



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-world 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 et 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 ($1-\beta = 0.80$, $p = .05$). 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 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.

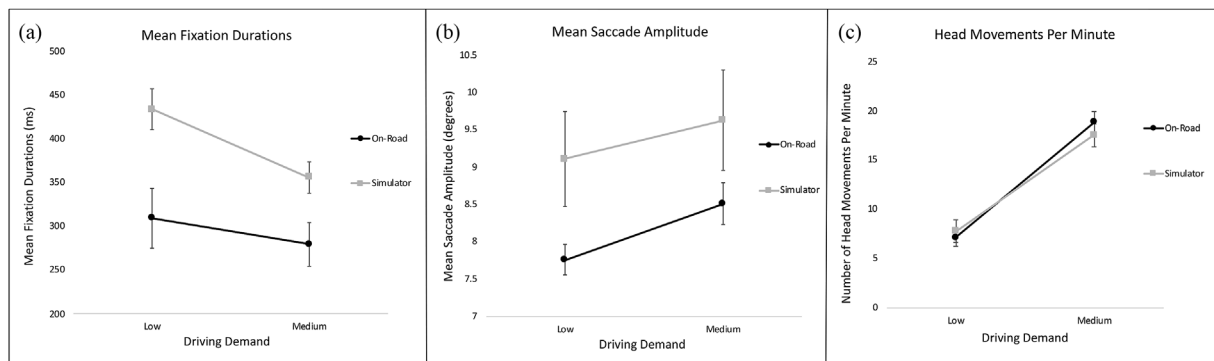


Fig. 3. a) Shows drivers' mean fixation durations (ms) in the simulator and on-road, for the low and medium demand driving situations. Error bars display one standard error above and below the mean. b) Shows drivers' mean saccade amplitudes (degrees) in the simulator and on-road, for the low and medium 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 ($90^\circ +$), 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 $2 \times 2 \times 3$ 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 $2 \times 2 \times 3$ 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

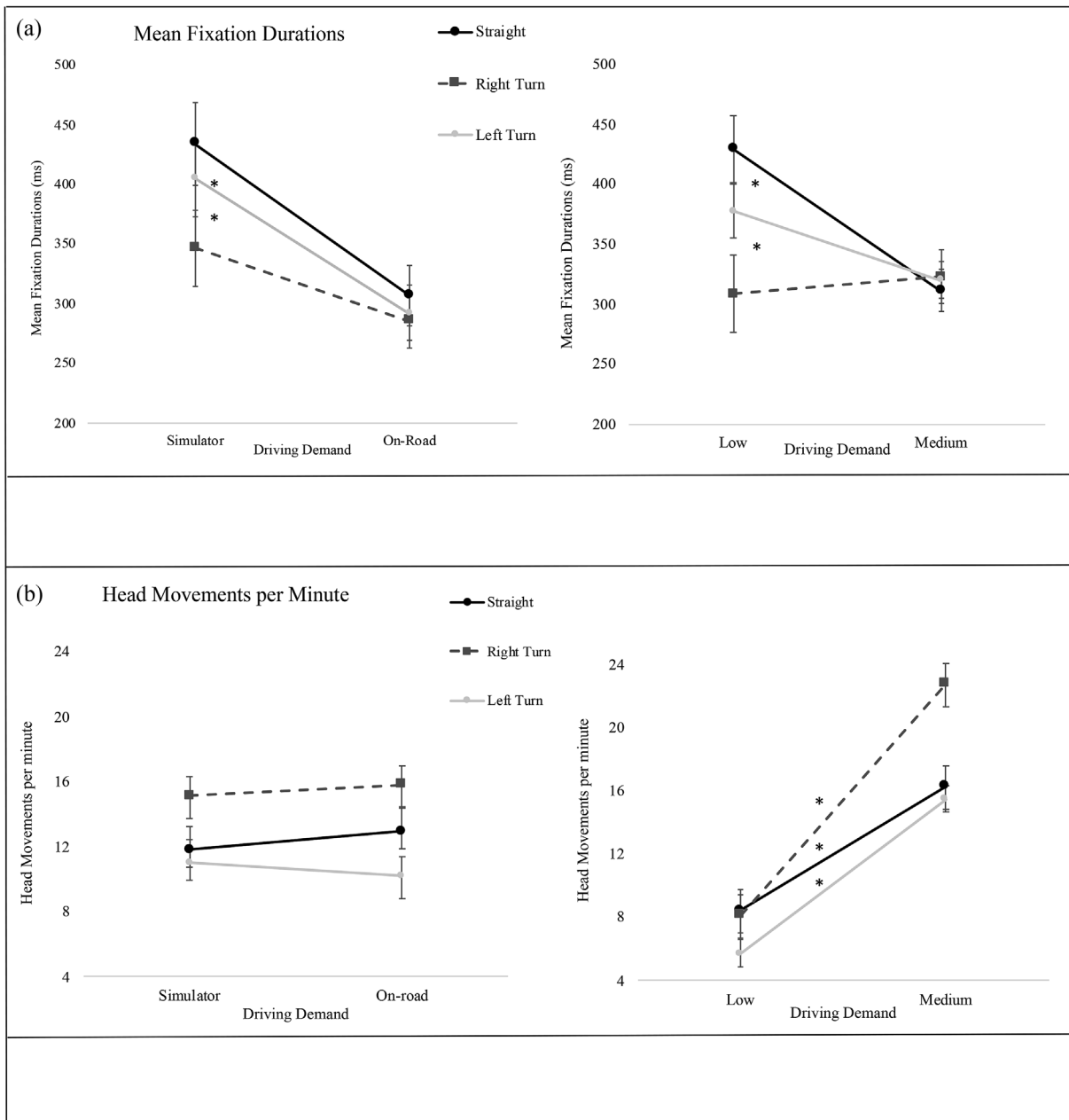


Fig. 4. a)Shows that there was a significant interaction between Driving Environment and Manoeuvre Direction, and Driving Demand and Manoeuvre Direction for mean fixation durations (ms). Error bars display one standard error above and below the mean. Statistically significant results are highlighted 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 [$F(1, 14) = 0.001, MSe = 18.625, p = .97, \eta_p^2 = .01, d = 0.01$], 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 [$F(1, 14) = 5.663, MSe = 8.786, p < .05, \eta_p^2 = .29, d = 0.43$], 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 [$F(1, 14) = 0.09, MSe = 8.134, p = .77, \eta_p^2 = .01$]. 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), particularly 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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