the time from the moment the driver had completed their turn until the nearest approaching vehicle reached the centre line) and turning time (the time it took the driver to make the turning operation). Results indicated that the time margin left for motorcycles was shorter than cars. As this experiment was naturalistic, the speed of the vehicles varied when approaching the junction, which makes it difficult to draw conclusions as to the mechanisms underlying the decision.

Many previous studies specifically investigating right of way accidents at junctions have important limitations because they use static images or video clips of junctions as stimuli (Crundall, Crundall, Clarke, & Shahar, 2012; Langham & Labbett, 2006; Lee & Sheppard, 2017). These methods fail to provide drivers with any vehicle control element – this may free more resources for a gap acceptance judgment, while additionally encouraging unrealistic assumptions about the efficiency with which they would be able to pull out and clear the gaps they are looking at. In the current experiment, we felt that it was important to allow participants to complete the full manoeuvre, both controlling the vehicle while approaching the junction, and actually pulling out into accepted gaps.

Some of the most relevant previous gap acceptance studies have studied drivers' behaviour using a fixed based, medium-fidelity simulator which includes a steering wheel, pedals and gear box for vehicle control. Mitsopoulos-Rubens and Lenné (2012) presented visual stimuli on three 19-inch LCD screens which covered 120-degrees. Beanland et al. (2013) projected the visual environment on a curved projection screen subtending 180-degrees, with a rear projection screen subtending 60-degrees. There are two potential problems with restricting the field of view available to the driver. One is that visual cues presented near the edge of the screen (as an approaching vehicle at a junction will often be) may be hard to detect or judge accurately because of the lack of realistic surrounding environment. The other is simply that the lower the fidelity of the environment, the less engaged participants may be with the task. This is particularly important in safety critical tasks – if drivers do not feel that they are surrounded by real vehicles in a realistic environment they may be prepared to take greater risks than they would in real life (Al-Shihabi & Mourant, 2003). In the current study, we have chosen to explore this possibility by systematically varying the visual fidelity of the simulator. This study therefore measured drivers' gap acceptance towards cars and motorcycles in a high-fidelity driving simulator with a 360-degree screen, and compared this with their performance in the identical task conducted in a medium-fidelity driving simulator with a 180-degree screen more similar to that which has been employed by previous authors.

1.3. The current study

Firstly, it was predicted that drivers will accept smaller gaps in front of motorcycles than in front of cars, using a more robust staircase procedure to measure individual drivers' gap acceptance thresholds.

Secondly, it is predicted that drivers' gap acceptance behaviour in the high-fidelity simulator will be closer to previous naturalistic results (Keskinen et al., 1998) compared to behaviour in the medium fidelity simulator, due to the increase in reality of the surrounding environment. We use two simulators which differ in fidelity, our medium fidelity simulator is similar to that used in previous research (Beanland et al., 2013; Mitsopoulos-Rubens & Lenné, 2012) however, our high-fidelity simulator has both a full field of view and an instrumented vehicle for full vehicle control.

As previous research has empathised the need to differentiate between gap acceptance and lag (Serag, 2015), the current study had four main dependent variables: Gap Acceptance Thresholds, Gap Accepted Lag, Time Difference and Cross Time. Gap Acceptance Thresholds were created using the QUEST adaptive staircase procedure (Watson & Pelli, 1983), estimating a distance where the driver was 50% likely to accept the gap. Gap Accepted Lag was the time of arrival of the target vehicle, when participants have accepted the gap in front of it. Time Difference was the time of arrival of the target vehicle, when the driver had cleared the junction. Cross Time was the amount of time it took the driver to complete the manoeuvre by crossing the junction.

2. Methods

2.1. Participants

Fifty-four participants took part in the study (27 in the high-fidelity simulator and 27 in the medium-fidelity simulator) based on a power analysis to detect a medium effect size, Cohen's f = 0.25 (This design provides good power to detect within-subjects differences and within-between subjects interactions, $1 - \beta = 0.95$, though it is underpowered to detect purely between subject effects, i.e. overall effects of simulator that apply to all conditions, $1 - \beta = 0.55$).

Twenty-seven participants completed the task in the high-fidelity simulator (Mean age = 22 yrs, SD = 3.49, Range = 18–31; Male = 16, Female = 11), and twenty-seven participants completed the task in the medium-fidelity simulator (Mean age = 22 yrs, SD = 3.12, Range = 18–27; Male = 12, Female = 15).

2.2. Design

The two independent variables of interest were Vehicle Type (car vs. motorcycle) and Driving Simulator (high fidelity vs. medium fidelity).

To allow comparison with previous studies, we calculated four main dependent variables of interest: Gap Acceptance Thresholds, Gap Accepted Lags (Beanland et al., 2013 and previously known as 'Time Gap' in Keskinen et al., 1998), Time Differences (Keskinen et al., 1998) and Cross Times (previously known as 'Turn Time' in Beanland et al., 2013; Keskinen et al., 1998). See Fig. 1.

Gap Acceptance Thresholds were the time (in seconds) that the vehicle from the right was from the junction where the driver was 50% likely to accepting the gap. This was the output of the QUEST adaptive staircase. The other three dependent measures were calculated using data from the 18 staircase trials, with the first 12 constant distances removed. This ensured that performance was only considered for trials where an effortful decision was made.

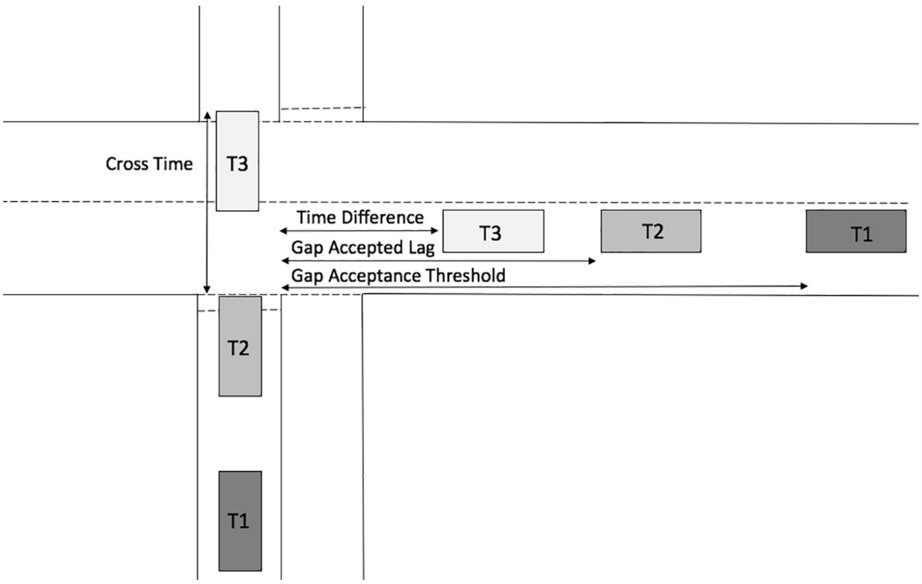

Fig. 1. This shows the approximate layout of the junction with the driver's vehicle and the oncoming vehicle from the right shown at three locations representing three separate time points (T1, T2, and T3) to help illustrate the different dependent variables. The Gap Acceptance Thresholds are a measure of how far the approaching vehicle needs to be from the centre of the junction to produce a 50% chance of the driver pulling out, represented by locations marked T1. The Gap Accepted Lag is how far the oncoming vehicle is from the centre of the junction when the driver subsequently enters the junction, represented by T2, and is only calculated on trials where the driver does accept the gap. On these trials, the Time Difference is how far the oncoming vehicle is from the centre of the junction when the driver reaches the point where the vehicle can pass, represented by locations marked T3. The Cross Time is the time from when the front of the drivers' car enters the junction (T2) to the moment where it has reached the point where the oncoming vehicle can pass without collision, also calculated from the front of the vehicle (T3). Unlike the previous two measures, this can be meaningfully calculated on occasions where the gap is not accepted by measuring the time to cross the equivalent distance when there is no longer any oncoming vehicle present. Note that although all four measures are represented as distances in this figure, the dependent variables are actually the time taken to travel these distances. Because the speed of the oncoming vehicle is constant the Gap Accepted Lag and Gap Acceptance Threshold are simply and linearly related to the distances shown, however the Time Difference and Cross Time will depend on the precise crossing behaviour of the driver on each trial.

The Gap Accepted Lags were calculated only for accepted gaps. The Gap Accepted Lag was the car or motorcycle's time-to-arrive at the centre of the junction at the moment where the front of the drivers' car had entered the junction by crossing the give way line. This depends on the Gap Acceptance Threshold and also the delay between the threshold and the manoeuvre by the driver.

The Time Difference was also only calculated for accepted gaps. The Time Difference is the car or motorcycles' time-to-arrive to the centre of the junction, measured at the point where the rear of the driver's car had cleared the point at the junction where the approaching vehicle would continue on an unimpeded path.

The Cross Time refers to the amount of time it took the driver's car from entering the junction (crossed the give way line) until when the rear of the driver's car had cleared the point at the junction where the approaching vehicle would continue on an unimpeded path. Therefore, Time Difference + Cross Time = Gap Accepted Lag.

The Gap Acceptance Thresholds, Gap Accepted Lag and Time Difference were analysed using a 2×2 mixed design ANOVA with a within factor of Vehicle Type (cars vs. motorcycles) and a between factor of Driving Simulator (high fidelity vs. medium fidelity).

The Cross Time was analysed using a $2 \times 2 \times 2$ mixed ANOVA with the additional factor of Driver Behaviour (before or after), which distinguishes whether the driver pulled out before or after the target vehicle had passed.

An adaptive staircase was used to estimate individual drivers' gap acceptance thresholds by manipulating the distance of the approaching vehicle. The staircase consisted of 12 initial trials (6 car, 6 motorcycle) which covered a range of constant distances to provide an initial estimate of each participants performance. Therefore, all participants completed an initial 12 trials with both a car and motorcycle placed at the following distances: 45 m, 55 m, 65 m, 75 m, 85 m and 95 m. The remaining 18 trials (9 car, 9 motorcycle) were at variable distances presented using a QUEST thresholding function implemented in Matlab (Kingdom & Prins, 2010).

The study used a QUEST adaptive staircase to estimate gap acceptance thresholds for cars and motorcycles separately for each participant. After each trial, the starting position of the vehicle from the right was adjusted. If participants had previously accepted a gap, the starting position was moved closer. If participants had waited for the vehicle to pass, the starting distance was increased. During the adaptive staircase procedure, drivers completed 30 trials in the driving simulator (15 for cars and 15 for motorcycles), estimating the gap acceptance threshold that offers 50% probability of accepting the gap, using the mode of the posterior probability density function. On all occasions, the staircases converged.

2.3. Apparatus

The experiment took place in Nottingham's Integrated Transport and Environment Simulation (NITES) facility, using both the high-fidelity driving simulator (NITES 1) and the medium-fidelity driving simulator (NITES 2). The high-fidelity simulator comprises of a full BMW Mini, housed within a projection dome and mounted on a six-degree motion platform with a 360-degree projection screen. The scenarios were formed on the screens using six projectors.

The medium-fidelity simulator is a fixed based driving simulator, consisting of a five-metre diameter hemicyclindrical screen, subtending 180-degrees, and a rear display screen. The scenarios were formed on the screens using three projectors. The fixed based driving rig consists of a car unit with adjustable seat, and a dashboard that included a steering wheel and speedometer. There was also a gear lever, brake, clutch and accelerator pedal for vehicle control.

XPI (XPI Simulation, London, UK) driving simulation software was used to create the scenarios. All scenarios were centered around the same intersection. The intersection was in an urban area, which was controlled by a 'Give way' sign. The intersection was a crossroad, therefore traffic could in principle be coming from the left, the right or straight ahead. This junction was chosen as it was flat junction, with houses either side of the road on the approach. The junction had equal visibility to the left and right, with all vehicles visible when the driver stopped at the junction.

On each trial, participants started 100 m from the junction, and the trial ended around 30 m after the participant had cleared the junction. Participants encountered two vehicles at the junction. Participants saw a car approaching from the left and a vehicle (car or motorcycle) approaching from the right. The car from the left was timed such that the driver always had to stop to allow it to pass. Each trial began with the car from the left placed 10 m away from the junction. This approach was introduced after a pilot study in which some volunteers adopted steadily increasing speeds approaching the junction in an attempt to clear predictable oncoming vehicles. After waiting for the vehicle from the left participants could then choose whether to pull out in front of the vehicle from the right, or to wait for it to pass.

On half the trials, the vehicle from the right was a car and on half the trials it was a motorcycle. This vehicle approached from one of 60 possible distances, ranging from 40 m to 100 m from the junction (1 m intervals). The exact distances each participant encountered were dependent on their responses on previous trials. The speed of the oncoming cars and motorcycles were kept constant, with both approaching at 30 mph. This is the average speed of these vehicles on British roads, with cars and motorcycles on average travelling at 30 mph (DfT, 2014).

2.4. Procedure

Participants completed a short 'Driving Experience' questionnaire and the 'The Extended Driver Behaviour Questionnaire' (Lajunen, Parker, & Summala, 2004), which is often used as a measure of self-reported violations, errors and lapses while driving. Following this, the primary task was explained to every participant by the following systematic instructions:

'In this experiment, you will encounter an intersection 30 times. Your task is to drive up to the junction at a speed of 20 mph and perform a manoeuvre at the end when it is deemed to be safe. You will always be going straight on at the junction. Shortly after clearing the junction, the scenario will end and the next scenario will begin. You must try and drive as naturally as possible throughout the experiment.'

Participants first completed the twelve constant distance trials, which also served as practice trials to allow the participants to become familiar with the simulator and the nature of the task. Participants then completed the remaining 18 trials, (9 cars, 9 motorcycles). To determine the next distance for each vehicle, this was calculated using the QUEST thresholding function from the Palamedes Matlab routine toolbox (Kingdom & Prins, 2010). Car and motorcycle trials were randomised. The whole experimental procedure lasted around 45 min.

3. Results

3.1. Driving experience

The twenty-seven participants in the high-fidelity simulator had held a driving licence for between 4 months and 13 years. They had a reported average annual mileage between 0 and 11,000 miles (Mean = 3823), a total mileage between 75 and 60,000 miles (Mean = 19,236) and reported an average of 321 hours travel per year.

The twenty-seven participants in the medium-fidelity simulator had held a driving licence for between 4 months and 10 years. They had a reported average annual mileage between 0 and 10,000 miles (Mean = 2710), a total mileage between 0 and 50,000 miles (Mean = 15,314) and reported an average of 360 hours travel per year.

Our sample thus over-represents relatively inexperienced drivers (those generally at highest risk of crash) but does include a wide range of driving experiences and the samples are well matched between the two simulator conditions.

Drivers' self-reported aggressive violations [t (52 = 1.84, p = .07], ordinary violations [t (52 = 1.22, p = .23], errors [t (52 = .84, p = .40] and lapses [t (52 = −.77, p = .47] on The Extended Driver Behaviour Questionnaire did not differ between the high-fidelity and medium-fidelity simulator group. These mean values were typical of previous research (Lajunen & Summala, 2003).

3.2. Gap acceptance thresholds

A main effect of Vehicle Type was found (F (1, 52) = 17.62, MSe = 41.76, p < .001), indicating that participants accepted significantly smaller gaps in front of motorcycles than in front of cars. There was no significant main effect of Driving Simulator [F (1, 52) = 1.25, MSe = 3194.58, p = .16], but there was a two-way interaction between Vehicle Type and Driving Simulator (F (1, 52) = 10.17, MSe = 41.76, p < .01), with the difference between cars and motorcycles being more pronounced in the high-fidelity simulator – see Fig. 2a.

The variance in thresholds was greater in the high-fidelity simulator than in the medium fidelity simulator so a log transformation of gap acceptance threshold data was conducted after which there was no longer a significant difference in variance between groups. There was a main effect of Vehicle Type found (F (1, 52) = 17.702, MSe = .001, p < .001). The main effect of Driving Simulator was not significant [F (1, 52) = 2.21, MSe = .031, p = .14]. The two-way interaction between Vehicle Type and Driving Simulator was significant (F (1, 52) = 11.55, MSe = .001, p < .01). A simple main effects analysis with Sidak correction was conducted. This revealed that the effect of vehicle type was mainly due to the differences found in the high-fidelity simulator. In the high-fidelity simulator, drivers' gap acceptance thresholds were significantly smaller for motorcycles than cars (p < 0.01) but that this was not significantly different in the medium fidelity simulator [p = .57]. An alternative way of conducting these comparisons would be to say that drivers' gap acceptance thresholds for cars were significantly higher in the high-fidelity simulator compared to the medium-fidelity simulator (p < .05), however, gap acceptance thresholds for motorcycles were not significantly different in the high-fidelity-simulator compared to the medium-fidelity simulator [p = .37].

3.3. Gap accepted lag

A main effect of Vehicle Type was found (F (1, 52) = 17.78, MSe = 56.49, p < .001), indicating that participants accepted significantly smaller gaps in front of motorcycles than in front of cars, however for this measure there were no significant effects of Driving Simulator or interactions involving this factor, see Fig. 2b.

3.4. Time difference

Again, a main effect of Vehicle Type was found (F (1, 52) = 16.15, MSe = 67.53, p < .001), indicating that the gap between the drivers' vehicle and approaching motorcycles are significantly smaller than approaching cars at the point the junction had been crossed, but there were no significant effects of Driving Simulator or interactions involving this factor, see Fig. 2c.

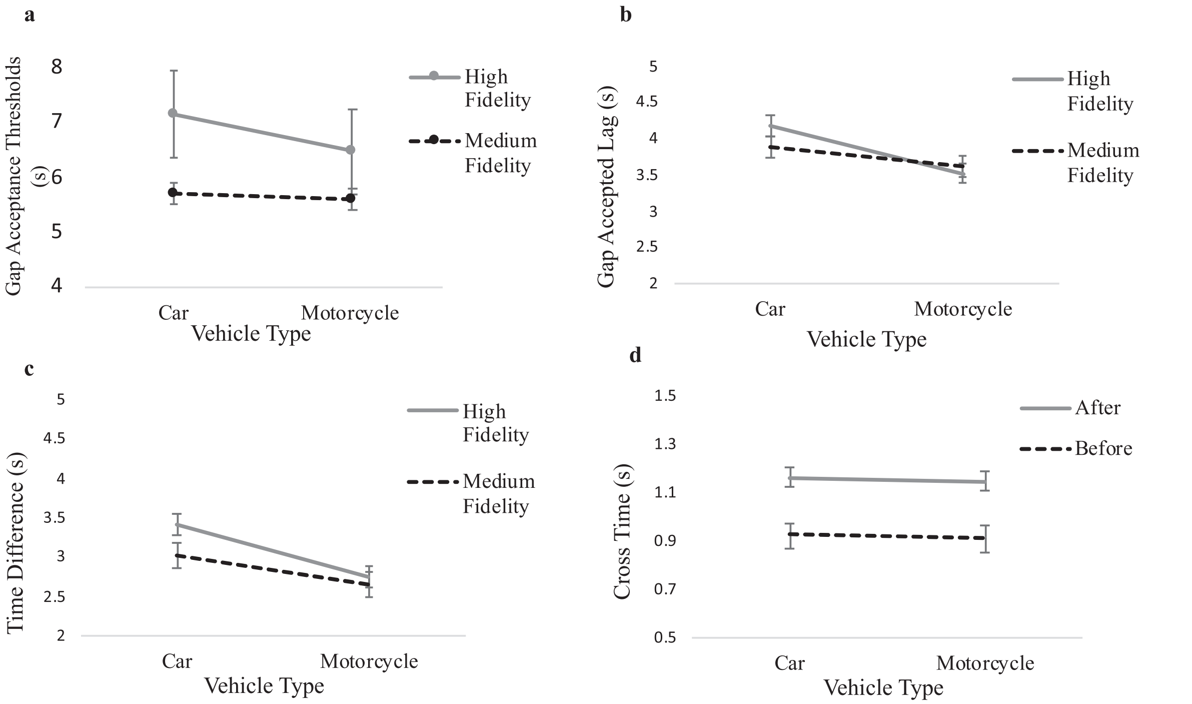

Fig. 2. (a) Shows the main effect of Vehicle Type and the interaction between Vehicle Type and Driving Simulator for Gap Acceptance Thresholds, (b) shows the main effect of Vehicle Type for Gap Acceptance Lag, (c) shows the main effect of Vehicle Type for Time Difference and (d) shows the main effect of Driver Behaviour for Cross Time. Error Bars show one standard error above and below the mean.

3.5. Cross times

A main effect of Driver Behaviour was found ($F(1, 52) = 73.73$, $MSe = .40$, $p < .001$), indicating that drivers cross the junction faster when pulling out before the vehicle than after the vehicle, see Fig. 2d. There were no significant effects of Vehicle Type, Driving Simulator or interactions involving these factors.

Cross Times were all calculated using the same formula irrespective of Vehicle Type. It must be noted that in practice, there is a slight difference in the time needed to physically cross the junction to reach the point where the approaching vehicle could continue on an unimpeded path, depending on the nature of the oncoming vehicle. As the physical width of a motorcycle is smaller than that of a car, it might be possible to safely cross in front of a motorcycle at a slightly smaller gap that that required for a car. This does of course assume that neither type of oncoming vehicle would modify its behaviour in any way, which is true in the simulator, but unlikely to be the case in the real world. Nonetheless, based on the actual size of cars and motorcycles in the simulation and the behaviour of our participants we calculated separate cross times for cars and motorcycles. On average the difference between these two times was 0.096 s, with cross times indeed being slightly lower for motorcycles than cars in all cases. There was no significant difference between this measure when it was calculated based on behaviour in the high-fidelity (.08) simulator compared to behaviour in the medium-fidelity (.11) simulator [$t(26.2 = 1.01$, $p = .32$].

3.6. Errors

On one occasion, out of a total of 1620 trials, a crash occurred with an oncoming vehicle. This was a motorcycle trial. Fig. 3 shows the view of the junction that was available to the driver on the particular trial where a crash occurred. The motorcycle was travelling at the standard 30 mph and started at 85 m from the junction. This was trial number 10 out of the 30 trials that were completed by the driver. This individual driver's threshold for motorcycles was calculated to be 83 m.

4. Discussion

The most immediate finding from the analysis is that despite the fact that motorcycles and cars were approaching the junction at identical speeds, participants accepted significantly smaller gaps in front of motorcycles than in front of cars but did not modify their behaviour by clearing the junction faster, leading to them passing motorcycles closer to the junction. This finding demonstrates that drivers in the study reliably leave a smaller safety margin when pulling out of a junction in

Fig. 3. An LBFTS error? This is the view to the right-hand side of the junction that was available to the driver on the particular trial where a crash occurred. This shows the oncoming motorcycle approaching the junction at the point the driver crossed the give way line, which subsequently resulted in a crash. The motorcycle was travelling at the standard 30 mph and there was no possible way in which the driver could have safely cleared the junction at this moment.

front of a motorcycle compared to a car. The finding that drivers adopt smaller safety margins around oncoming motorcycles than oncoming cars even in an environment where the behaviour of both vehicles has been kept identical is important and novel. It could, in part, explain the large number of crashes that occur at real junctions involving cars pulling out into the path of oncoming motorcycles.

In regard to drivers' junction cross times, the fact drivers are crossing the junction significantly faster when a vehicle is approaching compared to when the vehicle had passed the junction is comforting. This finding indicates that drivers are consciously modifying their behaviour in order to clear the junction quicker when they have pulled out before the oncoming vehicle – this shows that drivers are adjusting the dynamics of the behaviour in a way that is appropriate to the circumstances. Nonetheless, drivers' cross times did not differ dependent on what vehicle was approaching the junction. Therefore, although drivers are willing to accept smaller gaps in front of motorcycles than cars, they are not modifying their cross time behaviour to account for this. Even if we allow for a physical difference in crossing times between oncoming cars and motorcycles, this difference is less than 0.1 s. Although this may account for some small part of the difference between drivers' gap accepted lag for cars and motorcycles, it does not allow a difference of around half a second to be thought of as a rational adjustment to the actual vehicle sizes. If drivers do think they can clear oncoming motorcycles sooner than oncoming cars and using this idea to rationalise their behaviour they are clearly massively overestimating the true size of this difference.

The second immediate finding was that the difference between car and motorcycle gap acceptance thresholds was significant in the high-fidelity simulator but not in the medium-fidelity simulator. The significant difference in gap acceptance thresholds for cars and motorcycles in the higher fidelity simulator supports previous naturalistic findings that drivers leave a smaller time margin for motorcycles than cars (Keskinen et al., 1998). In addition, previous naturalistic research in the US, investigating drivers' gap acceptance towards cars have found that the average accepted gap is around 7.6 s (Tupper, 2011) and in simulation studies, a comparable measure of gap acceptance has been found at around 7–9 s for Australian drivers (Beanland et al., 2013). Drivers' gap acceptance in the current study for cars in the high-fidelity simulator was 7.1 s and in the medium-fidelity simulator was 5.6 s. This suggests that the behaviour witnessed in the high-fidelity simulator is more comparable to real world driving behaviour, with the gaps accepted in the medium-fidelity simulator being arguably relatively short.

