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Driver's visual attention as a function of driving experience and visibility. Using a driving simulator to explore drivers' eye movements in day, night and rain driving

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ABSTRACT

Road crashes are the main cause of death of young people in the developed world. The reasons that cause traffic crashes are numerous; however, most researchers agree that a lack of driving experience is one of the major contributing factors. In addition it has been demonstrated that environmental factors such as driving during night and rain increases the risk of a crash. Both of these factors may be related to drivers' visual search strategies that become more efficient with increased experience.

In the present study we recorded the eye movements of driving instructors and learner drivers while they drove three virtual routes that included day, night and rain routes in a driving simulator.

The results showed that driving instructors had an increased sampling rate, shorter processing time and broader scanning of the road than learner drivers. This broader scanning of the road could be possibly explained by the mirror inspection pattern which revealed that driving instructors fixated more on the side mirrors than learner drivers. Also it was found that poor visibility conditions, especially rain, decrease the effectiveness of drivers' visual search. The lack of interaction between driving experience and visibility suggests that some aspects of visual search are affected by general rather than situation specific driving experience.

The present findings support the effect of driving experience in modifying eye movement strategies. The high accident risk of night and rain driving could be partly explained by the decrement in visual search strategies during these conditions. Finally it is argued that the use of driving simulators can provide valuable insights regarding driving safety.

1. Introduction

The number of traffic crashes has decreased over the last decade both in USA and Europe (Eurostat, 2007; NHTSA, 2006). Despite this reduction, traffic crashes are still the most common cause of death for people aged less than 40 in the developed world (Plainis et al., 2006). There are numerous potential explanations of traffic crashes and it is not surprising that so many dimensions appear important since driving is such a complex task (Plainis et al., 2006). It is beyond the scope of this paper to cover all these factors. Here we will focus on the experiential differences in visual attention and specifically how drivers are impacted by driving under nighttime and rainy conditions. In the following introduction we will first discuss night and rain driving before going on to discuss the potentially moderating influences of experience. Finally, we will discuss the potential role of simulators in this research before explaining the current study.

1.1. Night and rain driving

The visibility conditions of interest in the current study are night driving and driving under rainy conditions which will be compared to day driving. It has been shown that time of day influences both the severity and the rate of crashes (Clarke et al., 2006). Moreover it has been shown that the risk of a fatal crash is increased up to four times when driving at night compared to daytime (Williams, 2003). It has been suggested that any increase in road crashes during nighttime is partly due to voluntary risk taking of the drivers (Clarke et al., 2005). Another possibility is that those types of crashes are due to sleepiness (Akerstedt et al., 2001). There is however evidence that a high number of crashes during night are primarily due to visual problems associated with low luminance conditions leading to an increase in reaction times (Plainis and Murray, 2002). More specifically it has been suggested by Leibowitz and Owens (1977)

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that although night driving conditions have little effect on peripheral vision, "focal" vision is degraded and this might cause neglect of low luminance objects during night driving.

Another factor that affects driving crashes is weather. Despite the fact that the link between weather conditions and traffic crashes is far from clear (Edwards, 1998) there are some common findings and suggestions. In regards to driving in rainy conditions it has been shown that there is an increased risk of a crash in wet rather than dry weather (Brodsky and Hakkert, 1988) and in a recent meta-analysis it was found that crash rates in rain are increased up to 71% (Qiu and Nixon, 2008). Rain conditions obviously make driving more dangerous due to the impact of decreased friction on stopping distances and handling. However, Brodsky and Hakkert (1988) claimed that as well as problems created by the loss of friction, visibility in rainy conditions may also play a significant role. Also, certain types of collisions, such as hitting objects, have been associated with driving in rain (Golob and Recker, 2003).

In addition to statistical analysis of crash records pertaining to night and rain driving there are studies that explore self-regulation in driving. Additional support that night driving is perceived as more difficult and demanding comes form self-report studies in which older drivers stated they self-regulate night driving (Reimer et al., 2007). In addition it has been shown that driving at night with rain is a situation that older drivers especially try to avoid (Baldock et al., 2006). In one study 80% of drivers older than 55 reported that they often or always avoid night driving (Ball et al., 1998). Finally, there are findings to suggest that older drivers with age-related maculopathy regulate their driving under night and rain (DeCarlo et al., 2003). It seems that both accident data analysis and self-reported methods show that night and rain driving have increased crash risk and they are perceived to be more demanding for the driver. However, it appears that more experienced drivers may not be affected in the same way as novices, since accident involvement (at-fault) drops around 6% per year of holding a driving licence (Clarke et al., 2006).

1.2. Driving experience and visual attention

Many researchers agree that driving experience is one of the key predictors of crash rates (Chapman and Underwood, 1998; Gregersen and Bjurulf, 1996), with young novice drivers being particularly at risk (Clarke et al., 2006; Neyens and Boyle, 2008). Although accident risk in young drivers has been decreasing both in the USA (Foss, 2007) and Europe (Twisk and Stacey, 2007) traffic crashes still constitute the most common cause of death for young people in the developed world (Clarke et al., 2005), with a global annual loss of around 400,000 people aged under 25 (WHO, 2007). In relation to night driving it has been found that young novice drivers are at proportionally higher risk (Clarke et al., 2006), with young drivers having up to three times more crashes at night than daytime (Williams, 2003).