This finding highlights problems with the previous methods used to investigate drivers' behaviour towards motorcycles at junctions. Static images and video clips may not provide the level of psychological reality, regarding how realistic and immersive the environment and task is, needed to elicit driving behaviour similar to that on real roads. One possibility is that in the medium-fidelity driving simulator, drivers are treating this environment more like a computer game, engaging in riskier behaviour that would not be witnessed in more immersive environments (Alexander, Brunyé, Sidman, & Weil, 2005). If this is indeed the case, then it is possible that the difference between gap acceptance between motorcycles and cars in the high-fidelity simulator is because the drivers feel at greater risk from approaching cars than approaching motorcycles. Where the feelings of risk are lower, in a medium fidelity simulator, the differences between vehicle types becomes less pronounced.

An alternative approach to thinking about the differences between the two simulators would relate to the visual field in which the drivers have access to. As the high-fidelity simulator has a visual field covering 360-degrees, all relevant background information surrounding the oncoming vehicle was available. However, as the medium-fidelity simulator only covers

180-degrees, in some instances the vehicles were near the edge of the display screen on the approach to the junction, therefore not all surrounding context was available. When judging the optic flow (pattern of apparent motion of objects in a visual scene), motion is easier to judge when there is relevant background information available. Research studies have found that drivers preferentially use optic flow information in time-to-collision estimates (McLeod & Ross, 1983).

However, it could be possible that if drivers' perception of optic flow is wrong, this will directly impact their sense of risk. Slater and Wilbur (1997) suggests that the immersiveness of the driving environment is dependent on factors such as the extent to which the visual display shuts physical reality out, the size of the field of view, and vividness of the display (resolution, richness, and quality) and levels of control. Therefore, if the optic flow was harder to judge in the medium-fidelity simulator, this may have caused risker behaviour compared to the high-fidelity simulator and real roads, with drivers accepting smaller gaps. Previous research also concerned with varying the visual components of the approaching motorcycle (e.g. headlights) has found that this changes the behaviour of the participants in terms of risk (Mitsopoulos-Rubens & Lenné, 2012). Although it is hard to see why this would change the size of the car-motorcycle difference in the two simulators, the present data do not allow for an unequivocal distinction to be made between these possible explanations. In future research, it would be interesting to take direct or indirect (e.g. skin conductance) measures of risk perception to see whether this does change as a function of vehicle type or simulator type.

In regards to previous naturalistic observation studies (Keskinen et al., 1998), drivers' gap accepted lags in the current study are shorter than those witnessed in naturalistic settings. For example, the gap accepted lag for cars in the high-fidelity simulator was around 4.1 s compared to 6.1 s (Keskinen et al., 1998). This however, seems to be due to the different manoeuvres taking place in these studies. The current study requires drivers to continue straight on at the junction however, in previous research the driver is required to make a right turn, therefore a full manoeuvre takes more time to complete in these instances. This can be reflected in the difference in cross times, with an average of 0.92 s in the current study and an average of 3.3 s in the naturalistic study (Keskinen et al., 1998).

In addition, the measures taken of gap accepted lag in naturalistic studies may be subtly different to specific measures taken in a driving simulator. In the driving simulation environment, the moment at which a driver's car has crossed the give way line can be exactly calculated however, in a naturalistic setting, video validation measures need to be in place to make sure the visually coded data accurately captures the driver's behaviour at the junction. Keskinen et al. (1998) used a single person for their final coding and stated that the observational data, in particular the visual attention measures, could only be estimated roughly. A more substantial reason for the difference may be our adaptive staircasing procedure. The current study's gap accepted lag was of course calculated only on trials which were around the drivers' gap acceptance threshold region, therefore it is likely that these times would be shorter than ones witnessed in everyday driving which will include large numbers of completely safe gaps.

When comparing the current findings to field studies conducted in developing countries, Ibrahim and Sanik (2007) found that drivers' gap acceptance was around 3.7 s for cars and 3.2 s for motorcycles, whereas Serag (2015) differentiated between gap acceptance and gap accepted lag, witnessing drivers' average gap acceptance around 4.8 s, and gap accepted lag around 3.9 s. These findings support the conclusions made by Serag (2015), suggesting that drivers from developing countries demonstrate risker behaviour at intersections than those witnessed in the current simulation study.

Regarding actual motorcycle accidents at junctions, the current study investigated drivers' gap acceptance behaviour as a function of approaching vehicle type. It was not expected that any of these scenarios would cause crashes, especially instances of 'Look But Fail To See' errors. While 'Look But Fail to See' errors might relate to specific occasions where the driver makes a clear and disastrous error, general differences in gap acceptance are more likely to have a small but continuous effect in increasing the risks faced by motorcyclists as opposed to cars approaching junctions. The current experiment involved multiple trials where the driver would quickly learn to expect two oncoming vehicles at every junction. We would thus expect that the drivers in our study would always look carefully at each approaching vehicle and make an informed decision about whether to accept or reject a given gap. However, one accident occurred with an oncoming motorcycle during the experiment. Given the shock and disbelief from the participant after the crash had occurred, is it possible that this could be an instance of a real LBFTS error. Fig. 3 is from a simulator replay of this trial, and shows the view that was available at the moment the driver pulled out into the junction. Although this was only one instance and should not be over-interpreted with respect to LBFTS errors, it is nonetheless surprising given the current task. The driver seemed to be attentive and behaving normally in all other ways, but still pulled out in front of a motorcycle that should have been fully visible to them.

In order to develop strategies that can support drivers' decision making at intersections, future research may need to further investigate whether this inherent difference in gap acceptance towards cars and motorcycles is due to an attitude bias or a perceptual bias. An attitude bias suggests that drivers perceive motorcycles to be less threatening compared to cars, displaying a basic human instinct of self-preservation, as a crash with a car may cause more harm to the driver compared to a crash with a motorcycle (Simmel, 1944). This could also explain the significantly larger gap acceptance for cars in the high-fidelity simulator compared to the medium-fidelity simulator, as an oncoming car in a more immersive environment may be seen as potentially more threatening. The perceptual bias explanation may suggest that drivers have a difficulty in judging the distance or speed of the motorcycle compared to the car. This effect is commonly known as the size-arrival effect, referring to the illusion of a smaller vehicle seeming further away than it actually is (Horswill, Helman, Ardiles, & Wann, 2005). A literature review focusing on gap acceptance studies (Pai, 2011), found that a speed/distance judgement error is likely to be attributable to larger vehicles being perceived as more threatening than motorcycles.

However, it should be pointed out that many of the included studies were not experimental studies, used static or intermittent stimuli and used varied tasks to investigate gap acceptance. To fully explore this possibility, it would be necessary to systematically vary the sizes of vehicle, the speeds they are travelling at, and the distances they start at to unconfound the various effects.

5. Conclusions

In summary, this study has provided evidence to suggest that drivers accept smaller gaps at junctions in front of motorcycles compared to cars. This noted difference suggests that the disproportionate number of accidents involving motorcycles at junctions may be partly attributed to inappropriate gap selection by drivers. The significant difference in drivers' gap acceptance thresholds for car and motorcycles in the high-fidelity simulator but not the medium-fidelity simulator suggests that future research investigating drivers' behaviour at junctions needs to be conducted in a realistic and immersive driving environment in order to generalise to real on-road driving.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.trf.2018.07.023.

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Paper 5

The ‘Saw but Forgot’ error: A role for short-term memory failures in understanding junction crashes?

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RESEARCH ARTICLE

The 'Saw but Forgot' error: A role for short-term memory failures in understanding junction crashes?

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Abstract

Motorcyclists are involved in an exceptionally high number of crashes for the distance they travel, with one of the most common incidents being where another road user pulls out into the path of an oncoming motorcycle frequently resulting in a fatal collision. These instances have previously been interpreted as failures of visual attention, sometimes termed 'Look but Fail to See' (LBFTS) crashes, and interventions have focused on improving drivers' visual scanning and motorcycles' visibility. Here we show from a series of three experiments in a high-fidelity driving simulator, that when drivers' visual attention towards and memory for approaching vehicles is experimentally tested, drivers fail to report approaching motorcycles on between 13% and 18% of occasions. This happens even when the driver is pulling out into a safety-critical gap in front of the motorcycle, and often happens despite the driver having directly fixated on the oncoming vehicle. These failures in reporting a critical vehicle were not associated with how long the driver looked at the vehicle for, but were associated with drivers' subsequent visual search and the time that elapsed between fixating on the oncoming vehicle and pulling out of the junction. Here, we raise the possibility that interference in short-term memory might prevent drivers holding important visual information during these complex manoeuvres. This explanation suggests that some junction crashes on real roads that have been attributed to LBFTS errors may have been misclassified and might instead be the result of 'Saw but Forgot' (SBF) errors. We provide a framework for understanding the role of short-term memory in such situations, the Perceive Retain Choose (PRC) model, as well as novel predictions and proposals for practical interventions that may prevent this type of crash in the future.

Introduction

An in-depth study of motorcycle crashes in the UK [1], revealed that more than 25% of fatal crashes involving a motorcyclist involved another road user moving into the path of the motorcyclist, typically at a junction. This corresponds to approximately 90 deaths in the UK per annum [2]. In the US, there were 5,172 motorcyclists killed on the roads in 2017 [3], and previous estimates have suggested that around 50% of US motorcycle crashes may involve other vehicles pulling into the motorcyclist's path [4]. European analyses have suggested that in 63% of crashes involving a powered two-wheeler and another vehicle, a traffic scanning error on the part of the other vehicle's driver contributed to the crash [5]. Based on international crash statistics [6], it is possible to estimate that around 100,000 fatalities per year may come from this type of crash. Clearly any research that improves our understanding of these crashes, and the kind of countermeasures that can be used to prevent them, has the potential to be a major contribution to world health.

Typical interpretations [7] of these junction crashes are based on the idea that the driver pulling out of the junction has failed to devote sufficient attention [8] to the traffic on the road he or she is entering, thus, they are often termed 'Look but Fail to See' (LBFTS). It is proposed that the crash is caused by failing to spot an oncoming vehicle. This is consistent with the psychological phenomena of change blindness and inattentional blindness, with explanations suggesting that even when attention is on an object it is not always associated with the detection and processing of this object [9, 10].

Other previous research has suggested that motorcycle accident risk is inflated due to the size-arrival effect, which suggests that smaller objects are perceived as further away, and to arrive later than larger objects [11]. Due to this perceptual error, drivers may adopt a smaller gap at the junction when a motorcycle is approaching compared to a larger vehicle such as a car or large goods vehicle. Data from both real and experimental simulations have found that crashes do occur when a car pulls into the path of an oncoming motorcycle, with the car driver thinking the motorcycle is further away than it actually is [11, 12].

In light of this, the initial intention of the current series of studies was to explore whether drivers show systematic biases in attention towards, and memory detail for different vehicle types. We analysed drivers' eye movements and tested their ability to report vehicles approaching junctions in a high-fidelity driving simulator. Although subtle biases in memory for vehicle locations were found, the most striking finding from the first study was not the subtle biases in memory detail, but the complete failure to report some vehicles, particularly approaching motorcycles.

Short-term memory is responsible for the encoding, temporary storage and retrieval of information for complex cognitive tasks [13] and thus, this system is responsible for offering drivers feedback about the traffic situation a few seconds earlier [14]. Therefore, drivers' ability to report vehicles depends not only on them being successfully encoded, but also on the storage of this information and its retrieval from short-term memory [15]. This suggests that report failures might not always be due to a failure in visual attention (encoding), which many previous researchers have suggested [8], but could sometimes be due to subsequent failures in memory [16].

Theoretically this should not be surprising as it has previously been argued that attention and memory modulate the comprehension of events [17, 18]. Memory errors are also a plausible explanation for driving errors, as previous studies which have investigated drivers' memories for vehicles on the road [19–21] have found that drivers' memories for their current environments are relatively poor [20]. Two further studies were thus conducted, using similar scenarios to the first, to explore the possible reasons for a complete failure to report approaching vehicles at junctions. We wanted to decide whether approaching vehicles were attended to on occasions where drivers failed to report them, and in particular, on occasions where drivers were willing to complete a manoeuvre in front of these oncoming vehicles.

The second and third studies analysed drivers' eye movements, and their ability to report oncoming vehicles and their locations, at the time drivers were making a risky decision to pull out in front of approaching vehicles. In the second study we again found that there were occasions where drivers completely failed to report approaching vehicles, particularly motorcycles.

Given that fixations on objects have been seen to be the best predictor of memory [22], it was important to investigate drivers' eye movements in more detail. The third study additionally investigated drivers' subsequent visual search after fixating on the motorcycle, on occasions where the driver failed to report it. Distinguishing between perceptual and memory explanations is a difficult task. However, post-event processes, i.e. ones that occur after the vehicle has been presented, should not influence the initial attention to and encoding of vehicles. Analysis of eye movements after fixating an oncoming motorcyclist allows us to explore the possibility that new information can interfere with the storage and retrieval of previous information held in short term memory [23].

To anticipate our results, failures to report a motorcycle were not predicted by how long a driver fixated on the vehicle, but were associated with their subsequent behaviour i.e. drivers were more likely to forget an oncoming motorcycle if they had made several head movements between looking at it and the subsequent memory test.

The raw data for the three studies presented in this paper can be found at: Robbins, C. J., Allen, H. A., Miller, K., & Chapman, P. F. (2019, May 10). The "Saw But Forgot" error. Retrieved from osf.io/nd6ug

Study 1: Drivers' behaviour and recall at junctions

The main aim of Study 1 was to investigate drivers' visual attention towards, and memory for the location of vehicles at junctions. We expected that drivers would have reduced attention towards smaller vehicles, as well as estimating smaller vehicles to be further away than larger vehicles. Given that this experimental set up requires drivers' memory for vehicles and their locations to be tested on numerous occasions, this study also tested whether the presence of a memory test changed participants' behaviour.

Participants

All studies had full ethical approval from the University of Nottingham Psychology ethics committee. All methods were carried out in accordance with the relevant guidelines and regulations, with written informed consent obtained by all participants.

The sample size for Study 1 was determined a priori based on a power analysis (medium effect size for repeated measure, within factor difference, Cohen's f = 0.25, 1-β = 0.90, p = .05) [24]. This was because our main comparisons of interest were the within groups differences in reporting location of approaching vehicles.

Drive only group participants. Data were collected from 30 participants (Mean age = 21.8, SD = 4.5, Range = 18–40; Male = 12, Female = 18) who had held a driving licence for between 1–22 years. They had a reported annual mileage between 0–10,000 miles (Mean = 3,670) and a total mileage between 30–120,000 miles (Mean = 21,826). Eight of the participants were recruited for first year undergraduate credit, six participants were recruited as part of a study swap and sixteen of the participants received a £5 inconvenience allowance for their time.

Memory test group participants. Data were collected from an additional 30 participants (Mean age = 21.2yrs, SD = 2.9, Range = 18–31; Male = 23, Female = 7) who had held a driving licence for between 8 months- 9 years. They had a reported annual mileage between 0–10,000 miles (Mean = 4,140) and a total mileage between 0–50,000 miles (Mean = 8,581). All participants received a £5 inconvenience allowance for their time.

Design

All driving scenarios required the participant to drive up to the same intersection. The intersection was a cross-road, therefore traffic could theoretically be coming from the left, right or straight ahead, although in the key trials in the current studies the road straight ahead on the other side of the junction was always clear. The driver did not have right of way over vehicles approaching from the left or right on the main road. The driver completed the scenario by pulling out of the junction when it was deemed to be safe and continuing straight on down the minor road at the far side of the junction.

A 2x3x3 mixed design formed the core of the study, with the between groups factor referring to whether the driver received memory tests (Memory Test Group vs. Drive Only Group). One within groups factor was the type of oncoming vehicles at the junction. On key trials there were always two oncoming vehicles, one from the left and one from the right. One of each pair was always a car, while the second varied such that there were three possible combinations (car-car, car-motorcycle, car-large vehicle). The vehicles on the two sides of the junction always came from the same distance as each other, and this distance formed the second within groups factor with three levels, (far distance (95m), medium distance (60m), near distance (25m)). Both oncoming vehicles were always visible when the participant arrived at the junction and were already travelling at a fixed speed of 30 mph. Each vehicle combination was repeated twice at each distance, with left and right vehicles swapped in location, providing 18 target trials (3 x vehicle type, 3 x distance, 2 x LR vs RL). Participants encountered these 18 key target trials along with 12 general traffic trials, where traffic was randomly generated in an unpredictable manner by the simulator. This totalled 30 trials, with the order being fully counterbalanced.

Memory test group only. Twelve of these 30 trials were memory test trials. On these trials, the scenario was terminated at the point where the driver reached the junction and a memory test was given. Drivers had to verbally indicate what vehicles they saw at the junction and using a laser pointer, indicate the location of each oncoming vehicle. These memory test trials consisted of 9 target trials and 3 general traffic trials. The 9 target trials were three of each vehicle combination (car-car, car-motorcycle, car-large vehicle), at each distance (near, medium and far).

Apparatus

Study 1 took place in the Nottingham Integrated Transport and Environment Simulation (NITES) facility's, high fidelity driving simulator (NITES 1). This simulator comprises of a full BMW Mini, housed within a projection dome and mounted on a six-degrees of freedom motion platform with a 360-degree projection screen. The scenarios were formed on the screens using six projectors.

XPI (XPI Simulation, London, UK) driving simulation software was used to create the scenarios. All scenarios took place at the same cross road intersection, which was based on an urban road. The intersection had a "Stop sign" at the end, reminding participants to check the junction before pulling out. The junction chosen for the scenarios was a flat junction, with houses either side of the road on the approach. The junction had equal visibility to the left and right when participants stopped at the junction. Each scenario started in the same location, which was around 80m from the junction. The scenario ended just after the participant had pulled out of the junction and continued straight on at the junction for around 30m. The speed of the approaching target vehicles remained constant throughout the experiment, travelling at 30mph, chosen as this is the average speed of both cars and motorcycles on British roads [25].

Drivers' eye movements were tracked using two linked FaceLAB 5.0 remote eye tracking systems (four cameras and two infrared sources), which allowed participants' eye movements to be tracked continuously over a range of approximately 120 degrees in front of the driver.

A KODAK PIXPRO 360-degree action video camera was mounted on top of the BMW Mini roof, directly above the driver's head, and not visible to the driver. This camera allowed for the full 180-degree front field of view to be visible. In the memory test condition these recordings were used to measure the location of the two oncoming vehicles at the time the simulation was paused. These locations were measured relative to the front of the vehicle (closest point to the driver) allowing us to calculate the visual angle away from straight ahead at the moment the simulation stopped. This measure was compared to the estimated locations of the vehicles as indicated by the participant shining a laser pointer onto the blank simulation screens and recorded using the same video camera.

Procedure

Participants completed a short 'Driving Experience' questionnaire which included questions on age, gender, years of licensure as well as miles and hours driven. The driver entered the driving simulator and the eye trackers were calibrated. Participants drove up to a series of intersections where there was oncoming traffic that had the right of way. They were instructed to approach the junction at a speed of around 20mph and drive across the junction, choosing to go either before or after the oncoming traffic arrived. They were encouraged to drive as naturally as possible throughout the experiment and obey all road signs. The first two trials served as practice trials, allowing participants to become familiar with the simulator as well as checking for any signs of simulator sickness. On average, each scenario took around 20 seconds to complete.

For drivers in the Memory Test condition, drivers were informed that on selected trials, the scenario would be terminated when they reached the junction, leaving a white simulator screen. On these trials, the participant should indicate verbally what vehicles they saw at the junction and using the laser pointer, indicate the location of each oncoming vehicle. Participants could not predict on which trials the memory test would occur.

Results

Dependent measures. For behavioural and eye movements measures, the dependent variables included Approach Time [26], Number of Stops, Wait Time and Cross Time [27], as well as Mean Fixation Duration, Proportion of Fixations and Proportion of Gaze [26]. A custom MatLab [28] script was used to automatically analyse these behavioural and eye movements.

Specifically, the MatLab script obtained the measure of Approach Time by calculating how long it took drivers to travel through the 'approach zone', which started at 35m away from the junction and finished at the moment where the front of the driver's car had entered the junction by crossing the junction entry line. The 'approach zone' thus started when the target vehicles first become visible, therefore this was the point where approaching traffic may start to alter the approach behaviour of the driver. Number of Stops and Wait Time were also calculated in the 'approach zone'. Number of Stops was calculated by the number of times the participants' vehicle speed went below 1mph, and Wait Time was the time that passed while the participants vehicle speed remained under 1mph. Finally, Cross Time refers to the amount of time it took the driver's car from entering the junction (crossed the give way line) until when the rear of the driver's car had cleared the junction (crossed the junction exit line).

In regards to eye movements, due to the fact drivers could generally only look at one vehicle at a time, measures of behaviour towards the two vehicles approaching the junction were not independent of each other. For this reason, in each scenario one vehicle was always designated as the target vehicle, where the visual attention towards that specific vehicle was analysed. For the car-car trials, the red car was always the target vehicle, and in the remaining trials, the motorcycle or the large vehicle was always the target vehicle.

In addition, given that drivers made large rapid head movements and fixations at wide eccentricities, it was difficult to always be sure of the quality of the eye tracking. For this reason, a conservative approach was adopted, focussing on the broad direction of fixation (towards or away from the target vehicle, rather than requiring an unambiguous fixation on the vehicle). A fixation dispersion threshold of 0.2 of a radian for 100ms was used to regard a fixation to be in progress. This wide threshold meant that smooth pursuit movements to oncoming vehicles were treated as equivalent to fixations. Proportion of Fixations was calculated by measuring the number of fixations towards and away from the target vehicle side of the junction. The proportion of all these fixations towards the target vehicle side of the junction was then calculated. The Proportion of Gaze was calculated in the same way as the previous measure with total gaze duration rather than number of fixations. Total gaze duration was the total time spent on fixations to the target vehicle side of the junction, so Proportion of Gaze gives a general measure of how much visual attention was towards the oncoming target vehicle. Mean Fixation Duration was calculated by dividing the number of fixations made towards the target vehicle side of the junction, by the total gaze duration towards the target vehicle side of the junction.

Drivers' reports of vehicles were coded as a dichotomous variable i.e. whether drivers ever failed to report a vehicle or notoss Time et v proproation of gaze on the target v ehciles. in groups differences in rerporting y on h the g. eaving a white, and therefore Cochran Q tests were conducted to investigate this measure as a function of Vehicle Type and Vehicle Distance. This simple coding of the variable was chosen as the frequency of forgetting was not high enough to justify another test. Finally, for drivers' recall of vehicle locations, these were analysed by Driver Bias. Driver Bias was defined as the difference between the actual visual angle of the vehicle from straight ahead at the moment the simulation stopped, and the estimated location of the vehicle as indicated by the participant's laser pointer. This value could have been negative (an overestimation of the visual angle with it being reported as further away than it really was) or positive (an underestimation of the visual angle with it being reported closer than it really was).

Effect of memory test on driving behaviour. There was a difference in driving experience between the Memory Test Group and Drive Only Group. To assess the effect of this confound, a correlation between experience and the key behavioural and eye movement measures was conducted (S1 Table). No significant correlations were found.

To test if the memory testing changed driver behaviour, a behavioural and eye movement comparison between the Memory Test Group and the Drive Only Group was conducted using a 2x3x3 mixed ANOVA, with a between group factor of Group (Memory Test or Drive Only) and within group factors of Vehicle Type (Car, Motorcycle, Large Vehicle) and Vehicle Distance (Near, Medium, Far).

There were no significant differences between groups in Approach Time [$F (1, 58) = 2.58$, $MSe = 9.51$, $p = .11$], Number of Stops [$F (1, 58) = 7.15$, $MSe = .38$, $p = .61$], Wait Time [$F (1, 58) = 1.76$, $MSe = 157.55$, $p = .19$] and Cross Time [$F (1, 58) = .19$, $MSe = 1.78$, $p = .67$]. There was also no difference in drivers' Proportion of Fixations [$F (1, 58) = 2.49$, $MSe = .24$, $p = .12$] and Proportion of Gaze [$F (1, 58) = 3.78$, $MSe = .23$, $p = .07$] however, drivers' Mean Fixation Durations were significantly longer in the Memory Test Group compared to the Drive Only Group ($F (1, 58) = 8.91$, $MSe = 288575.98$, $p < .01$). See S2 Table for full descriptive statistics for both groups.

Drivers' memory for vehicles and locations. The results from the memory test trials were analysed. Although it was expected that drivers would report all approaching vehicles, they failed to report one of the two oncoming vehicles on 7.4% of trials (20 occasions). These were split between failures of memory for motorcycles (14) cars (4) and LGVs (2), (Fig 1A). There was a difference in failure to report a vehicle as a function of Vehicle Type *($\chi^2(2)$ = 17.73, $p < .001$)*, showing that drivers failed to report significantly more motorcycles than cars and large vehicles *($p < .001$)*. There was also a significant difference in drivers' reports of vehicles as function of Vehicle Distance *($p < .01$)*, indicating that drivers failed to report more far target vehicles compared to medium and near distance vehicles.

For the location of vehicles, there was an overall tendency for drivers to underestimate the visual angle of oncoming vehicles, with drivers remembering oncoming vehicles to be closer than they really were (mean difference between true angle and indicated location = 8.7 degrees). There was a significant main effect of Vehicle Type ($F(2, 58) = 5.71$, MSe = 46.24, $p < .01$), with this tendency being stronger for motorcycles (11.72˚) than for cars (8.48˚) and LGV (5.79˚) ($p<0.01$). There was also a main effect of Vehicle Distance ($F(2, 58) = 11.23$, MSe = 55.68, $p < .001$), with this tendency being more pronounced for far vehicles than for medium or near vehicles ($p < .001$).