An important factor that links the potential increased crash risk of low visibility conditions with driving experience is the deployment of visual attention. This includes both foveal and peripheral attention, which have both been shown to change with increased task experience. For example it has been suggested (Ball et al., 1993) that the Useful Field of View (UFoV) is a better predictor of accidents in older drivers than the typical acuity tests. Also the extent of peripheral attention has been shown to be dependent on cognitive factors, such as processing load, which can be moderated by driving experience (Crundall et al., 1999, 2002). If night and rain driving increases cognitive demand then this may reduce the useful field of view in these conditions.

Indeed it has been claimed that the higher accident rate of young drivers is due to poor cognitive skills and not due to lack of vehicle control (Deery, 1999). In a review of the related literature findings Underwood (2007) suggested that the efficiency of visual search strategies is one of the fundamental changes in skill that marks the transition from novice to experienced driver. In addition, visual attention has been considered as a contributing factor for traffic crashes (Crundall et al., 2004). It is possible that the high crash rates of young drivers under night and rain conditions could also be attributed in part to the lack of adaptation in their visual strategies. This is in agreement with the notion that experienced drivers adapt their visual search strategies to anticipate various demands of different driving conditions in contrast to young drivers (Underwood, 2007). Finally findings from the 100-car naturalistic study showed that almost 80% of traffic accidents could be attributed to inattention (Klauer et al., 2006). However, in the latter study the term inattention includes drowsiness and dual task distraction in addition to visually related scanning patterns. Here we will focus more at the exploration of eye movement as a measure of visual attention.

Visual attention and eye movements are closely related, although this link is not perfect since covert visual attention can occur without eye movements (Engbert and Kliegl, 2003). Nevertheless, eye movements and visual attention are linked in most instances (Itti and Koch, 2001). In terms of driving research, eye movements' recording has been considered as an appropriate research tool to identify drivers' visual attention (Velichkovsky et al., 2003). Novice drivers were found to have higher processing time and less horizontal spread of search than experienced drivers as measured by the recording of eye movements while participants were driving a real car (Crundall and Underwood, 1998). In another study, experienced drivers had shorter fixation durations than novice drivers during the presentation of dangerous driving conditions (Chapman and Underwood, 1998). There is also evidence for a decreased horizontal spread of search at night compared to day in simulated driving (Crundall et al., 2004).

1.3. Driving simulators

Regarding the effect of visibility on drivers' visual attention there are some reasons why an on-road study is problematic. An on-road study might generate some safety and ethical issues, as well as reducing the level of experimental control. It would also be expensive to run. However, there is a research tool that will minimise these methodological and financial issues. Indeed, it has been suggested (Reed and Green, 1999) that safety, cost and experimental control are three of the advantages of using simulators. Moreover it was claimed that driving simulators can generate driving conditions that are relatively similar to on-road studies (Tornros, 1998). So it seems that in general driving simulators can be the middle ground between naturalistic on-road studies and accident data analysis studies, bridging the research gap between these methodologies. This may be one of the reasons that driving simulators are increasingly used to investigate drivers' visual skills and perception (Kemeny and Panerai, 2003). Hence, the use of a driving simulator to investigate different driving conditions, such as night and day, is considered appropriate.

However, the use of driving simulators is not without methodological concerns. One of the issues that researchers are concerned with when using driving simulators is the fact the drivers' behaviour will not be the same under simulated driving since there is not any risk involved (Reimer et al., 2006).

1.4. Present study

In the present study driving instructors (DIs) and learner drivers (LDs) drove under day, night and rainy conditions in a simulator while their eye movements were recorded. Based on the experimental findings mentioned above regarding driving experience we assume that DIs' eye movements will reveal shorter but more frequent fixations, reflecting reduced processing time, and a higher sampling rate of the visual scene compared to LDs. They should also show broader scanning than LDs. In addition, on the basis of the increased accident rates during night and rain driving reported in the literature, we hypothesise that drivers' eye movement patterns will be less efficient under night and rain driving than day driving (e.g. longer fixations, narrower spread of search). Also an interaction between driving experience and visibility is expected with LDs' visual search strategies degraded more than DIs' under night and rain driving. Finally the relative validity of the driving simulator will be examined by comparing eye movements to similar studies (on-road and video-based) since the comparison of physiological measures is considered acceptable for validation purposes (Reed and Green, 1999).

2. Method

2.1. Design

A mixed design was employed for this study. The between factor was driving experience with driving instructors and learner drivers as levels. The within factor was condition with day, night and rain as levels. The dependent variables were the number of fixations, as a measure of sampling rate; mean fixation durations as an indication of processing time; and the standard deviations of the fixation locations in *X* and *Y* coordinates as a reflect of spread of horizontal and vertical search. In addition a frame-by-frame analysis was conducted, on a video with the position of the eye overlaid o the field of view, in order to identify participants' attention allocation on mirrors. In order to investigate how often the speedometer was inspected by the participants, the speedometer was defined as one area of interest and only the fixations that fell within this area were calculated automatically on the basis of *X* and *Y* coordinates. In these analyses the independent variables were again visibility and group and the dependent variables were the number of fixations on the left, right and rear view mirror as well as the speedometer.