Eye movements during memory testing. Given the surprisingly frequent memory failures for motorcycles in the memory test group, we conducted additional detailed analysis of eye movements for these participants on the trials where their driving was not interrupted by a memory test. For this group, drivers' eye movements in the direction of the target vehicle were analysed using a series of 3x3 within subject ANOVAs, with factors of Vehicle Type (Car, Motorcycle, Large Vehicle) and Vehicle Distance (Near, Medium, Far). For the factor of Vehicle Type, two a priori orthogonal contrasts were specified that first compared motorcycles with cars and large vehicles together and secondly compared cars with large vehicles. For the factor of Vehicle Distance, contrasts were specified which tested for linear trends in the data.

Drivers had lower mean fixation durations to the side of the junction where a motorcycle was present (337.67 ms) compared with cars and large vehicles (415.68 ms) (Main effect: $F(2, 58) = 11.75$, MSe = 81303.89, $p < .001$; contrast for motorcycles vs. cars and large vehicles: $F(1, 29) = 4.21$, MSe = 130135.62, $p = .05$). However, there was no main effect of Vehicle Type for either Proportion of Fixations ($F(2, 58) = 1.54$, MSe = .08, $p = .22$) or Proportion of Gaze ($F(2,58) = 2.01$, MSe = .11, $p = .14$). These findings were consistent with the same analysis conducted for the Drive only and Memory test groups–S1 File. Thus although mean fixation durations were slightly lower, there was no evidence that drivers were looking at motorcycles less often than cars and LGVs, or for less time overall.

Discussion of Study 1

We had set out to investigate drivers' visual attention towards, and memory for different vehicle types approaching a junction. Firstly, we can conclude that drivers generally did not change their behaviour due to the presence of a memory test though they may have slightly increased their attention to oncoming vehicles as evidenced by the increase in fixation durations.

The most unexpected finding from Study 1 was that on some occasions, participants were entirely unable to report the presence of one of the oncoming vehicles, with 70% of these occasions involving oncoming motorcycles. The fact participants were unable to report oncoming motorcycles is remarkably consistent with the incidence of junction crashes involving cars pulling into the path of oncoming motorcycles, as well as predictions from inattentional blindness studies [9]. This study is therefore a novel demonstration of drivers experiencing complete report failures at a fully simulated junction, rather than just making judgments of safety about still images [8].

Although we found an overall significant underestimation of vehicle location, with this being particularly pronounced for motorcycles, much of this effect came from trials where the

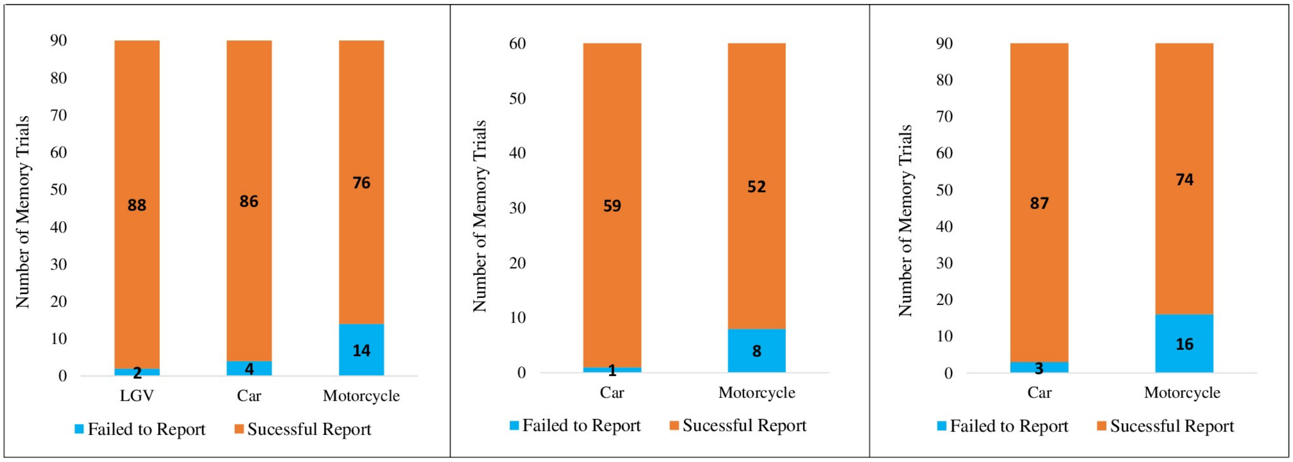

Fig 1. The number of occasions drivers failed to report a vehicle and successfully reported a vehicle (A) in Study 1, (B) in Study 2 and (C) in Study 3.

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driver may never have intended to pull out at the junction. This is a limitation of Study 1, as there is no measurement of whether the driver would actually have pulled out into the junction on the memory trials. Given that inattentional blindness and change blindness paradigms are based around the fact that it is expected that items are seen due to their behavioural relevance to the task [29], it is important that the vehicles in this paradigm are critical for a driver's decision to make a manoeuvre, and not occasions where the driver is always waiting for the vehicles to pass before pulling out. The next study we report was designed to investigate the possibility of complete report failures on occasions where drivers were actually pulling out into the junction with oncoming vehicles nearby.

Study 2: Failure to report vehicles when pulling out at a junction

This study is designed to investigate drivers' attention towards and memory for approaching vehicles in more safety critical situations, by presenting vehicles at driver's individual gap acceptance threshold. Gap acceptance methods are thought to produce rich sources of data, collecting data from gaps which are both accepted and rejected by drivers, and most importantly estimating the point of the 'critical gap' [30]. Given that the vehicles in these situations are more task relevant, with drivers having to make to more informed decision about when to pull out of the junction, the main aim is to explore whether the findings from Study 1 can be replicated on occasions where drivers are intending to pull out of the junction in front of the approaching vehicles.

Participants

The sample size for Study 2 was determined a priori based on a power analysis. The overall sample size of 30 had more than adequate power (.95) to detect a large within subject effect (d = 0.8) with the alpha level used for analysis being $p < .05$. Data were collected from 30 drivers (Mean age = 26.4, SD = 8.7, Range = 20–59; Male = 10, Female = 20) who had held a driving licence for between 3 months- 35 years. They had a reported annual mileage between 0–15,000 miles (Mean = 4739) and a total mileage between 40–200,000miles (Mean = 53,049). All participants received a £5 inconvenience allowance for their time.

Design

We used a recently developed paradigm that facilitates the measurement of performance when drivers pull out in front of approaching vehicles, by estimating each individual driver's gap acceptance threshold [27]. A series of 12 trials were presented to participants, where the vehicles were approaching at fixed distances (45, 55m, 65m, 75m, 85m and 95m). There were two vehicle combinations (car-car, car-motorcycle), where one vehicle approached from the left and one approached from the right. The order of the vehicle combinations, and the direction of the approaching vehicles (left or right) was randomised at each distance. Drivers could decide whether or not to pull out in front of the approaching vehicles. These fixed distances were used to estimate the distance oncoming vehicles had to be from the junction to create a 50% chance of each individual driver accepting the gap [31, 32]. The estimate of drivers' gap acceptance threshold could range from 40m to 100m from the junction (1m intervals). Although a gap acceptance threshold was calculated for car-car trials and car-motorcycle trials separately, there was also a combined threshold based on all trials irrespective of oncoming vehicle type.

Once the gap acceptance threshold had been calculated, approximately eight subsequent trials were conducted with the vehicles approaching from that individual's combined threshold distance. Participants were given a memory test on the first four occasions where they began to pull out in front of these oncoming vehicles. No memory test was given on the (approximately four) occasions were the driver was not willing to pull out. The experiment continued until four memory test trials had been conducted, consisting of 2 car-car trials and 2 car-motorcycle trials.

Apparatus

The apparatus used for the study was identical to that used for Memory Test Group in Study 1.

Procedure

The first part of the procedure was identical to the Memory Test Group in Study 1 however, the trials the participants were exposed to differed. The participant first completed a series of fixed distance trials to estimate their gap acceptance threshold. From this, the driver's individual combined threshold (using data from both car-car and car- motorcycle trials) was calculated and used for future trials. Drivers were then given a series of trials at this threshold, and on occasions when they started to pull out in front of oncoming vehicles they were given a memory test. On the memory test trials, the simulation was stopped at the moment the driver started to cross the junction ahead of oncoming vehicles. Drivers were then asked to report whether there were any vehicles present at the junction, and indicate the estimated location of these vehicles using a laser pointer. The experiment continued until four memory tests had been given.

Results

Dependent measures. Drivers' reports of vehicles and vehicle location were calculated using the same method as Study 1. Gap acceptance thresholds were the estimated distance vehicles had to be on car-car and car-motorcycle trials for drivers to be 50% likely to pull out in front of them.

In regards to eye movements, these were calculated and compared between trials where drivers had failed to report an oncoming motorcycle and trials were they successfully reported the motorcycle. Proportion of Fixations, Proportion of Gaze and Mean Fixation Duration to the side of the junction were defined in the same way as Study 1 using a custom MatLab [28] script. However, a fixation was only counted when it was made to the side of the junction where the target vehicle was approaching and was still visible.

For the analysis, vehicle location estimates, gap acceptance thresholds and eye movements were subject to a within subject t-test, with the factor of Vehicle Type (car vs. motorcycle).

Drivers' memory for vehicles and locations. As in the previous study, a Cochran Q test was conducted for the factor of Vehicle Type. We found that drivers sometimes failed completely to report one of the approaching vehicles at the junction—failing to report significantly more motorcycles (8 occasions) than cars (1 occasion) ($\chi^2(1) = 7.00$, $p < .01$, Fig 1B). When vehicles were correctly reported we found that participants generally estimated the location of vehicles to be closer to them than they actually were by, on average 18.7 degrees. In contrast to Study 1, there was a significant difference in driver bias for the location of cars and motorcycles (t (29) = 2.46, $p < .05$), with drivers having more of a bias to estimate cars to be closer to them than motorcycles (Cars: 21.1 deg, motorcycles 16.5 deg, $p < .05$).

Drivers' gap acceptance thresholds. The distance at which the drivers were 50% likely to pull out for car-car trials (M = 84.11m, SE = 2.63m) and car-motorcycle trials (M = 85.74m, SE = 2.42m) did not differ as a function of Vehicle Type (t (29) = 1.07, $p = .29$).

Drivers' eye movements. To test whether drivers attended less to a vehicle that they later failed to report, drivers' eye movements to the side of the junction on the eight occasions were a driver failed to report a motorcycle were compared to the other trial where they had correctly reported a motorcycle at the junction. It was found that there was no significant difference in the Proportion of Fixations [t (7) = .99, p = .36], Proportion of Gaze [t (7) = 1.04, p = .33], and Mean Fixation Duration [t (7) = 2.05, p = .08] to the side of the junction of the approaching motorcycle when drivers failed to report and successfully reported the approaching motorcycle. See S3 Table for descriptive statistics of all measures.

Discussion of Study 2

Study 2 demonstrates that drivers can fail to report approaching vehicles even when pulling out of a junction in front of them, with this being more prevalent for motorcycles than cars. This study created trials where the oncoming vehicles were as close as they could possibly be for the individual to still spontaneously choose to pull out in front of them, creating a much more realistic scenario for representing genuinely risky manoeuvres that might potentially lead to junction crashes in the real world.

In regards to drivers' estimated vehicle locations, there was an overall significant underestimation of estimated vehicle location, with this being particularly pronounced for cars compared to motorcycles (this differed from Study 1). This finding is consistent with research into the size-arrival effect, with the size of vehicles having an impact on the predicted motion of vehicles [11]. This is also supported by additional research focusing on road markings, which has found that drivers' perceived distance is dependent on many factors including size of the object [33, 34]. The difference in findings for Study 1 and Study 2 is thought to be due to vehicles being presented at unrealistically far and near distances in Study 1.

Given that junction manoeuvres require drivers to retain information about traffic in memory while scanning the junction, our results suggest that it could be possible that some of the vehicles which are later unreported have been attended to and processed, but have been forgotten before the decision to pull out is made. However, a limitation of Study 2 is that we cannot confidently conclude whether drivers actually fixated on the approaching vehicle before failing to report it. As previously mentioned, given that the length of a participant's fixation has been seen to predict memory for objects [22], it is important to firstly explore whether drivers directly fixate on vehicles when distinguishing between the explanations of a failure to attend and a failure to recall. In addition, a more explicit test of memory interference would be to explore drivers' subsequent visual behaviour after fixating on the approaching vehicle, as we may expect subsequent information after fixating on a motorcycle to interfere with previously encoded information in working memory [23].

Study 3: Failure to report vehicles with head-mounted eye-tracking

In Study 3 we replicated Study 2 but added lightweight eye-tracking glasses to obtain highly accurate measures of fixations at extreme eccentricities (e.g. after the driver has made a head movement to the left or right). We investigated whether oncoming vehicles were directly fixated, and investigated drivers' subsequent visual search behaviour after fixating on the target vehicles.

Participants

Data were collected from 45 participants (Mean age = 22.9, SD = 4.9, Range = 18–41; Male = 12, Female = 33) who had held a driving licence for between 4 months- 22 years (m = 5 years). They had a reported annual mileage between 0–16,000 miles (Mean = 3246 miles) and a total mileage between 0–154,000 miles (Mean = 20,185 miles). All participants received a £5 inconvenience allowance for their time.

The sample size for Study 3 was determined a priori, based on the number of participants who failed to report a motorcycle in Study 2. As there were 8 participants who unsuccessfully reported a motorcycle in Study 2, we calculated that we would need an overall sample size large enough to provide at least 12 participants with report failures in order to detect a difference in drivers' eye movements on successful and unsuccessful report trials (large effect size for within subject difference, Cohen's d = 0.8, 1-β = 0.80, p = .05). Based on the previous study, this required a total sample size of 45 participants, with the logic that at least 12 people will fail to report a motorcycle on at least one occasion.

Design

The design of the study was identical to Study 2.

Apparatus

The apparatus used for Study 3 was identical to Study 2 except that eye movements were recorded using Tobii Pro Glasses 2 (See Fig 2A). These glasses were attached to a small recording unit which was kept in the car door and allowed the participant to move freely in the car, not obstructing their movement or view. The glasses tracked the participants' pupil and corneal reflection, recording at a rate of 50hz. A successful calibration was needed for every participant before the memory trials could begin. The glasses also had a wide-angle HD scene camera in the centre (90 degrees), which captured the driver's natural viewing behaviour. The researcher could see this live viewing of the participant's view, overlaid with eye tracking, on a separate laptop (82 degrees horizontal, 52 degrees vertical).

Procedure

The procedure was identical to Study 2.

Results

Dependent measures. Drivers' reports of vehicles, vehicle location and gap acceptance thresholds were calculated using the same method as Study 2.

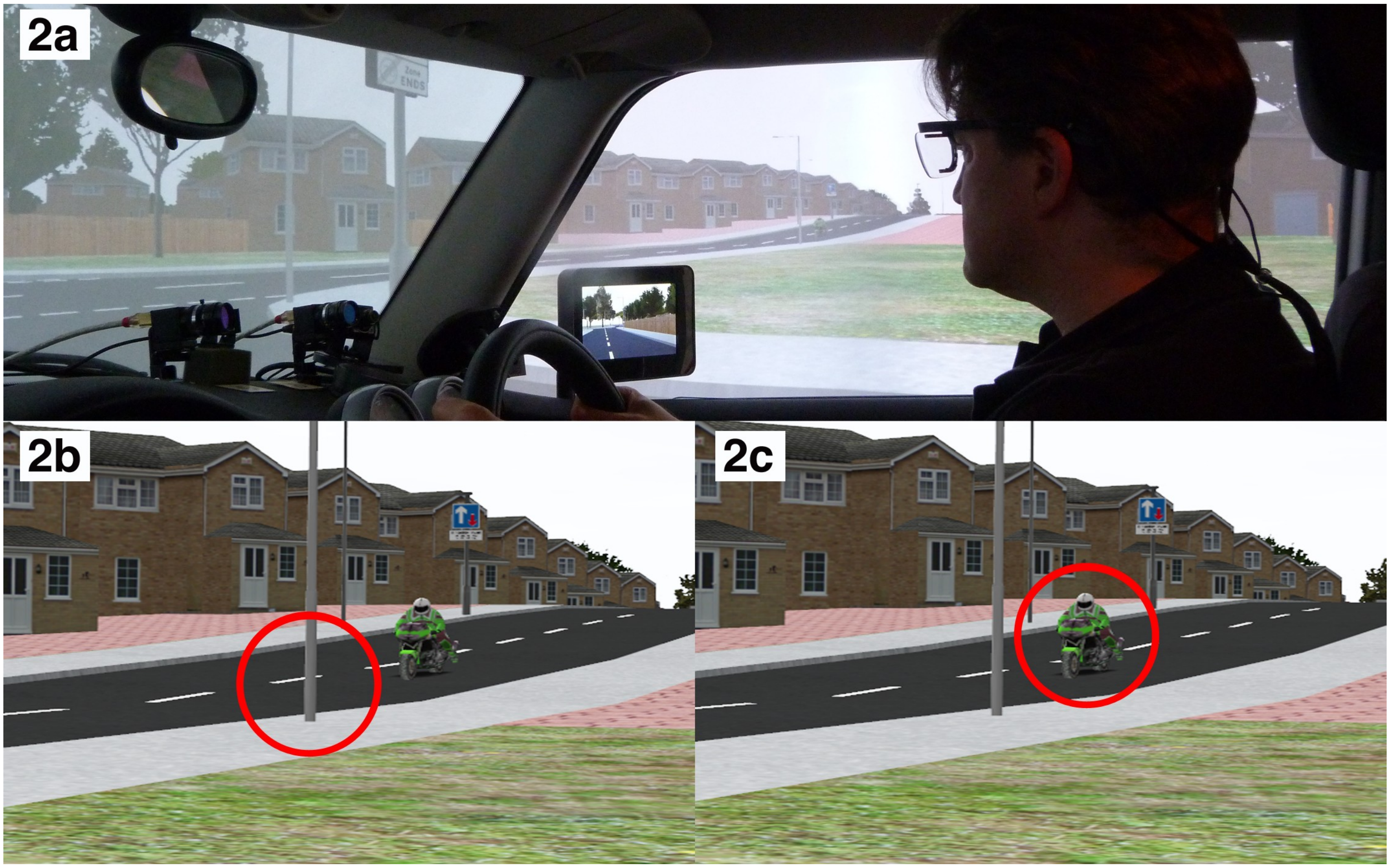

Fig 2. (A) A view to the right within the simulator vehicle showing one of the authors (PC) wearing the head-mounted eye-tracking glasses as used in Study 3 in a trial with a motorcycle approaching from the right-hand side of the intersection at a typical gap-acceptance threshold. Part of the FaceLab system used to record eye movements in Studies 1 and 2 are also visible on the dashboard in this Figure. (B) "Looked but Fail to See": A close up of the view of the eye tracking on one of the five occasions when a driver failed to recall the oncoming motorcycle without having previously fixated it. The red fixation circle has a radius of 1 degree of visual angle and represents the closest fixation this driver made to the motorcycle before entering the junction. (C) "Saw but Forgot": A close up of the view of the eye tracking on one of the eleven occasions when a driver failed to recall the oncoming motorcycle despite having previously fixated it. The red fixation circle has a radius of 1 degree of visual angle and represents an unambiguous fixation on an oncoming motorcycle that the driver will attempt to pull out in front of.

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Drivers' eye movements were calculated and compared on trials where they failed to report a vehicle and on trials were they successfully reported the vehicle. Eye movements were manually coded using the Tobii Pro Glasses Analysis software. Drivers' gaze on the vehicle was defined by the 1-degree radius fixation circle overlapping any part of the oncoming vehicle. When the driver's gaze was on a motorcycle, this was manually coded as an event. When the driver's gaze came off the motorcycle, this was coded as another event. The dependent measures on the approaching motorcycle were Number of fixations, Total Gaze Duration and Mean Fixation Duration. The Number of Fixations was the total number of times the driver's gaze was within 0.5 of a degree for over 60ms on the target vehicle. The Total Gaze Duration was the total time spent on fixations on the target vehicle. The Mean Fixation Duration was calculated by dividing the number of fixations made on the target vehicle by the total gaze duration.

Drivers' subsequent visual behaviour after fixating on the approaching motorcycle was also analysed, investigating the following variables: Subsequent Number of Fixations, Subsequent Number of Head Movements and Time of Last Fixation. Subsequent Number of Fixations was calculated by the number of times the driver made a fixation after the last fixation on the motorcycle until they pulled out of the junction. The Subsequent Number of Head Movements was the number of large clearly distinguishable head movements after their last fixation on the motorcycle before pulling out of the junction. Finally, the Time of Last Fixation was the time between the last fixation on the motorcycle and pulling out of the junction.

For the analysis, drivers' vehicle location estimates, gap acceptance thresholds and eye movements were subject to a within subject t-test, with the factor of Vehicle Type (car vs. motorcycle).

Drivers' memory for vehicles and locations. There were 16 drivers that failed to report a motorcycle and 3 drivers that failed to report a car when asked to recall the vehicles present (Fig 1C). There was a significant difference in drivers' recall as a function of Vehicle Type ($\chi^2(1) = 11.27, p < .001$), showing that drivers failed to report significantly more motorcycles than cars.

As previously, drivers generally underestimated the location of vehicles, estimating vehicles to be closer to them than they actually were. As in Study 2, drivers estimated cars to be closer to them than motorcycles (cars: 22.22 deg, motorcycles:15.50 deg; t (44) = 3.49, $p < .01$).

Drivers' gap acceptance thresholds. The distance at which drivers were 50% likely to pull out for car-car and car-motorcycle trials did not differ as a function of Vehicle Type (Car: 82.44m; Motorcycle 81.66m, t (44) = .65, $p = .52$). A point-biserial correlation also revealed there was no correlation between drivers' combined gap acceptance threshold and report of motorcycles, (r_{pb} = -.01, n = 45, p = .95) or cars (r_{pb} = -.15, n = 45, p = .32), indicating that drivers' reporting of vehicles was not related to how far away they were being presented.

Drivers' eye movements. On 5 of the 16 occasions on which a driver failed to report a motorcycle, the driver failed to fixate on the approaching motorcycle (Fig 2B). However, on 11 of these occasions the driver had already made an eye movement on the approaching motorcycle for at least 60ms (Fig 2C).

Drivers' eye movements on the vehicle. For the eleven participants who fixated on the motorcycle before subsequently failing to report it, their eye movements on the occasion when they did not report the motorcycle were compared to their eye movements on a trial where they had correctly reported a motorcycle at the junction (on the left or right). There was no difference in the number of fixations on the unreported (1.09) and reported (1.36) motorcycles (t (10) = 1.40, $p = .19$) and no difference in total gaze duration or mean fixation duration on the unreported and reported motorcycles (total gaze: t (10) = .37, $p = .72$; mean fixation duration; t (10) = 1.29, $p = .23$; Fig 3A). To further clarify this result, the eye movement measures were compared between the trials where the motorcycle was not reported and matched trials where another participant reported the motorcycle. Another 11 participants who reported the motorcycle on the same side of the junction were matched on the basis of combined gap acceptance thresholds. Again, there were no differences in drivers' eye movement measures (all p >.1), see S2 File.

Drivers' subsequent eye movements after fixating the vehicle. There was no difference in drivers' subsequent number of fixations after fixating on unreported motorcycles (3.91) and reported motorcycles (2.10) (t (10) = 1.73, $p = .11$) before pulling out of the junction. However, there was a significant difference in drivers' subsequent number of head movements after fixating on unreported motorcycles compared to reported motorcycles (unreported: 1.55, reported: .64; t (10) = 5.59, $p < .001$) before pulling out of the junction. Drivers had more subsequent head movements when they failed to report a motorcycle compared to when they correctly reported it. There was also a significant difference in the time of last fixation on the motorcycle before pulling out of the junction, for unreported motorcycles and reported motorcycles (t (10) = 3.32, $p < .01$). The time between last fixation on the oncoming

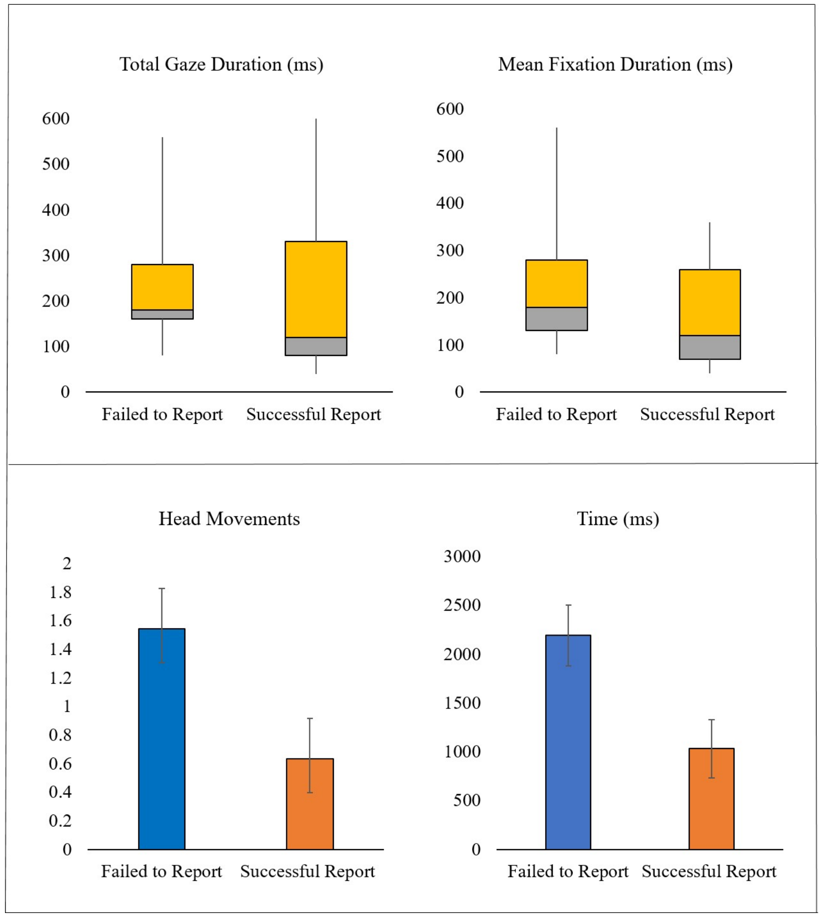

Fig 3. (A) Total gaze durations and mean fixation durations on reported and unreported motorcycles. (B) Post-fixation behaviour for reported and unreported motorcycles: Number of head movements and total time between fixating the motorcycle and pulling out at the junction.

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motorcycle and pulling out at the junction was more than twice as long for unreported motorcycles (2190.36 ms) compared to the reported motorcycles (1032.18 ms, Fig 3B).

In regards to cars, out of the three occasions on which a driver failed to report a car, the driver made an eye movement on the approaching car for at least 60ms on one of these occasions. Eye movements on the car, and subsequent visual behaviour after fixating on the approaching car can be seen in S3 File. Eye movement raw data and means from the 11 participants who failed to recall a motorcycle can also be seen in S4 Table.

Discussion of Study 3

Study 3 further demonstrated that driver's underestimation of vehicle location was more prevalent for cars compared motorcycles, which is also consistent with research into the size-arrival effect. More importantly, it was found that drivers failed to report approaching vehicles when pulling out of a junction in front of them, with this being more prevalent for approaching motorcycles than cars. These report failures were not predicted by the distances at which these vehicles were being presented, nor by how often or long the vehicles were being directly fixated. It seems that these report failures were associated with drivers' subsequent visual search behaviour after fixating on the approaching motorcycle and before pulling out of the junction.

In particular, drivers' subsequent number of head movements after fixating on the approaching motorcycle, as well as the time that elapsed between fixation and pulling out of the junction were the measures that predicted failures in report. These findings present the possibility that these report failures could be associated with a failure in working memory, as previous research has found that working memory is increasingly important in tasks that require the integration of information over different screens [35]. These findings could therefore be important in understanding drivers' manoeuvres at junctions which often require the integration of information over multiple fields of view while making head movements to the left and right. These findings will be discussed in more depth in regards to typical and alternative explanations for junction crashes.

General discussion

From this series of studies, it was found that drivers failed to report approaching motorcycles on between 13% and 18% of occasions when they were pulling out in front of another vehicle. The frequency of failure to report was significantly higher for motorcycles compared to cars. These findings are a clear and dramatic demonstration of failures of situational awareness during junction crossing in a controlled environment in a high-fidelity driving simulator. Similar failures in real world junction crashes have been attributed to LBFTS errors, but the current results suggest that there may have been many occasions on which the motorcycle was actually 'seen' but had been subsequently forgotten before the decision to pull out was made.

There were no substantial differences in drivers' visual attention assessed by eye movements on reported and unreported motorcycles. In contrast we did find that when drivers failed to report a motorcycle they had made more head movements and waited longer before pulling out after the initial fixation than on occasions where they reported it. Although we cannot say for certain that fixated vehicles have been processed, these findings do suggest that drivers' fixation durations on these motorcycles were sufficiently long for them to be fully processed on other occasions. This requires us to seriously consider the possibility that on at least some occasions oncoming vehicles have been attended to and processed, but have been forgotten before the decision to pull out is made.

On trials where drivers failed to report an oncoming vehicle, our results show that there were frequent occasions where the vehicle had been fixated. Previous theories regarding attention and awareness have suggested that awareness will occur when a sufficient amount of attention is allocated to an object, therefore a longer fixation, from which we are inferring more attention, would increase the likelihood that the object will be consciously perceived [9]. If this were the case, it would have been expected that more frequent and longer fixations would be associated with reported, as opposed to unreported objects. We do not find significant evidence for this, with no large differences in the number of, or length of fixations on reported and unreported vehicles.

Of course, the fact that an object has been fixated does not guarantee that it has been encoded, change blindness and inattentional blindness experiments have demonstrated that looking at an item is not always associated with awareness [9, 10]. Participants in such experiments have frequently been shown to fail to report clearly visible objects, even on occasions when the object has been fixated. In many classic inattentional blindness experiments [36, 37], the procedure requires observers to report an unexpected, or unattended object, with the primary task being unrelated to the detection of the stimulus. The miss rates for the target item in previous paradigms has been seen to be as high as 83%[33] and is modulated by the degree of match between the task and the items of interest [38]. However, in the current studies, the detection of approaching vehicles at the junction is the primary task for the driver, and we would therefore expect this information to be prioritised as it is critical for a safe manoeuvre.

More specifically, studies that have investigated the existence of inattentional blindness in a driving context have found that gaze durations on objects determine drivers' ability to perceive hazards, demonstrating that eye movement dynamics can provide a measure of a driver's hazard perception and prediction [39]. This was supported by research which investigated which eye movement measure best predicted whether a participant accurately reports an error in their own eye movements. Using a classic oculomotor capture paradigm, which encourages people to look at sudden irrelevant onsets of stimuli, it was found that longer fixation durations were associated with awareness of the error, suggesting that participants were aware of this object once it had been fixated sufficiently [22].

While the explanation of a failure in visual attention may account for at least some report failures, we must also consider the possibility that some of these errors may occur due to a failure in visual working memory. For the current findings, this explanation is particularly compelling as the results suggest that it is drivers' subsequent behaviour which predicts their ability to report vehicles [16]. For this interpretation, information held in visual working memory may be subject to interference by subsequent visual information. Head movements in this situation will provide a large quantity of new visual information to process and retain, and there is limited reason to believe that subsequent visual behaviour after fixating on the vehicle would predict earlier attentional errors.

One might argue that if the driver had failed to encode a vehicle, and was generally expecting two vehicles in the critical memory trials, this may influence their subsequent head and eye movements when scanning the junction. If the driver had initially failed to encode a motorcycle and was expecting two vehicles then they might make additional head movements to the other side of the junction or make subsequent fixations elsewhere in the visual scene to look for another vehicle before pulling out. However, in our studies, a typical pattern of head movements involved a driver making a head movement towards a motorcyclist, a head movement to the car coming from the other direction, and a final one on the road ahead before pulling out. Inattentional blindness studies have found that the expectancy of the number of targets reduces the occurrence of miss rates in everyday tasks, as participants continue to search the scene until they have found the expected number of items [40].

The influence of traffic controls and traffic flow were not considered in the current series of studies. The current studies used a controlled intersection, with a Stop sign. Intersection crashes have been seen to be prevalent at 'uncontrolled' intersections [41]. Consistent with this, a previous study conducted in the same simulator has found that drivers tend to direct more attention to the side of the junction of the oncoming vehicle when there is a 'stop sign' compared to a 'give way sign' [26]. We would expect, therefore, more memory errors at uncontrolled intersections, however this is a topic for future research. In regards to traffic flow, previous research has investigated drivers' memory for between three and eight vehicles, looking at changes in working memory load [19]. It was found that the percentage of vehicles recalled decreased with increases in memory load, with drivers on average, recalling five vehicles when there were eight vehicles present. This suggests that future work should manipulate environmental complexity, looking the links between visual scene complexity, working memory capacity and drivers' memory for vehicles.

An additional concern with the unreported vehicles in the current studies could be that these vehicles were far away at the time of fixation and thus more likely to be unprocessed. Studies 2 and 3 were designed to ensure vehicles were presented at distances close to the gap acceptance threshold. We found that failures in reporting approaching vehicles were not related to the thresholds of individual drivers, indicating that it was not the case that unreported motorcycles were generally travelling from a further distance from the junction.

While it has been previously mentioned that studies have found drivers' memories for their current environments to be relatively poor [19–21], explicit memory tests (where drivers are asked to recall vehicles and their locations) have been seen to not dramatically change participants' situational awareness [42], particularly when they are actively in control of the driving task and experiencing visual-motor interactions (as here) [43]. Previous research has also found that people prefer to maintain a consistent perspective when describing spatial properties from memory [44–47]. With this in mind, our studies provide a significant advance on previous research. Firstly, our study immerses the driver in a realistic driving scenario, and finds a case where memory may nonetheless be relatively poor. Secondly, unlike previous studies our memory test was presented from the drivers' perspective. Finally, our memory task was fully embedded, and infrequently and unpredictably presented, within a driving task. These differences make failures of memory in the current task even more surprising and encourage us to believe that they may have important implications in real driving.

These studies demonstrate that even in safety critical situations it may be possible to observe dramatic failures of visual memory–failures that could be responsible for crashes in the real world. One of the biggest challenges in this research was that such memory errors were rare—the majority of participants never made any memory errors at all. However, we were nonetheless able to observe such errors in 27 separate drivers even when they were about to pull out in front of the oncoming vehicles in Studies 2 and 3. Around 2/3 of the occasions on which these drivers pulled out in front of a vehicle that they would not subsequently remember were associated with seemingly adequate visual search. The occasional nature of such "Saw but Forgot" memory failures may be exactly why these right of way junction crashes on real roads often appear so mysterious.

Traditional models [7] which have been developed to understand LBFTS errors have problems accounting for the genuine surprise frequently experienced by motorists when they have a collision of this type [7]. To help us understand how drivers could have forgotten an oncoming vehicle that they had already looked at, we have developed a new model of dynamic risky decision making in which the role of short-term memory is emphasised. The model, the Perceive, Retain, Choose (PRC) model, expands on those previously used to provide a much more explicit series of cognitive processing steps that may be involved in the decision to pull out at a junction or make other risky dynamic decisions (Fig 4).

As can be seen from Fig 4, we propose five potential pathways for relevant information to be used in the decision to pull out at a junction. Pathway 1 is the traditional account in which we look at the scene, encode the visuo-spatial information in it, and use this directly to decide whether it is safe to pull out. There are some situations where this information is all that is required, however, more commonly it will be necessary to combine visual information from one head movement with that acquired from later head movements. Pathway 2 thus involves the retention of information from the first head movement in visuo-spatial working memory. We assume that such information is retained in a limited capacity store and is available to a central processor at the same time as new information is being acquired. Clearly anything that interferes with the retention of such information will allow people to make accidental unsafe decisions. It is worth noting here that a common pattern of head movements in our studies involves a head movement towards a motorcyclist, then one to a car coming from the other direction, and a final one on the road ahead before pulling out. This raises the possibility that information from the second or third head movement has overwritten the initial contents of visuospatial memory, and that these were no longer available at the time a decision to pull out was made.

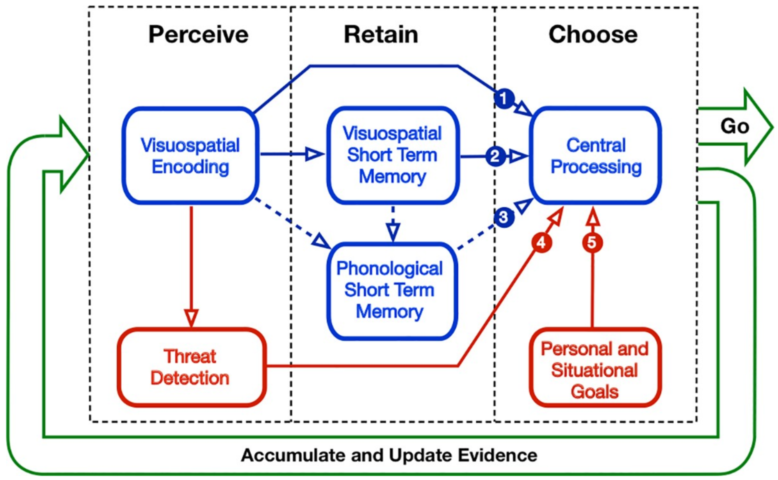

Fig 4. The Perceive, Retain, Choose (PRC) model has been developed as a new model of dynamic risky decision making. The role of short-term memory is explicitly emphasised, with possible processing pathways which inform a driver's decision about when to pull out of a junction or make other risky dynamic decisions.

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The PRC model has deliberate similarities to the predominant cognitive model of short-term memory–Alan Baddeley's working memory model [48]. This is important as it stresses that other memory systems are potentially available. The phonological loop is a critical part of working memory theory, and suggests a simple strategy that people may be able to use in order to overcome the limited capacity of short term visuo-spatial memory. If relevant visual information is encoded phonologically, it has been shown that it is no longer subject to visuospatial interference [23]. This may be an opportunity that is underused in normal driving. In fact, people have repeatedly been shown to be unaware of the limitations in visuospatial memory [23,49], and previous research has already noted that phonological and visuospatial information may be handled differently in such situations [50]. A simple intervention that may thus prove effective to overcome interference could be teaching people that if they see a motorcycle coming, they should verbally (even sub-vocally) [51] note the fact–"See bike, say bike". This would be represented by pathway 3 in Fig 4 and could clearly be combined with information from the earlier two pathways.

A more recent addition to Baddeley's working memory model is the hedonic detector [52]. In the working memory model this accounts for the preferential processing of emotional information, and in the PRC model, we have included a threat detector to perform a related function. There are a number of sources of data to suggest that threatening information may be preferentially processed in this context[8]. Our finding that motorcyclists were systematically remembered as being further away than cars, and previous findings related to safety margin differences as a function of vehicle type [11] could all relate to the concept of threat. It is easy to understand why a visceral response to a threat may dominate any other cognitive processing [53] and pathway 4 allows for such information to have direct access to decision making. For completeness, we have also included the role of personal and situational goals in the decision. Pathway 5 allows us to understand the way in which risky decisions may differ between individuals and situations. A simple example of this is that after waiting for some time at a busy junction a driver may accept a gap size that he or she had previously rejected [54], and inter-individual variation is the motivation for the individually determined threshold procedure we have used in the current studies and elsewhere[11]. The PRC model is not inconsistent with the traditional account of junction crashes involving LBFTS errors, which can be represented as failures of processing leading to dangerous decisions through Pathway 1, however, it highlights a number of additional possibilities that may provide a fruitful focus for future research and practical interventions.

Conclusions

The current studies explored drivers' systematic biases in their memory for, perceived location of, and attention towards different vehicle types approaching an intersection in a driving simulator. Throughout this series of studies, a methodology was developed which allowed for these measures to be taken on occasions where drivers were willing to complete a manoeuvre in front of the approaching vehicles, and determine whether drivers had fixated on vehicles before subsequently failing to recall them. The most striking finding was that drivers completely failed to report some vehicles approaching the junction, particularly motorcycles, with these occasions not associated with how long the driver fixated on the vehicle for, but associated with drivers' subsequent visual search between fixating on the oncoming vehicle and pulling out of the junction. Our results suggest that some junction crashes in which a driver reports being careful and attentive in their visual checks but nonetheless pulls out in front of an oncoming motorcycle, could be misclassified. While previous researchers suggest that this crash is associated with a failure in drivers' visual search for motorcycles–"Look But Fail To See", the current results highlight the possibility that at least some of these crashes could occur due to a memory deficit—a 'Saw but Forgot' error. These innovative and novel findings, along with the PRC model, can provide a basis for new practical interventions that may prevent SBF crashes from occurring.

Supporting information

S1 Table. A correlation of experience and the key behavioural and eye movement measures in Study 1.
(PDF)

S2 Table. Descriptive statistics for the Memory Test Group and Drive Only Group Comparison in Study 1.
(PDF)

S3 Table. Descriptive statistics for all behavioural and eye movement measures in Study 2.
(PDF)

S4 Table. Eye movement raw data from the 11 participants who failed to recall a motorcycle in Study 3.
(PDF)

S1 File. Additional statistical analysis for the factors of Vehicle Distance and Vehicle Type for the Memory Test Group and Drive Only Group comparison in Study 1.
(PDF)

S2 File. Study 3, between subject comparison.
(PDF)

S3 File. Eye movements and subsequent visual search behaviour on the unreported cars in Study 3.
(PDF)

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Supporting Information

S1 Table. A correlation of experience and the key behavioural and eye movement measures in Study 1.

Correlations (n=60)		Months held licence	Annual Mileage
Mean Fixation Duration (ms)	Pearson Correlation	0.108	-0.052
	Sig.	0.413	0.694
Proportion of Fixations	Pearson Correlation	0.244	-0.052
	Sig.	0.06	0.693
Proportion of Gaze	Pearson Correlation	0.241	0.011
	Sig.	0.064	0.931
Approach Time (s)	Pearson Correlation	-0.156	-0.139
	Sig.	0.233	0.29
Cross Time (s)	Pearson Correlation	-0.083	-0.103
	Sig.	0.527	0.435
Number of Stops	Pearson Correlation	0.029	-0.122
	Sig.	0.824	0.355
Wait Time (s)	Pearson Correlation	0.121	-0.008
	Sig.	0.356	0.954

S2 Table. Descriptive statistics for the Memory Test Group and Drive Only Group comparison in Study 1.

Measure	Condition	Mean	*SE*
Behavioural Measures			
Approach Time (s)	Memory	13.32	.35
	Drive Only	13.79	.35
Number of Stops	Memory	0.49	.07
	Drive Only	0.73	.07
Wait Time (s)	Memory	2.09	.31
	Drive Only	2.72	.31
Cross Time (s)	Memory	3.41	.14
	Drive Only	3.32	.14
Eye Tracking Measures			
Mean Fixation Duration (ms)	Memory	389.68*	32.69
	Drive Only	251.65*	32.69
Proportion of Fixations	Memory	.58	.03
	Drive Only	.51	.03
Proportion of Gaze	Memory	.59	.03
	Drive Only	.52	.03

S3 Table. Descriptive statistics for all behavioural and eye movement measures in Study 2.

Measure	Approaching Vehicles	Mean	*SE*
Behavioural Measures			
Thresholds (m)	Car	84.11	2.63
	Motorcycle	85.74	2.42
Estimation of Locations (degrees)	Car	21.08*	2.05
	Motorcycle	16.52*	2.10
Eye Tracking Measures			
Proportion of Fixations	Unreported Motorcycle	.25	.13
	Reported Motorcycle	.45	.17
Proportion of Gaze	Unreported Motorcycle	.46	.15
	Reported Motorcycle	.70	.16
Mean Fixation Duration (ms)	Unreported Motorcycle	63.76	43.12
	Reported Motorcycle	228.57	87.57

S4 Table. Eye movement raw data from the 11 participants who failed to recall a motorcycle in Study 3.

				Reported Motorcycle			Reported Motorcycle		
	Unreported Motorcycle			Within-Group Comparison			Between Group Comparison		
Occasion	**N of fix**	**Gaze (ms)**	**MFD (ms)**	**N of fix**	**Gaze (ms)**	**MFD (ms)**	**N of fix**	**Gaze (ms)**	**MFD (ms)**
1	2	180	90	1	60	60	2	360	180
2	1	300	300	2	120	60	2	220	110
3	1	80	80	1	80	80	1	120	120
4	1	180	180	1	360	360	2	680	340
5	1	240	240	2	120	60	2	640	320
6	1	180	180	2	600	300	1	180	180
7	1	480	480	1	120	120	1	100	100
8	1	120	120	1	80	80	1	300	300
9	1	560	560	1	200	200	1	220	220
10	1	140	140	1	300	300	1	100	100
11	1	260	260	2	400	200	1	60	60
Mean	**1.09**	**247.27**	**239.09**	**1.36**	**221.82**	**165.45**	**1.36**	**270.91**	**184.55**

S1 File. Additional statistical analysis for the factors of Vehicle Distance and Vehicle Type for the Memory Test Group and Drive Only Group comparison in Study 1.

Drivers' Behaviour

Although it was technically possible to cross the junction in front of approaching vehicles, participants generally chose to wait for the oncoming vehicles to pass before crossing the junction so our analyses focus on the dynamics of approaching the junction, stopping at it, and then crossing. In regards to drivers' Approach Time, a main effect of Vehicle Distance was found (F (1.38, 80.02) = 43.29, MSe=12.58, *p*<.001), with contrasts revealing a linear trend (F (1, 58) = 85.13, MSe=2.94, *p*<.001). Drivers spend the shortest time in the approach zone when vehicles were at a near distance (6.4s), more time at a medium distance (8.0s) and the most time at a far distance (9.4s). There was no main effect of Vehicle Type [F (2, 116) = .99, MSe=3.70, *p*=.37].

In regards to the Number of Stops drivers made at the junction, a main effect of Vehicle Distance was found, (F (2, 116) = 17.37, MSe=.27, *p*<.001) with contrasts revealing a linear trend (F (1, 29) = 40.68, MSe=.08, *p*<.001). Drivers stopped more often when vehicles were approaching from a far distance, then a medium distance and then a near distance. There was no main effect of Vehicle Type [F (2, 116) = 2.43, MSe=.13, *p*=.10].

For drivers' Wait Time at the junction, a main effect of Vehicle Distance was found (F (1.58, 91.71) = 51.41, MSe=6.26, *p*<.001), with contrasts revealing a linear trend (F (1, 58) = 114.62, MSe=1.47, *p*<.001). Drivers stopped more often when vehicles were approaching from a far distance, then a medium distance and then a near distance. There was no main effect of Vehicle Type [F (1.86, 107.97) = .80, MSe=3.39, *p*=.45].

Finally, in regards to Cross Time, there was no main effect of Vehicle Distance [F (1.20, 69.78) = .96, MSe=1.43, *p*=.39] and no main effect of Vehicle Type [F (1.24, 71.72) = 2.31, MSe= 1.20, p=.10].

Drivers' Eye Movements

In regards to drivers' Mean Fixation Durations, there was a main effect of Vehicle Type (F (2, 116) = 12.15, MSe=54565.66, *p*<.001), with a significant contrast for motorcycles vs. cars and large vehicles: F (1, 58) = 6.33, MSe=508284.776, *p*<. 05). Drivers had lower mean fixation durations to the side of the junction when a motorcycle was present compared to a car or large vehicle. There was no main effect of Vehicle Distance [F (2, 116) = 2.44, MSe=55.484.38, *p*=.06].

In regards to Proportion of Fixations, there was no main effect of Vehicle Type [F (2, 116) =2.30, MSe=.06, *p*=.11] and no main effect of Vehicle Distance [F (2, 116) =.19, MSe=.08, *p*=.83]. For Proportion of Gaze, there was also no main effect of Vehicle Type [F (2, 116) = 3.00, MSe=.07, *p*=.06) and no main effect of Vehicle Distance [F (2, 116) = .33, MSe=.08, *p*=.72].

S2 File. Study 3, between subject comparison.

Eye movement measures were compared between the trials where the motorcycle was not reported and matched trials where another participant reported the motorcycle. Another 11 participants who reported the motorcycle on the right-hand side of the junction were matched on the basis of combined gap acceptance thresholds.

Again, it was found that there was no difference in the number of fixations [t (20) = 1.54, p=.14], total gaze duration [t (20) = .30, p=.77] and mean fixation durations [t (20) = .98, p=.34] on unreported and reported approaching motorcycles. See s6 for the full eye movement descriptive statistics for the 11 participants who failed to recall a motorcycle, their reported within group comparison, and the reported between subject comparison.

S3 File. Eye movements and subsequent visual search behaviour on the unreported cars in Study 3.

Out of the 3 occasions were drivers failed to recall a car, on 1 of these occasions the driver fixated on the approaching car however, on 2 of the occasions the driver did not fixate on the approaching car.
Eye movement measures were compared between the trials where the driver failed to report and successfully reported the car. The number of fixations on the oncoming car was identical for the unreported trial and reported trial, with 1 fixation. The total gaze duration on the unreported trial was 264ms and on the reported trial was 260ms.

In terms of the subsequent eye movements, the driver made 2 subsequent fixations on the unreported and reported trial, made 1 subsequent head movement on the unreported and reported trial however, the time of the last fixation on the car before pulling out of the junction was earlier for the unreported car (1900 ms) compared to the reported car (1460 ms). Further investigations are needed to confirm whether the differences in eye movements between the unreported and reported motorcycles (see main article) are specific to motorcycles.

Paper 6

Comparing Drivers' Visual Attention at Junctions in Real and Simulated Environments

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Comparing drivers' visual attention at Junctions in Real and Simulated Environments

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ABSTRACT

Driving simulation is widely used to answer important applied research questions, however, it is vital for specific driving tasks to undergo appropriate behavioural validation testing. Many previous validation studies have used simple driving tasks and measured relatively low-level vehicle control. The purpose of the current study was to investigate whether drivers' visual attention at intersections with different levels of demand, are similar in the simulator and on the road. Unlike simpler driving tasks, crossing intersections requires complex interactions with other vehicles governed by sequences of head and eye movements that may not be accurately captured in a simulated environment.

In the current study we directly compare performance at simulated junctions with the same participants' behaviour in a real car. We compared drivers' visual attention in a high-fidelity driving simulator (instrumented car, 360-degree screen) and on-road in both low and medium demand driving situations. The low and medium demand driving situations involved the same motor movements, containing straight on, right turn and left turn manoeuvres. The low demand situations were controlled by the road environment and traffic lights, whereas medium demand situations required the driver to scan the environment and decide when it was safe to pull out into the junction. Natural junctions in Nottingham were used for the on-road phase and the same junctions were recreated in the simulator with traffic levels matched to those that were encountered on the real roads.

The frequency and size of drivers' head movements were not significantly different between manoeuvres performed in the simulator and those conducted when driving on real roads. This suggests that drivers' broad search strategies in the simulator are representative of real-world driving. These strategies did change as a function of task demand - compared to low demand situations, behaviour at the medium demand junctions was characterised by longer junction crossing times, more head movements, shorter fixation durations and larger saccadic amplitudes. Although patterns of head movements were equivalent on road and in the simulator, there were differences in more fine-grained measures of eye-movements. Mean fixation durations were longer in the simulator compared to on-road, particularly in low-demand situations. We interpret this as evidence for lower levels of visual engagement with the simulated environment compared to the real world, at least when the task demands are low. These results have important implications for driving research. They suggest that high fidelity driving simulators can be useful tools for investigating drivers' visual attention at junctions, particularly when the driving task is of at least moderate demand.

1. Introduction

In driving research, there are two major outcomes which both researchers and policy makers are interested in, driver safety and driver performance. Drivers' safety is concerned with collision involvement statistics, with safety measures aimed at reducing the total number of crashes. On the other hand, many experimental studies are concerned with measuring drivers' performance, with a greater interest in understanding the aspects of driver behaviour that might underlie the crash statistics. Experiments conducted in simulated driving environments provide the basis of much of the relevant driving related performance research (Underwood et al., 2011).

1.1. Advantages of driving simulators

The use of an advanced driving simulator to investigate drivers' performance has many advantages over other off-road evaluations which are often used to assess driving related skills (De Winter et al.,

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2012), as well as broadening the scope for potential research questions due to minimising many ethical concerns and practical issues associated with on-road testing. Firstly, a driving simulator provides a vehicle control element, requiring drivers to manually control the car while performing other tasks. Without this vehicle control element, it could be argued that the driver may have additional cognitive resources available, possibly encouraging unrealistic assumptions about the efficiency of the drivers' behaviour and visual attention (Robbins et al., 2018a). Secondly, one of the primary advantages of driving simulators is the possibility of encountering potentially dangerous driving situations without being physically at risk (De Winter et al., 2012). Simulators make it possible to study areas such as hazard anticipation, hazard perception and risky driving, which are ethically challenging to address in on-road studies (Underwood et al., 2011). Finally, simulators also offer a high degree of stimulus control, with the opportunity to manipulate the type, direction and speed of vehicles (Reed and Green, 1999). Scenarios can be repeated in a trial by trial format, which can be a very efficient way to measure a driver's behaviour in a very specific high-risk situation. Driving simulators are therefore becoming increasingly attractive for this purpose.

However, there are some possible disadvantages to driving simulators including simulator sickness and most importantly, validity (Godley et al., 2002). The ability of a driving simulation to accurately represent the visual complexity and conditions common in on-road driving situations is therefore critical in order for the findings found in simulation research to be generalised to on-road driving. It is thus important that driving situations in the simulator undergo appropriate validation testing.

1.2. Types of validity

When investigating the validity of a driving simulator, Blaauw (1982) distinguished between two types of simulator validity, physical and behavioural validity. Physical validity refers to the level of correspondence between the physical layout, configuration of the driver cabin, and the vehicle dynamics of the simulator relative to a real-world counterpart. Therefore, the closer a simulator is to on-road driving in the way the vehicle is driven, the presentation of the stimuli, and the way it physically reacts to stimuli, the greater the fidelity of the simulator (Triggs, 1996). However, it should be remembered that, ultimately, the level of physical validity is meaningless if behavioural validity cannot be established (Godley et al., 2002).

Behavioural validity refers to how close the driving behaviour elicited in the simulator is to that observed on real roads (Reymond, 2000), and is arguably the most important form of validity when it comes to the evaluation of a specific driving task. Blaauw (1982) has argued that the 'gold standard' approach for undertaking behavioural validation is to compare drivers' behaviour in the simulator and on the real roads, by replicating the real-word road geometrics in the two environments (Reimer et al., 2006).

Where behavioural validity is achieved, it can be of one of two levels - absolute validity or relative validity. Absolute validity is demonstrated by the results in the simulated environment being close to the exact size of the effects by results on real roads, whereas relative validity is demonstrated if the trend or direction of any effect is equivalent in the simulator and real roads (Kaptein et al., 1996).

Given that advanced driving simulators are developed independently of each other, simulator validity is dependent on the particular simulator of interest (Hoskins and El-Gindy, 2006), as driving simulators have different parameters such as the size and quality of the visual display, and the time delay between action and simulator response (Godley et al., 2002). Moreover, different driving tasks can also have different levels of validity (Hoskins and El-Gindy, 2006), with a validation study of an individual simulator using a specific driving task not being adequate to demonstrate the validity of that simulator on a different task.

That said, the accumulation of simulator validation studies in range of driving tasks, does expand the validity of simulator research. Many previous simulation studies have examined a single driving behaviour such as speed regulation or lane deviation (e.g. Blaauw, 1982), while other validation studies have compared specific groups of drivers such as novice and experienced drivers (e.g. Underwood et al., 2011), as well as older drivers (e.g. Lee, 2003; Lee et al., 2003). These studies concluded that a driving simulator is a valid tool to study longitudinal behaviour measures such as speed choice and lane deviation, with findings showing absolute validity for speed and relative validity for lateral control when driving a straight road (Blaauw, 1982), as well as differences in drivers' visual attention as a function of driving experience being seen in both simulation and real environments (Underwood et al., 2011).

Despite the above findings, the number of published driving simulator validation studies are quite limited, particularly in terms of the variety of driving tasks and measures being explored (Godley et al., 2002). There is no doubt that speed and lane variability are important measures when validating a driving simulator, but they measure relatively low-level vehicle control, rather than higher level cognitive measures such as drivers' situational awareness in specific situations associated with higher levels of visual search (Underwood et al., 2011). The current study is therefore focussed on investigating drivers' visual search at intersections, as this is one of the most researched driving situations, with junction safety being a major problem worldwide (Robbins et al., 2018a).

1.3. Validation of intersection behaviour

Right of way (ROW) crashes are the most common crash type to occur at intersections in the UK, when one road user, usually a car driver, pulls out into the path of an oncoming vehicle on a main carriageway (Clarke et al., 2007). Clarke et al. (2004) found that in over 65% of ROW crashes, these were typical 'look but fail to see' (LBFTS) instances with the driver generally reporting being careful and attentive with their visual checks, but nonetheless failing to see an oncoming road user (Brown, 2002). The majority of research investigating ROW accidents have reported that such crashes are more likely to be considered as the driver's fault, as they are violating the oncoming vehicle's ROW (Clarke et al., 2004; Robbins et al., 2018b).

Due to this, many research studies have turned their efforts to investigating drivers' visual attention at junctions (Pai, 2011; Crundall et al., 2008; Crundall at al., 2012b; Lee et al., 2015; Robbins and Chapman, 2018), with typical interpretations of the LBFTS crash suggesting that the driver pulling out of the junction has failed to devote sufficient attention to the traffic on the road which they are entering. This results in either a failure to spot an oncoming vehicle at all or not looking for long enough at it, leading to a misjudgement of its speed or distance (Horswill et al., 2005). While many previous studies have used videos of junctions to investigate drivers' visual attention towards oncoming vehicles (Crundall et al., 2008; Underwood et al., 2011; Crundall et al., 2012b; Lee et al., 2015), recent research has been investigating drivers' visual attention towards oncoming vehicles at intersections using interactive simulation environments (Cavallo et al., 2015; Robbins and Chapman, 2018).

Despite the wealth of research investigating intersection crashes, very few validation studies have explored behaviours as complex as drivers' visual attention at intersections (Laya, 1992; Shechtman et al., 2009), with this behaviour requiring drivers to retain task relevant information while simultaneously directing attention to new information in the environment. One of the few validation studies of drivers' behaviour at intersections in the US (Shechtman et al., 2009) compared drivers' errors in a high-fidelity driving simulator (180-degree field of view) and on-road when completing a series of manoeuvres (right and left turns) at suburban and urban junctions. The study used the same participants in the simulator and on real roads, and replicated the geometric design of the real roads in the simulator. Driving errors were recorded by trained driving evaluators who sat in the passenger seat of the car while the participants were driving, using a standardised performance sheet which was specifically designed for capturing errors while performing intersection manoeuvres. The error categories included vehicle position, lane maintenance, speed regulation, signalling and visual scanning. The visual scanning errors consisted of not checking the blind spot, not using the rear-view or side mirrors during lane changes, and not looking left/right before proceeding through an intersection. It was found that there was no main effect of driving environment for lane maintenance errors and visual scanning errors, and the authors conclude that the simulation had absolute validity for these types of errors. For vehicle positioning, signalling, and speed regulation, drivers committed more errors on the road than in the simulator, indicating that absolute validity does not exist for these types of errors.

However, it must be noted that although it was concluded that visual scanning errors demonstrated absolute validity, no visual scanning errors were committed by any of the participants, therefore a statistical analysis was not possible (Shechtman et al., 2009). This suggests that the visual scanning errors chosen in this study may have been too safety critical for the choice of task, as it is hard to imagine a driver passing through a junction without looking left and right for oncoming traffic. This suggests that future research studies should use more detailed parametric measures to investigate whether drivers' visual search strategies at junctions in the simulator are representative on real world driving. In addition, it should also be noted that the junctions used in this study were demanding driving situations, located in both suburban and urban environments which required participants to complete a manoeuvre at the intersection when they believed it to be safe (Shechtman et al., 2007). Given our current knowledge of the effects of driving demand on drivers' visual attention, these findings could also be extended to investigate the extent to which the demand of the driving situation affects drivers' visual attention in simulated and real road environments.

1.4. Effect of driving demand on visual search

Previous video clip and simulator studies have investigated the effect of driving demand on a range of drivers' visual attention measures (Chapman and Underwood, 1998a, 1998b; Underwood et al., 2002; Konstantopoulos et al., 2010). The typical findings from these simulator studies are that drivers' mean fixation durations tend to be relatively long in low demand (rural) and high demand (urban) road situations but are shorter in medium demand tasks (suburban). The opposite result has been seen for measures such as the variance of fixations along the horizontal axis and mean saccade amplitudes, with a narrower spread of search in low and high demand driving situations, but higher in medium demand situations (Chapman and Underwood, 1998a, 1998b). These differences in demand are extremely important when we come to consider the potential limitations for simulated and on-road research. What seems to be happening here is that in low demand situations drivers may produce long fixations on the focus of expansion or single vehicles or objects, because of the absence of other relevant stimuli to capture attention. Medium levels of demand require a more balanced search of the environment featuring a wide spread of search and medium fixation durations on a wide array of driving-related information. In contrast, research involving high demands has involved videos of risky situations (e.g. hazard perception tests). Visual search in such situations is characterised by a degree of attention focussing, with long fixations on key hazards and an associated narrowing of search (Chapman and Underwood, 1998a). These changes in drivers’ eye movements as a function of demand have also been shown on the road (Underwood et al., 2011; Engström et al., 2005).

Although previous studies have manipulated the demand of the driving situation to investigate its effect on drivers' visual attention, very few studies have investigated the effect of demand when comparing driver's behaviour in a driving simulator and on-road. Given that driving simulators are thought to yield sensory deprivation relative to the real world, with driving simulation scenery being quite repetitive, while the real world contains diverse contextual stimuli (Thiffault and Bergeron, 2003), it is possible that different driving demands could lead to differences in validity. For example, in low demand driving situations drivers will have free resources available to search for, and focus on visually engaging details anywhere in a real environment. If these details are not present in the simulated environment this may lead to overall differences in behaviour between the two environments. However, when the driving demand is increased, it is likely that the driving simulation environment has all the necessary visual information for the core driving task, and therefore differences between behaviour in the two environments may be reduced.

There has been no previous research which has investigated the effect of demand in the simulator and on-road to test the deprivation of the simulator environment, except a pilot study from our lab (Foy, 2017). This study used a high-fidelity driving simulator and on-road instrumented vehicle to compare drivers' visual attention on the road and in the simulator during everyday driving. Both the simulated and on-road drives included different road types that have been found to elicit different levels of workload (Foy and Chapman, 2018). A clear preliminary finding from this study was that drivers had much longer mean fixation durations and a reduced spread of search on the road compared to in the simulator. It is possible that the differences in drivers’ mean fixation durations between the two environments was due to drivers extracting more information from their fixations in the real world, since these could contain more information or detail than the simulation. It was also found that there was a significant increase in fixation duration on-road compared to in the simulator for dual carriageway and A-road situations (low demand situations as rated by participants in Foy and Chapman, 2018), but not for city centre and suburban routes, suggesting that there are larger differences for lower demand situations compared to higher demand situations between the two environments. One limitation with the Foy (2017) study was that a continuous drive was used making it impossible to match the exact traffic levels at each location between the two environments. To reduce the danger of simulator sickness, Foy (2017) did not focus on turns at intersections and made no attempt to balance the number or direction of intersection turns that were made.

1.5. The current study

The current study will systematically compare drivers' visual attention at intersections, in a simulated environment and on real (UK) roads, including junction scenarios which vary in task demand. Since the study was conducted in the UK, both real and simulated driving is done on the left-hand side of the road, with oncoming traffic on the right. This study is also one of the only studies to measure the validity of the University of Nottingham's Integrated Transport and Environmental Simulation (NITES) facility's high-fidelity driving simulator, expanding on the preliminary findings of Foy (2017), in a junction setting. This facility allows for the road geometrics in the simulator and on-road to be matched, and drivers' eye movements to be measured in detail using the same head-mounted eye tracker to record eye movements in the two environments. Because of the practical and ethical impossibility of having our participants deliberately encounter serious dangers in real driving conditions, we have focussed on comparing low demand driving situations with those of medium demand. Drivers' visual attention was thus measured at six junctions where their manoeuvre was controlled by the driver (medium demand) and in six similar road situations where the traffic was controlled by traffic signals and the road environment (low demand), but with equivalent motor behaviour.

1.6. Hypotheses

The current study was preregistered with Open Science Framework. The preregistration can be found here: Robbins et al., (2018, March 21). Comparing Drivers' Visual Attention at Junctions in Real and Simulated Environments. Retrieved from osf.io/feuhx

Three main visual attention dependent variables were pre-registered: mean fixation durations, mean saccade amplitude, and the number of head movements per minute. These general visual attention measures were chosen as we felt they would be relatively insensitive to small differences in the exact behaviour of other traffic between the road and simulator environment. Mean fixation durations measure how long drivers direct attention to individual parts of the visual scene, and mean saccade amplitudes and head movements measure drivers' visual search. Mean saccade amplitudes are a direct measure the spread of search between successive fixations, whereas head movements are an indication of more broad search strategies.

It was expected that fixation durations would be longer in low demand situations than medium demand situations, that saccade amplitudes would be narrower in lower demand situations than medium demand situations and head movements would be fewer in low, compared to medium demand situations.

To investigate simulator validity, we predicted an interaction of Driving Environment and Driving Demand such that driver performance would be more similar in the medium demand situations than the low demand situations. Specifically, it was predicted that drivers' mean fixation durations in the low demand driving situations would be longer in the real world compared to the simulator but that differences would be reduced for the medium demand situations. For mean saccade amplitude, it was predicted that in the low demand situations, saccade amplitude will be shorter in the real world compared to in the simulator however, there will be less difference between the simulator and the real world in the medium demand situations. Finally, in regards to the number of head movements per minute, it was predicted that in the low demand situations, drivers will perform more head movements in the real world compared to the simulator however, there will be less difference in the simulator and the real world in the medium demand situations.

Exploratory analyses were subsequently conducted to investigate whether the manoeuvre direction i.e. right turn, left turn or straight on manoeuvre, showed any differences in drivers' visual search strategies in the two driving environments. Previous research has investigated drivers' visual attention at junctions with differing manoeuvre demands (Hancock et al., 1990; Laya, 1992; Shinohara and Nishizaki, 2017), with results indicating that drivers display more head movements and shorter mean fixation durations during right turns compared to left and straight on manoeuvres. Given that right turns are seen in the majority of crashes at UK intersections (Clarke et al., 2007), and the current task also takes place with right-hand side oncoming traffic, these findings are intriguing, and therefore have the potential to be extended to investigate whether particular junction simulation tasks are more comparable to real world driving than others. Thus, to extend our understanding of demand and validity, the exploratory analysis looked at the effect of Manoeuvre Direction on drivers' mean fixation durations, mean saccade amplitude and the number of head movements per minute.

Exploratory analysis was also conducted on the Magnitude of Head Movements and Total Driving Time. Magnitude of Head Movements was calculated in order to categorise and analyse drivers' head movements more closely. Given that the road section of interest is a junction, this requires a variety of head movements including predictive head movements made to wide eccentricities to check for oncoming traffic and smaller/reactive head movements to make closer checks (Stern and Ranney, 1999). Total Driving Time was calculated in order check for any obvious differences in overall driving behaviour between the two driving environments.

2. Methods

2.1. Participants

A power analysis was conducted in G*Power (Faul et al., 2007) to determine the number of participants for a 2 × 2 repeated measures ANOVA. Previous preliminary data by Foy (2017) found a very large effect between drivers' eye movements in the simulator and on-road ($f = 0.59$) therefore the current study was designed to detect at least the standardised large effect size ($f = 0.4$). This power analysis indicated that a sample size of 15 was needed to detect a large effect size ($1\text{-}\beta = 0.80$, $p = .05$). Data were thus collected from 15 participants (Mean age = 28.0 years, SD = 6.14, Range = 19–42 years; Male = 8, Female = 7) who were all staff or students at the University of Nottingham. Drivers had held a driving licence for between 16 and 300 months (Mean = 113 months). They had a reported annual mileage between 50 and 15000 miles (Mean = 7403 miles) and a total mileage between 150 and 250000 miles (Mean = 69495 miles). All participants received a £10 inconvenience allowance for their time.

Drivers' self-reported aggressive violations (m = 1.56), ordinary violations (m = 1.91), errors (m = 1.53) and lapses (m = 2.25) on the 27 item 'Extended Driver Behaviour Questionnaire' (Lajunen, Parker & Summala, 2004) were typical of previous research which has sampled both driving instructors and students (Lajunen & Summala, 2003- aggressive violations (m = 1.48)), ordinary violations (m = 1.89), errors (m = 1.66) and lapses (m = 1.97).

2.2. Design

A 2 × 2 repeated measures design formed the core of the study, with factors of Driving Environment (simulator vs. on-road) and Driving Demand (low vs. medium). All participants drove in both environments, completing both the low and medium demand driving situations.

Eight of the participants completed the simulator drive first and seven of the participants completed the on-road drive first. These two drives were completed on separate days. Within each drive all participants completed the driving situations in a fixed order, which was determined by the constraints of the on-road route. Drivers completed the low demand driving situations first, which consisted of situations that were controlled by traffic lights and the road environment, with the road environment only making it possible to manoeuvre in a certain direction. These six low demand situations were completed in a fixed order, with situations differing in manoeuvre direction: straight on, right turn, left turn, straight on, right turn, left turn.

Drivers then completed the medium demand driving situations which consisted of six further junctions. These road situations were either intersections or T-junctions, with the driving situation being controlled by the driver, as they had to decide when it was safe to pull out of the junction. Drivers also completed these in a fixed order, with the manoeuvre direction being completed in the same order as the low demand situations: straight on, right turn, left turn, straight on, right turn, left turn. The low and medium demand situations differed in the control the driver had in these situations, but they required broadly equivalent motor behaviour with the manoeuvre direction being the same.

The exact same junctions were presented in the simulator and on-road, however, as the NITES database does not include all Nottingham's roads, it was not possible to have exactly the same continuous route between junctions in the simulator. Instead, in the simulated environment, the driver completed each driving situation in a separate scenario, similar to the presentation of previous simulator research studies (Robbins and Chapman, 2018; Robbins et al., 2018a). Drivers were placed around 50 m away from the relevant junction, which gave enough time to get up to speed on the approach. The scenario ended when the driver had fully completed the manoeuvre. Although the journey between junctions in the two environments was different, effort was made to match the timing of the environments, with the time gaps between the presentation of the simulation scenarios roughly matching the time the driver would have arrived there if they were completing the continuous route.

As on-road traffic is unpredictable, there is a danger that the traffic experienced in the two driving environments would be markedly different and this could mean dramatic differences in drivers' behaviour in the two environments. In order to minimise these differences, we used a form of yoking to ensure that there were no overall differences in traffic level between real and simulated environments. Yoking refers to a controlled research design where participants receive matched stimuli, but where there cannot be full control of the stimuli. The first participant completed both phases of the study with the simulator set to include moderate levels of randomly generated traffic. After the first participant had completed the study, we watched the on-road videos and measured the amount of actual traffic present at each junction. We then matched this level of traffic in the simulator and presented this for the second participant. We then measured the level of traffic experienced by the second participant at the real junctions and used this traffic in the simulated drives for the third participant. This procedure continued for all participants.

2.3. Stimuli and apparatus

The experiment took place in the Nottingham Integrated Transport and Environment Simulation (NITES) facility's high-fidelity driving simulator (NITES 1) and on-road instrumented vehicle (NITES 3). The high-fidelity simulator comprises of a full BMW Mini, housed within a projection dome and mounted on a six-degree of freedom motion platform with a 360-degree projection screen, See Fig. 1. Six high resolution projectors, each running a resolution of 1600 × 1200 pixels are used to form the scenarios on the dome walls. The mini is located in the centre of the 4 and a half metre dome, with the driver's seat located to the right hand side of the vehicle. The motion base for the current experiment was turned off because the abrupt terminations of each trial made the motion cues confusing.

XPI (XPI Simulation, London, UK) driving simulation software was used to create the scenarios in the simulator. The scenarios were chosen from a virtual loop of Nottingham, which has been created in the simulator using LiDAR (Light Detection and Ranging) scanning technology, which allows participants to drive the same road situations in both the simulator and on-road. See Fig. 2 for an example of a medium demand junction in both the high-fidelity driving simulator and on-road. XPI software also provides a scenario editor where the traffic can be altered, and vehicles can be added in order for the route sections to be representative of real-world driving.

The on-road car is an instrumented 2009 Ford focus (1.6 L) five door saloon car. The car is fitted with Race Technology (Race Technology, Nottingham, UK) hardware which records driving behaviour measures and GPS position. The car is also fitted with four bullet cameras, positioned to record the road ahead of the driver, the road ahead of the driver at 45° to the left, the road ahead of the driver at 45° to the right, and the driver's facial and head movements.

Although both the simulator and car are fitted with fixed dashboard-mounted eye trackers, we have found that for extreme head movements (such as those typically made when pulling across a junction) it is more reliable to use a head-mounted tracking system. Drivers' eye movements in the two environments were thus recorded using a Tobii Pro Glasses 2 system, which uses lightweight glasses that are worn by the participant. These glasses are attached to a small recording unit, allowing for the participant to move freely in the car, not obstructing their movement or view. The glasses track the participant's pupil and corneal reflection, recording at a rate of 50hz. The head unit contains 4 eye cameras. A successful calibration was obtained for every participant before the experiment could commence. The glasses also have a wide-angle HD scene camera in the centre (90°), which captures the driver's natural viewing behaviour.

In addition, a Dräger Alcotest 6810 breathalyser device (Dräger Safety, Germany) was used to measure participants' breath alcohol concentration (BrAC). If any alcohol content had been detected, the participants would have been be excluded from the study, irrespective of whether they were currently taking part in the on-road or simulator section of the study. This breathalyser required participants to blow continuously in a disposable mouthpiece for around 5 s, after which the device automatically calculates breath alcohol concentration. No measurable breath alcohol content was found for any participant in the study.

2.4. Procedure

Fifteen participants completed the on-road and simulator drives. The on-road part of the experiment was carried out in dry, clear conditions in order to keep the on-road and simulator scenarios as similar

Fig. 1. The NITES high-fidelity driving simulator which comprises of a full BMW mini, housed within a projection dome and mounted on a six-degree of freedom motion base.

Fig. 2. An example of a driver's view ahead when approaching the same medium demand junction in both the high-fidelity driving simulator (top panel) and on the real Nottingham road (bottom panel).

was possible. The experiment did not take place during rush hour therefore did not take place between 7am and 9am and 4pm-6pm, in order to promote continuous driving behaviour.

Firstly, participants were given an information sheet and were informed on the order in which they would complete the drives. Once the participant had filled out the consent form, they completed a short 'Driving Experience' questionnaire with the main purpose of understanding how often the participant drove, and the 'Extended Driver Behaviour Questionnaire' (Lajunen, Parker & Summala, 2004) which measures self-report driving errors, violations and lapses. All participants also completed a simulator sickness questionnaire (Kennedy et al., 1993) before and after both sections of the study.

For the simulator part of the experiment, the participant entered the simulator and the Tobii glasses were adjusted until these were comfortable. Following this, the participant completed two practice junction trials, allowing them to become familiar with the simulator and the eye tracking glasses as well as checking for any signs of simulator sickness. Once the participant was comfortable driving in the simulator and did not display any signs of simulator sickness, eye tracking glasses were calibrated and the recording was started. All participants were told systematic instructions before starting the simulation part of the experiment:

'In this part of the experiment, you will encounter 12 driving scenarios. Your task is to complete the scenario by driving as naturally as possible and obeying all speed limits and road signs. You will be given verbal instructions by the experimenter throughout the scenarios on which direction to go. After the scenario has ended, the next scenario will begin shortly after'.

For the on-road part of the experiment, the participant made themselves comfortable in the car and with the eye tracking glasses. Participants were given a practice drive around the University of Nottingham campus, lasting around 5 min, in order to familiarise themselves with the car controls and the eye tracking glasses. Once the participant was happy to continue, the eye tracking glasses were then calibrated and the recording was started. All participants were told systematic instructions before starting the on-road part of the experiment:

'In this part of the experiment, you will be driving an on-road route of Nottingham. You will be given verbal instructions by the experimenter on which direction to go. After the experimental session, either the participant or the researcher can drive back to campus. You must try and drive as naturally as possible throughout the experiment, obeying all speed limits and road signs.'

Verbal direction instructions were given to the participant to keep this consistent across the two driving environments. The participant completed the on-road route, experiencing the same driving situations as in the simulator, in the same order. After the experimental drive, the participant or the researcher drove the car back to the university campus.

2.5. *Measures and analysis*

2.5.1. *Pre-registered analysis*

For the pre-registered analysis, three dependent variables were specified: Mean Fixation Durations, Mean Saccade Amplitude and the Number of Head Movements per minute.

All dependent variables were analysed between the same pre-defined start and end point at each intersection. These points were purposefully positioned, with the specific location of these points chosen from landmarks that were seen easily in the simulator and on road, from the Tobii Pro glasses scene camera. These start points were chosen such that the driver had time to reach a suitable approach speed in the simulator and the end points were set at road locations just after the manoeuvre would have been completed.

For mean fixation durations, the data were extracted from the Tobii Pro Glasses Analyser (Version 1.29.1745), using the default gaze filters.

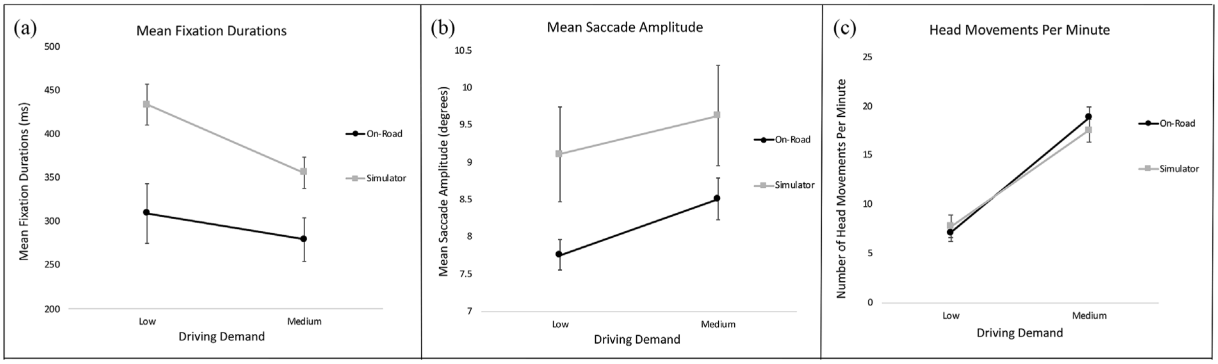

Fig. 3. a)Shows drivers' mean fixation durations (ms) in the simulator and on-road, for the low and medium demand driving situations. Error bars display one standard error above and below the mean. b)Shows drivers' mean saccade amplitudes (degrees) in the simulator and on-road, for the low and medium demand driving situations. Error bars display one standard error above and below the mean. c)Shows drivers' number of head movements per minute in the simulator and on-road, for the low and medium demand driving situations. Error bars display one standard error above and below the mean.

Under the default gaze filters, eye movement samples were classified as a continuous fixation if they provided a minimum gaze duration of 60 ms, a maximum angle between samples of 0.5°.

Mean saccade amplitude was the average distance between successive fixations. Drivers’ saccades were also extracted from the Tobii Pro Glasses Analyser, along with the gaze X and Y point (horizontal and vertical coordinate of the averaged left and right eye gaze point) at the start and end of each saccade, in degrees of visual angle. Saccades were only calculated when a head movement was not taking place. Where a mean saccade amplitude is large, this indicates that drivers were scanning widely within each head movement, and where it is small it suggests that drivers were concentrating successive fixations within a relatively small area.

Finally, a count of the number of times the driver turned their head in the driving situations was taken. This measure was also taken from the Tobii Pro Glasses scene camera, as this video was available in both driving environments and was positioned on the driver's head, therefore it was the most practical way to detect a head movement. The classification of a head movement was when there was at least 20 degrees of horizontal movement detected. In order to calculate head movements per minute, the drivers' head movement count for each driving situation was multiplied by 60 (seconds), and divided by the total time in the scenario (in seconds) to get a measure of head movements per minute.

These dependent measures were analysed using a 2 × 2 repeated measures ANOVA, with factors of Driving Environment (simulator vs. on-road) and Driving Demand (low vs. medium). Partial eta squared and Cohen's *d* are reported throughout the results section to show effect sizes. The most common equation for Cohen's d, taken from Cumming and Calin-Jageman (2016) and recently used in Hirst et al. (2018), was used to calculate the effect sizes.

2.5.2. Exploratory analysis

For the exploratory analysis, additional measures were analysed - Total Driving Time, Magnitude of Head Movements and the effect of Manoeuvre Direction on previously reported eye movement measures.

Magnitude of Head Movements was manually categorised using the Tobii Pro Glasses Analyser (Version 1.29.1745). The Tobii scene camera displayed in the analyser covered a horizontal range of 90°. On this basis, head movements were categorised into large (90° +), intermediate (between 45° and 90°) and small head movements (less than 45°) based on the amount of horizontal movement detected. The categories used were chosen because they were the most practical for unambiguous manual calculations: A head movement with a horizontal component of over 45° was defined as an occasion when the central point on the screen was no longer visible after the head movement; a head movement with a horizontal component of more than 90° was defined as an occasion when no part of the scene visible before the head movement is still visible on the display after the head movement and is typical of large side-to-side scanning at junctions.

In addition to the two original design factors of Driving Environment (simulator vs. on road) and Driving Demand (low vs. medium), additional exploratory analysis was conducted with the added factor of Manoeuvre Direction (Straight On, Right Turn, Left Turn). This 2 × 2 × 3 repeated measures analysis was also conducted with the three pre-registered eye movement measures which were Mean Fixation Durations, Mean Saccade Amplitude and Head Movements per minute.

3. Results

3.1. Driving environment and driving demand

3.1.1. Mean fixation durations

A main effect of Driving Environment was found (F (1, 14) = 11.57, MSe = 13056.83, $p < .01$, $n_p^2 = .45$, $d = 0.98$), indicating that drivers had longer mean fixation durations in the simulator compared to on-road. There was a significant main effect of Driving Demand (F (1, 14) = 30.80, MSe = 1407.70, $p < .001$, $n_p^2 = .69$, $d = 0.48$), indicating that drivers had longer mean fixation durations in the low demand driving situations compared to the medium demand driving situations. There was no significant interaction between Driving Environment and Driving Demand [F (1, 14) = 2.13, MSe = 4053.07, $p = .17$, $n_p^2 = .13$]. See Fig. 3a.

3.1.2. Mean saccade amplitude

There was no main effect of Driving Environment found [F (1, 14) = 3.90, MSe = 5.91, $p = .07$, $n_p^2 = .22$, $d = 0.65$], indicating that the distance between drivers' fixations did not differ in the simulator compared to on-road. There was a significant main effect of Driving Demand (F (1, 14) = 5.77, MSe = 1.04, $p < .05$, $n_p^2 = .29$, $d = 0.31$), indicating that the distances between drivers’ successive fixations were shorter in low demand driving situations compared to the medium demand driving situations. There was no significant interaction between Driving Environment and Driving Demand [F (1, 14) = 0.27, MSe = 0.75, $p = .61$, $n_p^2 = .02$]. See Fig. 3b.

3.1.3. Number of head movements per minute

There was no main effect of Driving Environment found [F (1, 14) = 0.26, MSe = 19.24, $p = .62$, $n_p^2 = .02$, $d = 0.05$], indicating that drivers’ head movements per minute did not differ in the simulator and on-road. There was a significant main effect of Driving Demand (F (1, 14) = 152.67, MSe = 33.97, $p < .001$, $n_p^2 = .92$, $d = 2.95$), indicating that drivers had a higher number of head movements per minute in the medium demand driving situations compared to the low demand driving situations. There was no significant interaction between Driving Environment and Driving Demand [F (1, 14) = 2.17, MSe = 19.99, p = .16, n_p^2 = .13]. See Fig. 3c.

3.2. Manoeuvre direction analysis

3.2.1. Mean fixation durations

In addition to the main effect of Driving Environment and Driving Demand (section 3.1.1.) there was also a main effect of Manoeuvre Direction found (F (2, 28) = 7.93, MSe = 5709.02, p < .01, n_p^2 = .36). Pairwise comparisons with Bonferroni correction (p < .016) indicate that right turn manoeuvres (m = 315.76 ms) significantly differed from straight on (m = 370.31 ms) (p < .01, d = 0.43) and left turn manoeuvres (m = 348.61 ms) (p < .01, d = 0.27), with drivers having shorter mean fixation durations for right turns compared to straight on and left turns. Straight on manoeuvres and left turn manoeuvres did not significantly differ (p = .14, d = 0.15).

There was also a significant interaction between Driving Environment and Manoeuvre Direction (F (2, 28) = 3.44, MSe = 5319.80, p < .05, n_p^2 = .20). Post Hoc tests with Bonferroni correction were conducted (p < .016). This revealed that drivers' mean fixation durations in the simulator and on-road were not significantly different when drivers performed a right turn (p = .06, d = 0.82) but were significantly longer in the simulator than on road when performing a straight on manoeuvre (p = .001, d = 1.14) and left turn manoeuvre (p = .01, d = 0.98), see Fig. 4a.

Finally, there was a significant interaction between Driving Demand and Manoeuvre Direction (F (2, 28) = 11.62, MSe = 5633.82, p < .001, n_p^2 = .45). Post Hoc tests with Bonferroni correction were conducted (p < .016). This revealed that drivers' mean fixation durations for low and medium demand situations were not significantly different when drivers performed a right turn (p = .40, d = 0.22) but were significantly longer in the low demand situations than the medium demand situations when performing a straight on manoeuvre (p = .001, d = 1.20), and left turn manoeuvre (p = .006, d = 0.61), see Fig. 4a.

There was no significant three-way interaction between Driving Environment, Driving Demand and Manoeuvre Direction [F (2, 28) = 0.214, MSe = 4667.82, p = .81, n_p^2 = .02].

3.2.2. Mean saccade amplitude

There were no significant effects found with the added factor of Manoeuvre Direction for drivers' mean saccade amplitude, with no main effect of Manoeuvre Direction [F (2, 28) = 1.95, MSe = 3.59, p = .16, n_p^2 = .12], no two way interactions between Driving Environment and Manoeuvre Direction [F (2, 28) = 0.69, MSe = 2.35, p = .51, n_p^2 = .05], and Driving Demand and Manoeuvre Direction [F (2, 28) = 0.16, MSe = 3.94, p = .86, n_p^2 = .01], and no three way interaction between Driving Environment, Driving Demand and Manoeuvre Direction [F (2, 28) = 1.30, MSe = 2.99, p = .29, n_p^2 = .09].

3.2.3. Number of head movements per minute

In addition to the main effect of Driving Demand on drivers' head movements (section 3.1.3.), there was also a main effect of Manoeuvre Direction found (F (2,28) = 14.71, MSe = 24.869, p < .001, n_p^2 = .51). Pairwise comparisons with Bonferroni correction (p < .016) indicate that right turn manoeuvres (m = 15.48) significantly differed from straight on manoeuvres (m = 12.38) (p < .01, d = 0.37) and left turn manoeuvres (m = 10.60) (p < .001, d = 0.61), suggesting that drivers made more head movements per minute for right turns, than for straight on manoeuvres and left turn manoeuvres. Left turn manoeuvres and straight on manoeuvres did not significantly differ (p = .48, d = 0.26).

In addition, there was a significant interaction between Driving Demand and Manoeuvre Direction (F (2,28) = 10.51, MSe = 17.47, p < .001, n_p^2 = .43). Post Hoc tests with Bonferroni correction were conducted (p < .016). This revealed that drivers had a significantly lower number of head movements per minute in low demand situations compared to medium demand situations when performing a straight on manoeuvre (p = .001, d = 1.50), a right turn (p = .001, d = 2.90), and left turn manoeuvre (p = .001, d = 3.11), see Fig. 4b.

In contrast, there was no significant interaction between Driving Environment and Manoeuvre Direction [F (2, 28) = 1.00, MSe = 15.49, p = .38, n_p^2 = .07] and no significant three-way interaction between Driving Environment, Driving Demand and Manoeuvre Direction [F (2, 28) = 0.666, MSe = 11.45, p = .52, n_p^2 = .05], see Fig. 4b.

3.3. Magnitude of head movements

Table 1 below shows the total number of head movements made by drivers in the simulator and on-road, categorised into small, intermediate and large head movements and broken down into low and medium demand situations.

A 2 × 2 × 3 repeated measures ANOVA was conducted on the total number of head movements with factors of Driving Environment (simulator vs. on-road), Driving Demand (low vs. medium) and Size of Head Movement (small, intermediate, large).

There was no significant main effect of Driving Environment [F (1, 14) = 2.51, MSe = 10.54, p = .14, n_p^2 = .15, d = 0.10], showing that the total number of head movements made by drivers did not differ between simulator (m = 7.20) and on-road (m = 7.97). There was a significant main effect of Driving Demand (F (1, 14) = 172.77, MSe = 11.93, p < .001, n_p^2 = .93, d = 0.95), showing that drivers made more head movements in the medium demand situations (m = 10.97) compared to the low demand situations (m = 4.20). There was also a significant main effect of Size of Head Movement (F (2, 28) = 234.42, MSe = 9.16, p < .001, n_p^2 = .94). Pairwise comparisons with Bonferroni correction (p < .016) indicate that the number of small head movements (m = 3.20) significantly differed from intermediate head movements (m = 14.40) (p < .001, d = 1.77) and large head movements (m = 5.15) (p < .001, d = 0.40), and intermediate head movements significantly differed from large head movements (p < .001, d = 1.28). This indicates that the majority of head movements drivers made were intermediate, followed by large, and then small.

There was also a significant interaction between Driving Demand and Size of Head Movement (F (2, 28) = 103.99, MSe = 10.43, p < .001, n_p^2 = .88). Post Hoc tests with Bonferroni correction were conducted (p = .016). This revealed that small head movements for low demand (m = 4.57) and medium demand (m = 1.83) situations were significantly different (p < .001, d = 1.03), with drivers performing more small head movements in low demand situations than medium demand situations. Intermediate head movements (p < .001, d = 3.88) and large head movements (p < .001, d = 3.40) were also significantly different for low demand (intermediate = 7.57, large = 0.47) and medium demand (intermediate = 21.23, large = 9.83) situations, with drivers' performing more intermediate and large head movements in medium demand situations than low demand situations.

There was no significant two-way interaction between Driving Environment and Size of Head Movement [F (2, 28) = 2.23, MSe = 9.97, p = .13, n_p^2 = .14] or three-way interaction between Driving Environment, Driving Demand and Size of Head Movement [F (2, 28) = 4.46, MSe = 11.59, p = .06, n_p^2 = .24].

The pre-registered analysis used the number of head movements per minute as a dependent variable to reflect the rate of broad visual scanning, while the exploratory magnitude of head movements analysis above used the absolute number of head movements as a measure of the total amount of search conducted. Although the patterns of results observed were similar for both measures, these measures could in principle differ if drivers spent dramatically different amounts of time

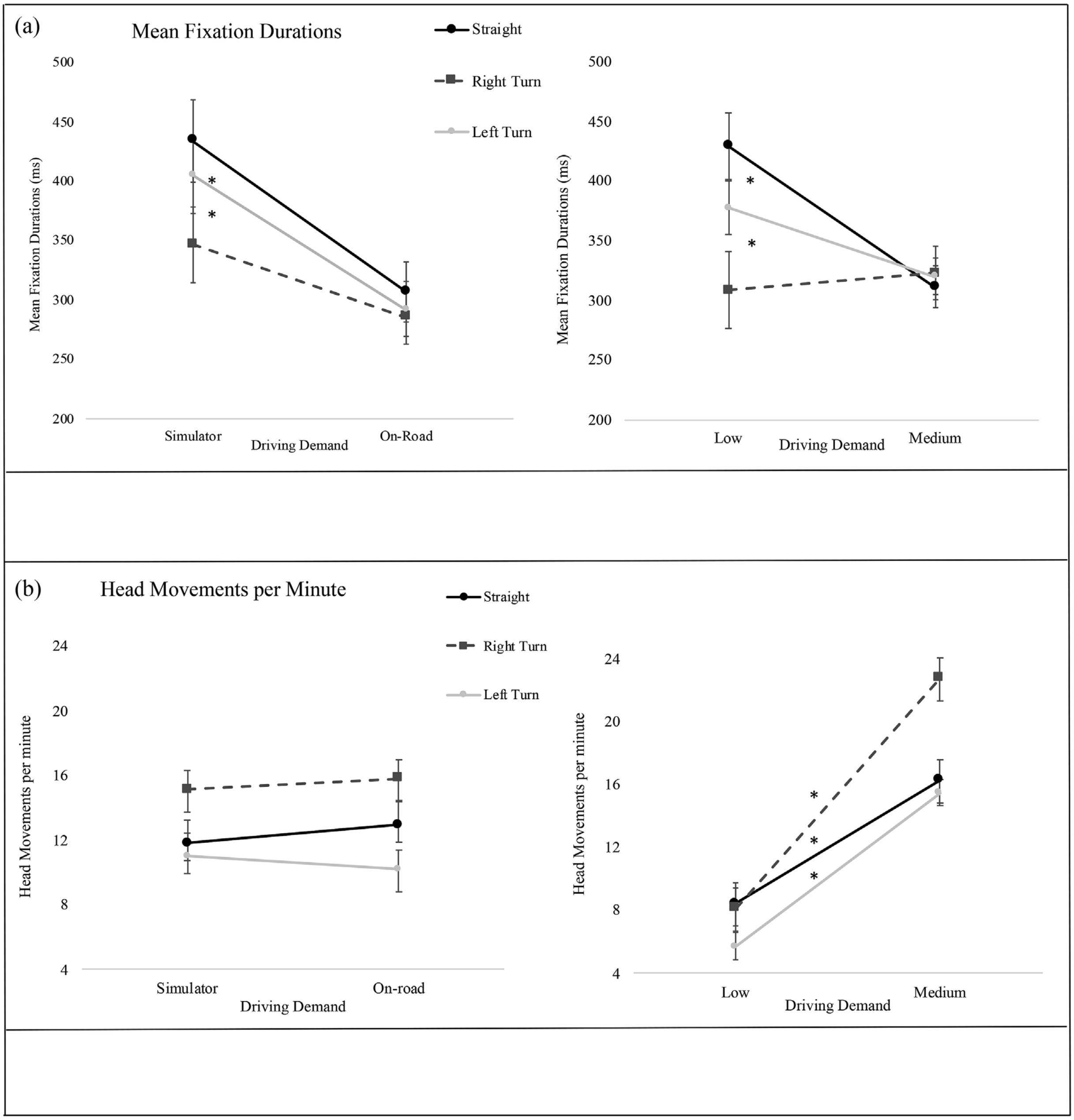

Fig. 4. a)Shows that there was a significant interaction between Driving Environment and Manoeuvre Direction, and Driving Demand and Manoeuvre Direction for mean fixation durations (ms). Error bars display one standard error above and below the mean. Statistically significant results are highlighted with (*). b)Shows that there was no significant interaction between Driving Environment and Manoeuvre Direction, but a significant interaction between Driving Demand and Manoeuvre Direction for head movements per minute. Error bars display one standard error above and below the mean. Statistically significant results are highlighted with (*).

Table 1
The absolute number of head movements made by the 15 drivers in the simulator and on-road, categorised into small, intermediate and large head movements and broken down into low and medium demand situations.

Head Movement	Simulator Low Demand	Percent	Simulator Medium Demand	Percent	On-Road Low Demand	Percent	On-Road Medium Demand	Percent
Small	57	31.14%	27	5.81%	80	41.03%	28	5.36%
Intermediate	114	62.29%	325	69.89%	113	57.95%	312	59.77%
Large	12	6.57%	113	24.30%	2	1.03%	182	34.87%
Total	**183**		**465**		**195**		**522**	

at junctions in different environments. The following analyses allow us to assess the degree to which this happened.

3.4. Similarity of driving environments

3.4.1. Traffic

As aforementioned, substantial effort was made to keep the traffic in both the simulator and on-road environment similar over all participants. For the 12 driving situations of interest, a vehicle count was performed for every participant in both driving environments, taken from the Tobii Pro Glasses eye tracker head mounted video camera. The vehicle count was taken from this camera as this video was the same for both environments, and showed all vehicles that were clearly visible to the driver. A within subject *t*-test confirmed that the average number of vehicles encountered by participants on-road (m = 17.52) and in the simulator (m = 15.12) over all driving situations did not significantly differ [t (14) = 1.06, p = .31, d = 0.48].

3.4.2. Total driving time

In regards to drivers' total driving time in the situations of interest, there was no significant main effect of Driving Environment [F (1, 14) = 0.001, MSe = 18.625, p = .97, n_p^2 = .01, d = 0.01], indicating that drivers' time to pass through the driving situations did not differ between the simulator (m = 17.99s) and on-road (m = 17.95s). There was a significant main effect of Driving Demand (F (1, 14) = 5.663, MSe = 8.786, p < .05, n_p^2 = .29, d = 0.43), suggesting that drivers took longer to drive through the medium demand situations (m = 18.89s) compared to the low demand situations (m = 17.10s). There was no significant interaction between Driving Environment and Driving Demand [F (1, 14) = 0.09, MSe = 8.134, p = .77, n_p^2 = .01]. This finding confirms that, as expected, the head movement validation findings reported above are the same for both head movements per minute and absolute number of head movements, and that demand increases both the frequency and rate of head movements.

4. Discussion

This study compared drivers' visual search at intersections, in a simulated environment and on real roads, in situations with low and medium task demands. Our main prediction was that there would be a greater similarity between the two environments in medium demand situations. In brief, the study found that there was no interaction between driving environment and driving demand for mean fixation durations, mean saccade amplitudes and number of head movements per minute. When we considered manoeuvre direction, however, we found that mean fixation durations were not different between environments for right turn manoeuvres (across traffic), but were different for both straight on and left turn manoeuvres.

4.1. Simulator validity

This study was designed to investigate the validity of a high-fidelity driving simulator. Although we were expecting an interaction between driving environment and driving demand, it is notable that on several of our measures, there were no significant differences between performance in the two environments at either demand level. For instance, drivers made approximately 12 head movements per minute in both the simulator and on-road, and there were no interactions between driving environment and driving demand. Overall, the agreement between drivers' broad visual search behaviour in the simulator and on real roads was even greater than we had predicted, with head movements proving to be comparable even in low demand situations, despite the fact that there was a clear effect of demand on drivers' head movements per minute.

Our exploratory analyses on the magnitude of drivers' head movements also showed no effect of driving environment on both the absolute number of head movements and the general size of head movements made by drivers. In regards to total amount of head movements, drivers made an average of 7 head movements per driving situation in both the simulator and on-road. As expected, drivers' head movements in the two driving environments were sensitive to the demand of the driving situation, with drivers displaying more larger head movements for more demanding driving situations. This finding suggests that drivers are adapting an arguably effortful visual search measure to meet the demands of the driving task, in order to search effectively for dangers in more potentially hazardous road situations, but this is done to a similar degree in both driving environments.

It should be noted that with regards to drivers' mean saccade amplitudes, the results, although consistent with the results above, should be interpreted with caution, as although the distance between drivers' successive fixations in the simulator and on-road did not differ significantly, the effect sizes were comparatively high (d = 0.65).

The one measure on which there were clear differences between the real and simulated environment was mean fixation duration, with drivers' having longer fixation durations in the simulator compared to on the road. There was also an effect of demand on mean fixation durations, with drivers fixating for longer in low demand situations compared to medium demand situations. The exploratory analysis, with the additional factors of manoeuvre direction indicated that the differences found in drivers' fixation durations in the two environments were more apparent when the driving manoeuvre was relatively easy, i.e. a straight on or left turn manoeuvre, and smaller differences were seen between the two driving environments when the task was more difficult i.e. a right turn manoeuvre. These results provide the encouraging suggestion that visual search in a high-fidelity driving simulator is comparable to that observed on real roads as long as the task demands are at least moderate.

4.2. Effects of demand on driver behaviour

Overall our results are consistent with a characteristic change in driver behaviour at different levels of demand. In the section above, although the number of head movements did not differ between real and simulated environments, they did vary with demand. In addition, mean saccade amplitudes were significantly shorter in low demand driving situations compared to medium demand situations.

This conclusion was supported by the additional analysis of manoeuvre direction, as it was found that drivers performed the most head movements on right turn manoeuvres, then on straight manoeuvres, and then on left turn manoeuvres. This finding is logical, given that right turns on UK roads are considered the most difficult manoeuvre, as this behaviour involves crossing two lanes of potential oncoming traffic and manoeuvring the vehicle to merge with this oncoming traffic. Straight on manoeuvres also involve crossing two lanes of potential traffic, however, they do not require as much motor movement or the successful merge afterwards. Left turn manoeuvres only require drivers to check for potential traffic in one lane in order to merge, and therefore it is understandable that this behaviour can safely be conducted using fewer head movements. This finding suggests that drivers are aware of the potential danger associated with these three manoeuvre directions, as they adapt their visual search strategy in both the simulator and in the real world to account of this. This finding is consistent with the work of Hancock et al. (1990) and Shinohara and Nishizaki (2017) who found that drivers' head movement frequency was higher in right turn, straight on and left turn manoeuvres respectively.

Our finding that mean fixation durations were longer in low demand situations compared to the medium demand situations is in accordance with findings from previous research. Drivers' visual attention changes depending on the demands of the task, with drivers displaying longer mean fixation durations in low and high demand conditions (Chapman and Underwood, 1998a, b; Underwood et al., 2011; Crundall et al., 2012a), and shorter mean fixations in medium demand driving situations. The current study's findings on mean fixation durations in regards to demand suggests that low and medium demand situations were achieved in the current study, and supports the idea that low demand driving situations are characterised by long fixation durations and relatively short saccadic amplitudes. These results can be potentially explained by the idea that in low demand driving situations, drivers do not feel the need to look around for potential danger, and instead fixate for longer periods of time within a relatively small area, investigating specific items of interest or simply 'resting' their eyes on the road ahead. This raises the question of why drivers' mean fixation durations were longer in the simulator compared to the real world, therefore it is worth considering the interpretation of this measure carefully.

This finding did not support the original hypothesis, as although we had correctly predicted that the environments would be more similar in the medium demand, the direction of the difference between environments in low demand situations was opposite to that we had expected. We had predicted that mean fixation durations would be higher in the real world than in the simulator on the grounds that more detail in the real-world environment would encourage longer processing (Foy, 2017). The contrary finding, of longer fixations in a simulated environment, is, however, supportive of some previous research (e.g. Laya, 1992). Laya (1992) found that drivers' mean fixation durations were shorter in real situations than in simulated situations, when drivers were navigating round curves. A possible interpretation of this result is that although the driving simulator does yield greater sensory deprivation than the real world with less diverse and interesting stimuli as previously mentioned (Thiffault and Bergeron, 2003), in relatively low demand situations the main determinant of fixation durations is not what you are looking at currently, but what alternative objects of interest are present.

This is compatible with models such as that proposed by Findlay and Walker (1999) in which saccades are generated from a competition between "When" and "Where" pathways. Here drivers may fixate on certain areas of the environment for much longer than needed, as there are no other potentially interesting stimuli to move to and focus attention on. The difference in mean fixation durations in the two environments is more profound in the low demand driving situations, where the driving task was relatively easy for the driver when navigating around a curve controlled by the road environment (similar to Laya, 1992), compared to when the task was more demanding and required a decision from the driver. This suggests that the simulator may be a good resource for investigating drivers' visual attention at junctions when the demand is higher, but more problematic when the driving demand is low.

4.3. Implications

These findings have many important implications, as researchers have already started researching the reasons for the high number of crashes at junctions, with studies investigating drivers' visual attention at junctions with the use of a driving simulator (Konstantopoulos et al., 2010; Robbins and Chapman, 2018). The finding that drivers' broad visual search strategies when approaching and performing a junction manoeuvre, even in low demand situations are comparable to those observed on real roads supports the suggestion that future research on this topic can generally be validly conducted using a high-fidelity driving simulator, which has both a full instrumented vehicle and a 360-degree visual display.

With specific regard to right turns - these manoeuvres have been seen to be the most prevalent cause of junction crashes in the UK (Clarke et al., 2007), particularity with motorcyclists and pedal cyclists (Jannat, 2014). These situations are arguably the most important ones to be investigated in terms of drivers' visual search strategies, in order to explain the most common intersection crash. Therefore, if driving situations are made demanding enough in the simulator, i.e. requiring drivers to make right turn manoeuvres in demanding situations (e.g. Robbins and Chapman, 2018) we can have reasonable confidence that the visual behaviours observed in the simulated environment should be similar to those obtained in real world driving.

Conversely however, given that it is proposed that simulator validity decreases with lower task demand, this could have important implications for simulator research on automated driving and supervised automated driving (Trimble et al., 2014). Previous research using automated driving scenarios have been seen to produce lower workload for the human operators compared to manual scenarios. This was evident by drivers' perception, in terms of increased driver situational awareness in automated scenarios compared to manual scenarios (Parasuraman et al., 2009). Given that automated driving research is on the rise (Jääskeläinen, 2012), this research could be problematic in a driving simulator environment, given that the primary aim of automated driving is to significantly reduce the demands placed on the driver.

However, the generalisability of these findings and implications should be taken with caution, as behavioural validity is dependent on the specific simulator and specific driving task (Hoskins and El-Gindy, 2006). That said, this study was conducted in accordance to the highest standards of validity testing, in terms of comparing drivers' behaviour at junctions in a high-fidelity driving simulator (full instrumented vehicle and a 360-degree visual display) and on the road, using the same road geometry in the two environments.

4.4. Limitations

The current study procedure matched aspects of the driving task as closely as possible in the simulator and on-road, however, it must be noted there were some parts of the design that could not be controlled for. Firstly, it must be acknowledged that the simulator vehicle (a BMW mini) and the on-road vehicle (a Ford Focus) were different. This was a necessary compromise between needing a relatively small vehicle for the projection dome, but a slightly longer vehicle to provide equipment space for on-road testing. However, given that the two vehicles were similar in performance characteristics in normal driving and neither vehicle was immediately familiar to the driver, we doubt that this would confound the comparisons between the two driving environments. In contrast, some previous on-road driving research has been conducted using the drivers' own vehicles and familiarity of the vehicle has been seen to affect drivers' behaviour (Lerner and Boyd, 2005). Secondly, the driving simulator in the current experiment had the motion base turned off due to the abrupt termination of the scenarios. Although this reduced motion could potentially affect drivers' visual attention, this is unlikely given that previous research has found that the absence of motion cues produces larger differences in drivers' behaviour when the visual demand is high compared to lower demand situations (Fisher et al., 2011), which is contrary to the results found in the current study.

It was possible that the incidental differences in driving environment would affect our results via changes in the driving performance itself. For this reason, we compared the traffic and total driving times between the two environments. There were no differences in traffic. There were also no differences in driving time between the simulator and on-road, with it taking drivers on average 18 s to pass through the driving situations in each of the two environments. This differs from previous research that showed that participants generally drove faster through intersections on-road compared to in the simulator (Godley et al., 2002). It is possible that this inconsistency in results may be due the previous study using different participants for the on-road and simulator part of the task, with research suggesting that faster driving speeds are as associated with individual differences in terms of personality and motivation (Elander et al., 1993). The current study's finding suggests that participants' driving behaviour in a high-fidelity driving simulator does not differ to that on real roads, indicating that drivers are taking the situations in the simulator as seriously as on-road situations.

Finally, it could be argued that the presentation order of the driving scenarios may cause a confound between driving demand and order, with the low demand situations being presented before the medium demand situations in the current study. This was unavoidable given the practicalities of constructing matched on-road and simulated drives but does create a problem. It could be argued that the differences found in drivers' eye movements as a function of demand could be due to fatigue, with drivers experiencing more fatigue in the medium demand situations compared to the low demand situations. However, previous research looking at changes in eye movements over long continuous drives have found that fatigue is associated with higher mean fixation durations and decreased mean saccade amplitudes (McGregor and Stern, 1996), which have been interpreted as the driver having a decreased interest in scanning the road environment (Schleicher et al., 2008). The opposite result was found in the current study, with the findings being more consistent with the effect of a demand manipulation on drivers' eye movements. These findings also address the difference in the presentation of the task in the two driving environments, with participants being presented with a continuous on-road route and separate simulation driving scenarios. Again, it could be argued that the continuous on-road route may have been more demanding for the driver, and induce more fatigue compared to a series of short drives. Fatigue resulting from the task of driving has been seen to affect drivers' performance (Crawford, 1961), with this impairment having been seen to appear around 15 min into a driving task (Chapman et al., 1999). However, as aforementioned, increased levels of demand (Chapman and Underwood, 1998a, b) and fatigue (Schleicher et al., 2008) are seen to increase mean fixation durations, which is the opposite of the longer mean fixations seen in the driving simulator compared to on-road continuous drive in the current study.

5. Conclusions

In summary, this study provides good evidence for the validity of a high-fidelity simulator in regards to drivers' visual attention at junctions. We found very similar trends in drivers' broad visual search strategies in terms of head movements in the simulator and on-road, demonstrating good levels of validity. However, there were differences in mean fixation durations, with these being longer in the simulator compared to on-road, particularly in low demand situations. It is thought that this difference can be explained by the fact that the simulator is less visually engaging, with less diverse stimuli compared to the real world, leaving drivers fixating on a certain area of the environment for longer than required in the absence of alternative search locations. There was a marked effect of driving demand in all visual attention measures, with medium demand driving situations eliciting shorter mean fixation durations and longer mean saccade amplitudes, suggesting that drivers were sampling more of the visual scene compared to low demand driving situations. Drivers also seem to adapt their visual search strategy in accordance with the difficulty in driving manoeuvre, with drivers looking around more for potential danger during right turn manoeuvres compared to straight on and left turn manoeuvres. Finally, it seems that more complex manoeuvres i.e. right turns, reduce the difference in drivers' mean fixation durations between the two environments, suggesting that for all visual attention measures to be comparable in the simulator and on-road, the demand of the driving task needs to be at least moderate. These findings have important implications for driving research, suggesting that high fidelity driving simulators can be useful tools in investigating drivers' visual attention at junctions as long as the task demands for the driver are at least moderate.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2019.05.005.

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2. General Discussion

2.1. Brief Summary of Results

The aim of this thesis was to use an extended theoretical model, based on basic psychological processes and previous research, to better understand the potential causes of junction crashes that have been traditionally attributed to LBFTS errors. The main methodological considerations for the current thesis were to improve the immersiveness of the methodology used in previous studies, increase the complexity of the driving environment and to use a more efficient psychophysical technique to simulate and measure drivers' behaviour, by creating instances where drivers would pull out in front of approaching vehicles, similar to LBFTS situations.

Initial exploratory ideas were described in Papers 1 and 2. Interestingly, the opinions of car drivers and motorcyclists regarding the cause of junction crashes systematically varied given the context of the situation, with both road users demonstrating a basic psychological process of in-group bias when asked generally about junction crashes, i.e. they blamed the other road user group. However, when asked about specific junction scenarios, this extra information caused a reduction of in-group bias with car drivers more likely to blame car drivers, and motorcyclists more likely to blame motorcyclists than in general questions. However, there was a general consensus that car drivers' lack of observation in ROW situations was the cause of many of these types of crashes.

Given the acknowledged importance of appropriate visual search at junctions, Paper 2 presented a systematic review and meta-analysis of studies that explored visual search when driving. One specific claim that has been made in the literature and helps provide a theoretical basis for understanding visual search in driving is that it develops with experience. However, the analysis in Paper 2 revealed that differences in novice drivers' and experienced drivers' visual search are not so apparent when studies are pooled together compared to the conclusions of previous individual studies. While it was found that novice drivers had a narrower horizontal spread of search compared to experienced drivers, there was no evidence of a difference in fixation durations, vertical spread of search and number of fixations over the visual scene. Many reported differences in novice drivers' and experienced drivers' visual search seem to be driven by the inclusion of extreme driver groups, i.e. drivers with advanced training or learner drivers with minimal driving experience. The lack of differences in visual search as a function of experience was consistent with results from the studies reported in Paper 3, which looked more specifically at whether experience in a specific mode of transport alters car drivers' visual attention towards this specific road user. It was found that, contrary to previous research using drivers with motorcycling experience (Crundall, Crundall, Clarke & Shahar, 2012), there were no apparent differences between drivers with considerable cycling experience and drivers with limited cycling experience in terms of their visual search towards approaching pedal cycles, motorcycles or cars.

Experimental research conducted in a high-fidelity driving simulator was reported in Papers 3, 4, 5 and 6. These studies produced a variety of novel and important findings with regards to visual search, gap acceptance, and memory. In Papers 3 and 4 it was found that while drivers' general visual search strategies were appropriate for scanning for approaching vehicles at the junction, drivers were prepared to accept riskier gaps when smaller vehicles were approaching the junction i.e. pedal cycles and motorcycles, compared to approaching cars. Paper 3 revealed that drivers pulled out in front of near pedal cycles more often than they pulled out in front of other motor vehicles. Following on from this, the study reported in Paper 4 developed a more precise method of measuring gap acceptance thresholds and demonstrated that drivers were prepared to accept smaller gaps in front of motorcycles compared to cars.

Given that drivers' riskier behaviour around smaller vehicles could be explained in terms of a distorted representation, e.g. estimating motorcycles to be further away than they actually are, this element of the framework was investigated in more depth in Study 5, where drivers' situational awareness for approaching vehicles in terms of memory for their type and location was the main focus. In terms of estimated location, it was revealed that drivers had a general bias to estimate vehicles to be closer to them than they actually were, with this bias being larger for cars than motorcycles. However, the most striking finding from this series of studies was that drivers failed to recall relevant vehicles at all on between 13-18% of occasions, with drivers failing to recall significantly more motorcycles than cars. These failures in recall were predicted by what the driver looked at subsequently after fixating on the vehicle, and not by their fixation behaviour on the vehicle. These findings produced evidence for the partial representation explanation of the extended framework, suggesting that many junction crashes that have been traditionally attributed to LBFTS errors may be a result of a memory deficit rather than a simple deficit in visual search. These findings were interpreted in terms of limitations in drivers' working memory, with the temporary storage of visuospatial information being subject to interference when engaging in a complex dynamic gap acceptance task.

The final stages of the research involved a validation study which compared drivers' general visual attention at junctions, which differed in demand, in the high-fidelity driving simulator and on real roads. The need to validate the use of the simulator has been highlighted throughout the thesis as both the systematic review in Paper 2 and psychophysical thresholding study in Paper 4 highlighted a need for an immersive method when investigating drivers' visual attention and gap acceptance behaviour. It was found that while there were differences in detailed measures of eye movements, with drivers' mean fixation durations in the simulator being longer than those in the real world, there were supportive findings in regards to drivers' broad visual search strategies, with no differences between real and simulated junctions in the frequency or size of drivers' head movements.

2.2. Assessment of the Framework Adopted in the Thesis

In regards to the extended framework, this research explored the framework using a wide variety of methods including online questionnaires, a systematic review and meta-analysis, experimental simulator studies and an on-road study. The series of six papers presented in the thesis were successful in providing further insights into all stages of the framework, each to a different extent, as highlighted in the Gantt chart in Figure 1.3. Papers 2, 3 and 6 in this series focussed on the look and recognise sections of the framework, validating the fact that drivers perform appropriate visual search strategies when approaching a junction, directing their attention towards vehicles approaching from the left or right. These broad visual search strategies witnessed in the high-fidelity driving simulator were also seen to be comparable to those witnessed on real roads in Paper 6. Paper 5 later established that drivers generally fixate directly on approaching vehicles before deciding to pull out in front of them. Given these findings, the main theoretical focus of the thesis has thus been to explore the possible difficulties drivers may have in appraising the situation.

One possible influence on drivers' ability to appraise the situation correctly when pulling out of the junction is a distorted decision, with this explanation being partly addressed in Papers 1,3 and 4. Although drivers often report looking for, but failing to see an oncoming vehicle, it could be possible that a car driver does not want to admit to a deliberate driving violation, such as accepting a risky gap between traffic in front of a smaller, less threatening vehicle. While the findings in Paper 1 show that both car drivers and motorcyclists are more favourable about their own road user group when generally asked about junction crashes, this in-group bias is reduced when specific situations, such as the typical ROW crashes, are presented. This reduction in in-group bias therefore may suggest that in specific ROW situations, possible negative attitudes towards other road users are not influencing their behaviour. That said, as these situations were presented on a questionnaire, they may not be comparable to real life situations and therefore a negative attitude towards a specific road user may affect their assessment of risk and their subsequent behaviour.

When directly investigating drivers' crossing behaviour at junctions in Papers 3 and 4, it was found that drivers displayed risker behaviour around smaller vehicles at junctions, by accepting smaller gaps, or taking more of a risk compared to when larger vehicles were approaching. Again, it is possible that this is a result of a distorted decision, with drivers perceiving motorcycles to be less threatening than cars and therefore choosing to accept smaller gaps in front of them. While this explanation is possible, the findings from Paper 4 also show that drivers did not have faster cross times (the time from when the front of the drivers' car enters the junction to the moment where it has reached the point where the oncoming vehicle can pass without collision) when pulling out in front of motorcycles than cars. If the driver had deliberately accepted what they believe to be a risky gap in front of a motorcycle, it would be expected that they would accelerate and clear the junction faster than when they had accepted a larger gap. Therefore, while attitude bias may play a role in the differences in these gap acceptance thresholds, a more compelling explanation for these results may be a distorted representation, where drivers believe they have not committed a violation and have sufficient time to cross the junction.

An alternative explanation for drivers' difficulty in appraisal has come from a wealth of literature which suggests that a driver's judgement about when to pull out of the junction requires an estimate of the vehicle's time-to-arrive (Horswill et al., 2005), with smaller vehicles having been seen to be predicted to be further away than they actually are (DeLucia, 1991). This explanation would suggest that many LBFTS errors are caused by a distorted representation. When drivers' representations for approaching vehicles were explored in more depth in the three studies presented in Paper 5, there was evidence for small biases in drivers' estimation of vehicle location, with drivers' generally underestimating the locations of vehicles.

Although there was a general underestimation in vehicle location, the results from Study 1 in Paper 5 contrasted with Study 2 and 3. Study 1 found that the underestimation of vehicle location was larger for motorcycles than for cars and large vehicles, whereas Study 2 and 3 found a larger underestimation for cars compared to motorcycles. This difference in findings is thought to be due to vehicles being presented at unrealistically far and near distances in Study 1, as well as participants being exposed to many trials of vehicles at the same distance, which could account for the fact that participants were generally more accurate in Study 1 compared to the later studies (average study underestimation: Study 1=8.7 degrees, Study 2= 18.8 degrees, Study 3= 18.9 degrees). Moreover, it can be seen that when drivers' estimation of vehicle location was measured when drivers were pulling out in front of vehicles in Study 2, this finding was well replicated in Study 3.

The fact that drivers underestimated the location of cars more than motorcycles in Studies 2 and 3 in Paper 5 indicates that drivers were actually more accurate in estimating motorcycles locations. However, this could be dangerous for motorcyclists from a safety perspective, partly supporting the claim that drivers tend to estimate motorcycles to be further away than larger vehicles (Grigg et al., 2010). This is consistent with the suggestion that some junction crashes involving motorcyclists and pedal cyclists may indeed result from drivers looking at the smaller vehicle and misjudging that the gap is safe to cross into when it is in fact not.

Although this is an important crash type and one that deserves further exploration, it is not a typical LBFTS situation, as the driver has both looked at and seen the oncoming vehicle. The other thing to note is that, while small biases in location estimates were found, it was the occasions where drivers had a complete absence of a representation for approaching vehicles which became of particular interest.

Given that there were occasions where drivers had an absence of a representation for approaching vehicles in the first study in Paper 5, two subsequent studies further explored the possibility of drivers having a partial representation. It was important that these recall failures were replicated, but it was also essential that the accuracy of the eye tracking was improved in order to expand our knowledge in regards to the nature of these report failures. It was important to decide conclusively whether drivers had fixated directly on the approaching vehicles before subsequently failing to report them. Clearly, one explanation for the LBFTS error would be that a driver has made a head movement in the right direction and looked broadly down the road but failed to actually detect the oncoming motorcycle.

When investigating the nature of these report failures, it was also important to explore drivers' subsequent visual search behaviour after fixating on the approaching vehicle. This analysis provided additional support for the theoretical interpretation of these memory deficits, suggesting that drivers' limited visuospatial working memory storage is being subject to interference by subsequently fixated information. By breaking down the initial framework (Crundall, Clarke, Ward & Bartle, 2008) into more specific testable stages at the start of the thesis, this revealed the possibility of this alternative and novel explanation for LBFTS errors, which may account for many deaths on the road.

The theoretical interpretation of these findings implicates the importance of working memory when performing high-level processes such as monitoring traffic and making decisions at junctions, allowing for the development of the Perceive, Retain, Choose (PRC) model of risky dynamic decision making, introduced in Paper 5. While working memory performance has been briefly addressed in previous research studies investigating intersection behaviour (e.g. Guerrier et al., 1999; Liao et al., 2016), the PRC model integrates both cognitive and perceptual-motor processing stages which directly incorporate elements of the well-known model of working memory (Baddeley, 2000). Previous research has also stressed that driver behaviour models should include well tested predictions regarding the constraints of cognition (e.g. memory and forgetting errors, and attention allocation), as well as characterising driving as a multitasking activity which does require task prioritisation and attention management (Salvucci et al., 2001). This model has therefore expanded on previous frameworks used to explain junction crashes, and can produce quantitative predictions about drivers' cognitive abilities at junctions.

It should be noted that these conclusions are derived from a relatively small number of experimentally observed memory errors and it could be argued that this is a limitation of the current research. This problem is inevitable given the phenomenon under investigation, as junction crashes are rare events with the vast majority of manoeuvres that occur on the road being conducted safely. Given this, we would not expect to witness these memory errors from all participants, or repeatedly from individual participants. This problem has been mitigated to a large extent during the current studies, as a more efficient method was developed to create instances where drivers would pull out in front of approaching vehicles, as well as increasing the number of vehicles in the scenarios to produce a more sensitive measure of memory.

The method developed throughout these studies to measure drivers' gap acceptance behaviour represents a major methodological advance when studying junction crashes, and in particular the LBFTS phenomenon. By combining a method from visual psychophysics to an applied driving task, this enabled drivers' gap acceptance thresholds to be measured efficiently. The adaptive thresholding technique chosen to estimate drivers' gap acceptance thresholds was designed to place vehicles in the most efficient locations in order to increase the measurement precision but also minimise the number of trials required to estimate the threshold (Leek, 2001). Given the complexity of simulator studies, this was an important practical implication of the chosen method. The other great strength of this method is that we were able to determine critical distances for each driver. Where previous research has used a mixture of clearly safe and clearly dangerous gaps, we were able to conduct critical memory tests only on trials where the driver was already making a difficult decision.

The fact that memory errors were observed even on trials which represented difficult choices for the driver makes them even more striking.

The main limitations of previous methodologies in the context of intersection behaviour are the assumptions of consistency and homogeneity in behaviour, as drivers' gap acceptance has been seen to change over time (Bottom & Ashworth, 1978), as well as individuals not always accepting gaps above a certain value and rejecting gaps below a certain value (Pollatschek et al., 2002). These two assumptions ignore the decision-making process, with gap acceptance varying among and within drivers in different situations. Given these assumptions, traditional methods have therefore taken a macroscopic gap acceptance approach (e.g. Raff, 1950), which is based on an estimation of a 'critical gap' value for all drivers. However, it has been highlighted that there should be more emphasis on microscopic critical gap estimation for individual drivers, considering individual differences (Pollatschek et al., 2002). More recently, simulator studies have used simple experimental manipulations such as including instructions which encourage participants to complete driving routes in as short time as possible, in order to encourage 'go' behaviours from all drivers (Ba et al., 2016; Paschalidis, Choudhury & Hess, 2018).

The current adaptive threshold method, documented in Paper 4, continuously updates the estimate of each individual driver's gap acceptance threshold throughout the duration of the experiment, while encouraging drivers to drive as naturally as possible. This microscopic method therefore accounts for individual differences in drivers' behaviour, and can be adapted to look at the changes in thresholds as a function of, for example, vehicle type, number of vehicles, time and the inclusion of a secondary task while driving. This method therefore has expanded the possible experimental designs that can be achieved when studying the LBFTS error, particularly when investigating drivers' behaviour at junctions in immersive driving environments.

That said, despite the adaptive threshold procedure minimising the overall number of trials needed, this procedure had to be shortened even further when conducting the experiments in Paper 5, as the investigation of drivers' situational awareness required additional memory trials. Threshold estimations were therefore calculated using a ‘fixed method’, with the vehicle distances being determined before the experiment. The adaptive thresholding function was then used to estimate the individual driver’s threshold, based on their responses at these fixed distances (Taylor & Creelman, 1967). However, it is acknowledged that this method does violate some assumptions of the adaptive thresholding procedure, as the distance of the vehicles to be presented is usually always updated in response to their previous behaviour (Kingdom & Prins, 2010).

Given that the findings in Paper 5 changed the direction of the thesis, the finding that drivers display riskier behaviour around smaller vehicles at junctions in Papers 3 and 4 was not investigated any further, and it remains to be determined whether they are result of distorted decisions or distorted representations. Although this remains an interesting question, the proposed extensions to the current research are based around both expanding evidence for ‘Saw but forgot’ (SBF) errors, but also highlighting future experimental ideas which could address the explanations of a distorted decision or distorted representation more directly.

2.3. Proposed Extensions to Current Research

2.3.1. A Secondary Task to Load Visuospatial and Phonological Subsystems

The most obvious extension to the current research is to build upon the theoretical avenues presented in the PRC model. Given that it was concluded in Paper 5 that failures in recalling approaching vehicles at junctions occur due to limited visuospatial capacity, it would be expected that if drivers’ visuospatial or phonological working memory subsystems were loaded by a secondary task while driving, this would increase the number of memory errors witnessed during the task. Based on theories of risk compensation, it would also be expected that drivers would adjust their gap acceptance thresholds in response to an increase in the level of risk on the road (Fuller, 2005). Therefore, when performing a secondary visuospatial task while driving, this would lead to compensatory behaviours to restore control of the situation, for example leaving larger (safer) gaps when performing a gap acceptance task.

An initial version of this study has already been conducted during the PhD, although it has not been included in the thesis (Robbins et al., under review). In this study we gave drivers either a visuospatial or phonological secondary load to remember at the start of each driving scenario. Drivers then completed the driving task by approaching an intersection and performing a manoeuvre when they deemed it to be safe. Once the driving scenario had terminated, drivers' memory for all items on the secondary task was tested. The results revealed that drivers' gap acceptance behaviour, situational awareness in terms of drivers' maintenance of memories for vehicles, and eye movements did not change in the presence of a visuospatial or phonological memory load. The only form of compensation witnessed in the experiment was drivers' performance in the visuospatial secondary task, with this being significantly worse than performance on the phonological task. The total amount of memory failures witnessed during the study was similar to those found in the studies conducted in Paper 5, but not affected by secondary load.

Although this result is of interest, our interpretation is that the drivers may have been able to perform the secondary memory task without active rehearsal. The precise timings of the secondary tasks presented in Robbins et al., (under review) led us to conclude that this information was being encoded into drivers' long-term memory before they started the junction task and not being actively rehearsed by visual and phonological working memory subsystems during the actual gap-acceptance phase. This possible explanation is consistent with a series of forced-choice discrimination experiments, similar to the responses drivers made for the secondary tasks, which have investigated participants' memory and eye movements over 3D complex natural scenes (Hollingworth & Henderson, 2002; Hollingworth, 2004).

These experiments made a distinction between the use of working memory and long-term memory in such scene exploration, with working memory being available when memory is immediately tested during the exploration of the scene, whereas long term memory being available when the scenario has been removed after a number of minutes (Henderson & Hollingworth, 2003). These findings suggest that the accumulation of visual information from both the driving task and the secondary task can be supported by both the visual short term and long-term memory systems. Therefore, although it was initially thought that these secondary tasks shared both cognitive resources and timings with the central driving task, this may not be the case. Therefore, an alternative approach that we hope to be able to explore is loading visuospatial or phonological systems with continuous tasks, or by directly changing the visuospatial and phonological content of the driving environment.

2.3.2. Increase Environmental Complexity

As aforementioned in the thesis overview, the complexity of the driving environment was increased throughout the current experimental studies, by using two vehicles in each scenario as opposed to a single target vehicle used in previous research. This manipulation increased the potential sources of danger on the road, and created an environment where all parts of the extended framework could be tested. This was particularly important for experimentally testing the possibility of drivers having a partial representation of the environment, as multiple vehicles have the potential to act as a source of interference.

However, there is still scope for future research to increase the scene complexity further, particularly given that previous research has found a direct link between visual scene complexity, working memory capacity and memory. This research has suggested that visual working memory is not fixed by the number of items it can hold, but is a limited resource that is shared out between all items of potential relevance in the visual scene. The amount of allocated attention to each item has therefore been seen to determine how well an item is remembered, as information in visual working memory is updated during eye movements over the scene. Therefore, memory for fixated items can be subsequently degraded when memory resources are reallocated to another object in the visual scene (Bays & Husain, 2008). These laboratory findings have also been seen to apply to driving contexts (Bellet et al., 2009), and therefore may explain why the majority of junction collisions that involve a motorcycle have been seen to occur at times of peak traffic flow (Clarke et al., 2004), where it is expected that environmental complexity is high.

By increasing the amount of traffic approaching the junction, this could act as a naturalistic way of loading drivers' visuospatial short-term memory, extending the current theory regarding SBF errors. It would be expected that an increase in vehicles in the visual scene would increase the amount of memory errors that are witnessed in these situations, as visual working memory resources need to be allocated to more sources of information. Practically, this would also be beneficial for experimentally testing SBF errors, as this allows for a more sensitive measure of memory, which is less susceptible to ceiling effects. Given that the absolute memory errors in the previous studies are relatively low, with drivers forgetting a vehicle on between 13-18% of occasions, this means that the majority of trials were not used in the analysis. By using multiple vehicles in the scenarios, it is thought that more memory errors will be found therefore, producing more critical trials for analysis.

In addition, given that more environmental complexity is likely to increase the number of head movements and fixations drivers make towards approaching vehicles at the junction, this will allow for a more detailed analysis of drivers' subsequent visual search behaviour after fixating on a vehicle they later fail to recall. It would be expected that the more subsequent head and eye movements a driver makes between fixating on a vehicle and pulling out, the more likely that are to fail to recall that particular vehicle.

Given that previous research, including Robbins et al. (under review), has found that visual working memory capacity is around 4 items when driving (Eng et al., 2005; Bays & Husain, 2008), an example study could expose drivers to simulated scenarios which include 1-4 vehicles approaching an intersection. Given that the aim of the study is to create an environment where drivers will need to selectively allocate their attention to all present vehicles in the scenario, it is important that vehicles are positioned in locations where they are seen as a potential threat, and ultimately influence a driver's decision on when to pull out of the junction. Therefore, there could be up to two vehicles approaching from the sides of the junction (one from the left and one from the right), and vehicles three and four approaching from the other side of the intersection and from behind the participant's vehicle. Drivers' gap acceptance thresholds and memory for all vehicles would continue to be measured as a function of the number of vehicles present in the scenario.

2.3.3. Using Physiological Measures

Although the focus of the thesis became centred around investigating a possible partial representation, there is still scope for future studies to focus on the possible explanations of a distorted representation and a distorted decision from the extended framework. Given that the experimental work in Papers 3 and 4 clearly shows that drivers are willing to accept riskier gaps in front of smaller vehicles at junctions, and Paper 5 indicates that motorcycles are systematically remembered to be further away than cars, these findings could possibly relate to the concept of threat. As shown in the PRC model by the inclusion of the threat detector, it may be the case that when the vehicle is looked at, possible threat dominates any other form of cognitive processing, i.e. a driver may choose to reject a gap in front of an approaching car or truck due to them seeming to be more threatening compared to a motorcycle (Simmel, 1944). To explicitly test this possible explanation, a more direct measure of drivers' threat assessment can be measured by monitoring their physiological responses such as skin conductance and heart rate throughout the manoeuvre.

Previous driving studies investigating threat have found that general threat on the road increases physiological reactivity (Tomaka et al., 1993; Palomba et al., 2000), with this increase being seen to occur when viewing dynamic as well as static stimuli (Barnard & Chapman, 2016). It would be possible to expose drivers to different vehicle types at the junction i.e. large goods vehicles (LGVs), cars, motorcycles and pedal cycles to see if drivers' responses differ when pulling out at threshold in front of these vehicle types. A basic prediction would be that drivers' mean skin conductance would increase when pulling out in front of LGVs compared to smaller vulnerable road users. The opposite result would be thought to be true for heart rate, as it has been seen in a driving context that heart rate deceleration allows for heightened attention and increased intake of information in order to deal with more potentially threatening situations (Barnard & Chapman, 2016).

2.3.4. Drivers' Estimation of Vehicle Location

In regards to drivers' estimation of vehicle location, the current series of experiments in Paper 5 were the first to investigate drivers' situational awareness of vehicles with the driving task and memory test being performed using a consistent spatial representation. As previous research investigating drivers' situational awareness for vehicles on the road has not presented the situational tests in the same environment as the main driving task, (Gugerty, 1997; Groeger et al., 2002; Ma & Kaber, 2005), their findings are hard to interpret unambiguously as it has been found that people prefer to maintain a consistent perspective when describing spatial properties from memory (Diwadkar & McNamara, 1997; Shelton & McNamara, 2001; Rieser, 1989). In addition, many previous studies used basic computer driving tasks to measure situational awareness, which has also been seen as a limitation given that spatial memory directly benefits from experiencing visual-motor interaction (Gaunet et al. 2001). Although the current experimental studies have improved the way in which drivers' situational awareness is measured during this applied task, this could be further improved in future research.

Despite providing drivers with the same perspective for the driving task and the situational awareness tests, the simulator screens were blank during these tests. Due to this, it was noted that the vertical variability on some estimates of vehicle location were implausible, and therefore may have been a result of not providing the background of the road that the vehicles were travelling along. This limitation is supported by previous research which suggests that while the freeze probe recall technique for measuring situational awareness has been seen to be the most valid measure in applied contexts (Salmon et al., 2009), it has been indicated that for situational awareness to be measured accurately, all aspects of the road environment need to be in place (Salmon et al., 2012). Practically, during the current experiments, removing the oncoming vehicles from the scenarios would have required the termination of the scenario, the removal of the relevant vehicles, and reloading the scenario from the exact same perspective. This procedure meant that is was not possible to test drivers' memory for vehicles immediately, and therefore it was a concern that this passing of time may interfere with drivers' short-term temporary storage of information. These practical issues may indicate why this method has only been previously performed when investigating drivers' long-term spatial memory, where precise timings are not essential (Sandamas & Foreman, 2015). Nonetheless it might be possible to streamline the process by which relevant vehicles are removed and it is an approach that we will consider in future research.

Secondly, it is acknowledged that the current situational awareness test required drivers to convert the estimated vehicle location into both a manual movement (via the laser pointer) and a verbal response. Previous research, which has investigated verbal report methods in applied sporting contexts, has suggested that verbalising information can interfere with task performance, and disrupt the automaticity of the task (Williams & Davids, 1997). In addition, visual memory content is not always probed in memory test questions, and therefore eye movements are seen as a more reliable measure (Garrison & Williams, 2013).

The use of eye movements as an alternative measure of situational awareness has been seen as a popular method in applied contexts such as aviation (van de Merwe et al., 2012). In a driving context, this could be achieved by explicitly instructing participants to look at where they think approaching vehicles should be when the simulation is frozen, combining both the freeze probe paradigm and eye movements. An additional advantage of the use of eye movements is that, due to its non-intrusive and continuous manner (van de Merwe et al., 2012), participants could also be asked to look back at the location of the approaching vehicle after performing an additional head movement, potentially capturing additional elements of situational awareness such as level 3, projection of future system states (Endsley, 1995). By incorporating more levels of situational awareness in the study design, this is highlighting that situational awareness is more of a process as opposed to a one-off action.

2.4. Implications and Proposed Intervention Studies

2.4.1. General Methodological Implications

The main aim of the current thesis was to increase our understanding of junction crashes that have been previously attributed to LBFTS errors by breaking down a previously used framework, which focused on drivers' visual processes, into more specific theoretically testable stages. Overall, the series of studies presented in this thesis have highlighted important implications for future research when investigating the LBFTS error. These general implications fall into the three broad categories of driving method, driving demand and developing practical interventions based on theoretical models.

Throughout the thesis, it has been highlighted that an immersive driving method is vital when investigating junction crashes, particularly when generalising the results to real roads. As previously mentioned, findings from Paper 2 showed that differences in novice drivers' and experienced drivers' fixation durations and horizontal spread of search were clearer in studies using immersive driving environments rather than simple methodology (videos and static images). In Paper 4, it was also found that drivers' gap acceptance behaviour in the high-fidelity driving simulator was more comparable to real-world studies than that observed in the medium-fidelity driving simulator. These findings are in accordance with previous literature (Crundall, Chapman, Trawley et al., 2012; Alberti et al., 2014), which suggest that the immersiveness of the driving environment, in regards to differences in vehicle control and the visual scene, have a significant impact on drivers' behaviour.

This argument was also addressed in Paper 6, where it is found that drivers' general search strategies in the high-fidelity driving simulator and on the road were comparable. Although it is acknowledged that the driving simulator was not absolute in replicating all measures of visual attention as seen on real roads, these findings suggest that a high-fidelity simulator is the best compromise when investigating this phenomenon, as research involving safety-critical situations cannot be easily conducted on real roads but simulation results can be generalised and used to confidently inform on-road interventions. Secondly, the importance of the demand of the driving task was also highlighted in Paper 6, with differences in drivers' visual search in the two driving environments being smaller when the driving demand was at least moderate.

Together these findings indicate that future research, particularly when considering the previously discussed proposed extensions, should acknowledge the factors of driving method and driving demand. More specifically, previous literature has found that the realism of the driving method is particularly important when investigating the effects of a secondary task on the primary task of driving (Santos et al., 2005). It has been found that behavioural compensation in measures such as speed are witnessed in laboratory studies, simulator studies and on -road studies however, differences in visual attention due to work load (i.e. eye movements) were not reflected in laboratory driving experiments (Brookhuis et al., 2003). In addition, previous research which has specifically looked at everyday memory has highlighted that while increasing ecological validity is not always required in research, when looking at memory in applied contexts such as traffic accidents, high fidelity environments are preferable in order to capture performance as it would be in a real environment (Banaji & Crowder, 1989).

Likewise, in regards to drivers' physiological responses towards approaching vehicles at intersections, previous research has found that both the level of simulation validity (Slater et al., 2009) and the level of threat can affect participants' physiological responses in a driving environment. Parsons et al. (2012) assessed whether participants had increased psychophysiological responses in highly immersive virtual environments compared to lower immersion environments, as well as whether the level of stimuli threat in these environments impacts the users' experience of the virtual environment. It was concluded that highly immersive environments are more effective for eliciting increased arousal and predicting threat responses compared to low immersion virtual environments. The results from this indicate that sensitive changes in drivers' physiological responses may only be witnessed in highly immersive, threatening situations.

Finally, given the proposed alternative explanation of SBF errors for the majority of previously attributed LBFTS errors in Paper 5, these findings have important implications in terms of the avenues it opens for novel practical interventions which could ultimately save lives. However, for any intervention to be successful, it not only has to be underpinned by theoretical predictions, but also needs to be accepted by the target road users. This implication was highlighted in Paper 1, which stated that opinions of road users are considered vital in the engagement of safety interventions.

2.4.2. Practical interventions to prevent 'Saw but forgot' errors

The current road safety campaigns which are in place to reduce crashes with motorcycles are based around the idea that drivers are not actively thinking about approaching motorcyclists when scanning a junction, as well as drivers not devoting enough time to scan the junction for potential approaching motorcycles. In the UK the main government road safety campaign THINK!, which has been established since 2000, televised a ‘Think! Bike’ campaign in 2002 and 2012 which urged drivers to maintain awareness at junctions. To help with this, there was a particular empathasis on educating drivers to think about the person riding the bike, increasing both the personalisation of the motorcyclist and the empathy between the car driver and the motorcyclist. This approach has been supported by previous research which has found that empathy, brought about by the perception of familiarity, similarity and friendship, is important in a motorcycle safety context, with the greatest empathy towards motorcyclists coming from drivers’ who are motorcyclists themselves (Magazzu et al., 2006). In addition, car drivers who have close family members or friends that ride motorcycles have also been shown to have better observations towards motorcycles (Brooks & Guppy, 1990). Therefore, this campaign is a deliberate attempt to encourage car drivers to take the other person’s perspective (Batson & Shaw, 1991).

The approach taken from the Think! Bike campaign could be used as a way to improve drivers’ memory for motorcycles on the road, as previous research suggests that increasing cognitive empathy, specifically perspective taking, increases recall performance (Wagner, Handke & Walter, 2015). However, the campaign’s justification was drawn largely from the testimony of car drivers during face to face interviews and online questionnaires, with the key findings highlighting that there was limited evidence on the impact of this intervention on drivers’ behaviour on the road (DfT, 2014). This suggests that while drivers testify that the introduction of the Think! Bike campaign makes them actively think more about approaching motorcycles at junctions, it does not mean that this is reflected in the behaviour of drivers when encountering these situations.

Similarly, in the US, the Texas Department of Transportation also launched their “Share the Road: Look Twice for Motorcycles*”* campaign which encourages drivers to check the junction twice before pulling out, even when the junction was believed to be clear after the first time of checking. This intervention was introduced due to motorcycles being easily overlooked due to their size, and therefore based their idea around that fact that drivers may not look at the motorcycle in the first instance and need to check the junction for a second time before performing a manoeuvre. In regards to the SBF error, while this intervention may often provide situations where the approaching motorcycle is the last object to be fixated upon before pulling out of the junction, it is not always guaranteed that this object would not be subject to interference by additional information in the visual scene.

While both interventions claim to have reduced fatality rates, they have not been fully successful in preventing these crashes, with 349 motorcyclists still killed in road crashes in the UK in 2017 (DfT, 2017). This suggests that while existing campaigns may be helpful, it is likely that interventions which additionally focus on drivers' failures in working memory, have the opportunity to provide substantial additional reductions in casualties.

2.4.2.1. The 'Look Last' Intervention

In order to mitigate the number of crashes that involve a motorcycle at junctions, the next stage would be to experimentally test possible interventions, based on the theoretical underpinnings of the research presented so far. The first proposed intervention, termed the 'Look Last' intervention is based around the findings in Paper 5, with this intervention focusing on preventing the most safety critical information being subject to interference by subsequent visual information. As the name suggests, the 'Look Last' intervention tests the possibility that if drivers see a motorcycle at the junction, they should make this the last thing they look at before pulling out and therefore this should be the last information to be stored in drivers' visuospatial working memory. This intervention is also based on the recency effect, a theoretical characteristic of short-term memory where the most recent information presented is well remembered in free recall tasks (Baddeley & Hitch, 1993). Recency effects have been seen to occur across many cognitive components which are relevant to performing dynamic decisions at intersections, including perception (Maloney et al., 2005) and selective attention (Kristjansson, 2006).

More specifically, studies that have investigated the dynamic updating of working memory for visual objects have found that when information is presented sequentially, there is a clear recency effect with the last object in the sequence being the best remembered. The sequential presentation of information has also been compared to simultaneous presentation, where it was found that the last item presented sequentially was the only item to be recalled as well as items that were presented simultaneously (Gorgoraptis et al., 2011). It is this serial pattern of fixations on objects in the scene which leads to serial memory performance, with strong primary and recency effects (Zelinsky & Loschky, 2005). Additional experimental manipulations have found that this recency effect is due to the interference of subsequent items being displayed, and not due to temporal decay (Allen et al., 2006; Gorgoraptis et al., 2011). This 'look last' intervention is therefore a direct application of the theory of working memory, in regards to the suspected interference of sequentially encoded vehicles in a junction setting.

In addition, although visual checks to the left and right of the junction can be completed in quick succession, there is evidence to suggest that drivers may not be aware of the possibility that their working memory capacity may be subject to immediate interference when they are looking for vehicles, and therefore believe they have checked the junction appropriately. Previous research on meta-cognition, which refers to the insight a person has to their own cognitive experiences and processes (Bona & Silvanto, 2014), has suggested that the relationship between the objective accuracy of visual short-term memory and subjective experience is dissociable, with subjective ratings being significantly better than objective memory (Bona, et al., 2013).

However, it is acknowledged that search strategy interventions may be difficult to implement as they require the changing of habitual search behaviour. Broader psychological theories, such as the Theory of Planned Behaviour, indicates that habit formation can directly impact intentions and behaviour on the road (De Pelsmacker & Janssens, 2007), as habits lead to 'automatic' behaviour (Mittal, 1998). It is therefore thought that habits could be one of the factors responsible for the attitude-behaviour dissociation (Rothengatter, 1991). However, despite many previous research studies attempting to change drivers' visual attention on the road, there are very few examples that have investigated the success of the intervention through both drivers' behaviour on the road, as well as drivers' attitudes towards performing the intervention.

For this reason, a pilot study was conducted with 12 participants, with the main aim of investigating whether drivers are able to abide by instructions to adjusting their visual behaviour, but also whether they felt comfortable following the intervention. The pilot study compared two types of instruction which either encouraged the driver to look last at the approaching motorcycle, or look at least twice in each direction before pulling out, similar to the "Share the Road: Look Twice for Motorcycles" campaign in the US.

Drivers' head movements at the junction suggested that drivers were able to successfully adopt these strategies, by either looking at the motorcycle last or checking the junction at least twice before pulling out, depending on the instruction they were following. However, responses to post-experimental questions suggested that while both instructions were clear to follow, drivers did not feel overly comfortable with either instruction. In regards to the 'look twice' intervention, the general consensus was that drivers did not feel it was always necessary to look at least twice in each direction before pulling out, 'It was sometimes not necessary, I found it was more convenient to follow my own strategy'. In regards to the 'look last' intervention, drivers felt they had to concentrate too much on the instruction, and wanted to fall back into habitual search strategies, 'If the motorcycle was coming from the left, my instinct was to look right again before pulling out'.

These results suggest that while drivers may perform the correct behaviour in the short term, the acceptability of these interventions over the long-term may not be as successful, as it has been highlighted that attitudes have a large influence on drivers' intentions and behaviour. Therefore, based on these results, a less intrusive countermeasure which requires no changing of habitual strategies would be more likely to succeed.

2.4.2.2. The 'Say Bike' Intervention

The second intervention which is discussed in Paper 5, is based on the avenues highlighted in the PRC model for dynamic risky decision making. Given the nature of working memory, it is believed that the visuospatial and phonological subsystems are independent in regards to the information they store (Baddeley, 2007). Therefore, the overloading of visuospatial working memory, which is thought to be the most commonly used subsystem when driving, would not affect the retention of phonological material. The secondary task study described earlier supports this claim (Robbins et al., under review), with the results indicating that visuospatial processing is the prominent working memory system, with drivers displaying compensatory behaviour in the visuospatial secondary task, but not the phonological task.

Therefore, the proposed ‘Say bike’ intervention tests the possibility that the phonological loop could provide a simple strategy to overcome the limited capacity of the visuospatial subsystem, by encoding safety relevant information phonologically. As the phonological subsystem automatically stores information when encoded verbally, it is guaranteed to be encoded into the phonological working memory sub-system. The basic concept behind this intervention is that if drivers can be trained to verbally express the fact they have seen an approaching motorcycle by saying ‘Bike’, this would cause this information to be coded phonologically and therefore is unlikely to be subject to inference by visuospatial information. This application of working memory theory has been generally documented, with verbal labels enhancing object memory performance (Lloyd-Jones et al., 2008). Previous lab studies have also found that stimuli which have concreate labels/names associated with them are recalled significantly better than stimuli which cannot have associated verbal labels (Brown et al., 2006) however, this concept is yet to be used in an applied driving context.

Given that the ‘say bike’ intervention is less intrusive in regards to changing habitual behaviour compared to the ‘look last’ intervention, it may be that drivers are more comfortable in accepting and adopting this particular intervention. This intervention could be experimentally tested by having three conditions, a ‘say bike’ condition, a control condition and a ‘press bike’ condition. In the control condition, the driver would not be given any instructions when approaching the junction. In the ‘press bike’ condition, this would encourage drivers to press a button on the steering wheel when they see an oncoming motorcycle. This ‘press bike’ action is thought not to evoke phonological encoding as this manual movement is very similar to the ‘random time interval generation’ tapping task used in Robbins et al. (under review). This tapping task was seen to be one of a few tasks to interfere with general central executive functions while keeping the load on visuospatial and phonological systems relatively low (Vandierendonck et al., 1998).

In addition, as the ‘press bike’ condition has no phonological component, there is no guarantee that this information will be stored in short term memory at the time of retrieval unlike the phonological ‘say bike’ condition. The ‘press bike’ condition, like the ‘say bike’ condition, also requires the driver to perform a specific behaviour when they see an oncoming motorcycle, which is potentially drawing drivers’ attention more towards approaching motorcycles. It has been seen in previous research that tapping (or a form of manual movement) can be used to help with recall when memory load is heavy, compared to just looking alone (Epelboim et al., 1995). Therefore, the inclusion of the ‘press bike’ condition helps to distinguish between whether drivers’ memory for vehicles is dependent on the phonological encoding of this information, or simply the fact drivers’ attention is being drawn towards motorcycles more than the control condition.

2.5. Conclusions

In summary, the aim of the thesis was to use an extended theoretical model, based on a previous framework (Crundall, Clarke, Ward & Bartle, 2008), to understand the potential cause of junction crashes that have been previously attributed to LBFTS errors. In addition, throughout the thesis there was an emphasis on improving the methodology of previous research, by advancing the efficiency and complexity of the driving task.

While initial work focused on the look stage of the framework, more emphasis was later put on the appraisal stage of the framework, and in particular, the idea of a partial representation. The surprising finding which encouraged the continuation of this work was that drivers did not have an accurate representation of their environment when pulling out of a junction, demonstrating occasions where a driver would fail to report a safety critical vehicle at a junction, despite having previously fixated upon it. Based on drivers’ subsequent eye movements, it was concluded that drivers’ visuospatial working memory was subject to interference from the subsequent visual information the driver fixated on. These findings indicated that many LBFTS errors may be better categorised as ‘Saw but forgot’ (SBF) errors, resulting from a memory deficit as opposed to a visual deficit.

Given that this finding changed the direction of the thesis, there are a number of proposed extensions to the current research, which would increase the support for the existence of SBF errors, but also extend current findings regarding the possibilities of a distorted representation or distorted decision. The current findings, which have made a significant contribution to the existing literature, have also highlighted methodological implications for future research and potential interventions for preventing SBF errors. Firstly, the immersiveness of the driving environment and the demand of the driving task have been seen to be important considerations for future research when investigating junction crashes. Secondly, the creation of the Perceive Retain Choose model (PRC) to explain dynamic risky decision making has created theoretical avenues for future interventions, in order to ultimately reduce the amount of road fatalities that occur at junctions.

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