2.2. Participants

Twenty-four participants were recruited for this experiment. The data for 3 participants were excluded from further analysis due to technical failure of the recording apparatus. The remaining participants formed two groups. The first group consisted of 10 DIs, 2 females, with mean age of 51 years (SD = 11). The mean driving experience for this group was 34 years (SD = 11). Their experience as driving instructor was on average 9.2 years (SD = 9). The other group consisted of 11 LDs, of which 7 were females, with a mean age of 21 years (SD = 2). Their driving experience was measured in hours of driving lessons with a mean of 24 h (SD = 11). The driving lessons included practical training and verbal instructions according to UK common practice (some examples of instructions about visual scanning can be found at Miller and Stacey (2006, p. 79).

2.3. Stimuli and apparatus

Participants drove three predetermined routes on a Faros GB3 driving simulator. The driving routes were geographically the same and the only difference between routes was visibility with the employment of three conditions day, night and rain (see Fig. 1). The starting point for each route was the same for all participants as it was defined geographically (e.g. when the car passed a certain point of the route). No extra processing was done for the finish point of the route since this was done automatically by the software when the cars passed a certain point. The speed limit was 30 miles per hour (mph).

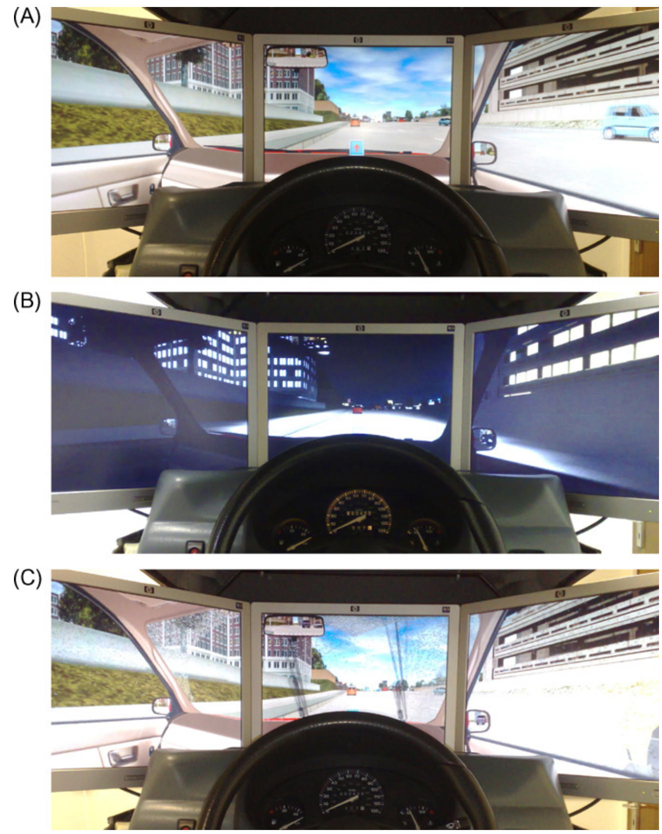

Fig. 1. Example screenshots to demonstrate simulated conditions. (A) illustrates "Day", (B) "Night" and (C) "Rain" driving conditions.

During the route, participants had to encounter variable driving conditions due to the interactive nature of the simulator (e.g. some participants had to stop at a red light while others might have encountered a green light at the same point). All three routes incorporated a 4-lane (2-lanes per direction) urban road with moderate traffic that included traffic lights, right and left turns, intersections, etc. The driving conditions included other road users that moved normally on the road, obeying traffic laws, and it was possible for them to overtake the driver on some occasions. We did not implement any hazards during the routes in order to focus on visibility issues. The dynamic environment was presented on three 19″ LCD monitors (380 mm × 300 mm). Eye movements were recorded by using a SMI iView XTM HED, 50 Hz video-based/corneal reflection tracker. Fixation was calculated with the velocity based algorithm and the minimum duration was set to 100 ms. Also the fixation calculation algorithm allowed pursuit tracking to be registered as one fixation.

2.4. Procedure

All participants first completed a questionnaire asking some demographic questions. They were then seated at the simulator and told to adjust the driving seat in order to have a comfortable driving posture. In order to familiarise themselves with the simulator all participants drove a 5 min practice route which was different than the test route. Participants' eye movements were calibrated using a 13 point calibration screen. After calibration participants drove all three routes in a counterbalanced order in order to minimise any effects of route familiarity, however the possibility that the drivers could have different fixation patterns as their familiarity improved (Mourant et al., 1969) should be taken into account. Participants were instructed to drive as they would do normally and

Table 1
Means and standard deviations for eye movement measurements for DIs and LDs across visibility conditions.

Condition:	Day		Night		Rain	
Group:	DIs	LDs	DIs	LDs	DIs	LDs
Driving time (min)	5.3 (0.4)	5.2 (0.4)	5 (0.4)	5.4 (0.6)	5.2 (0.4)	4.9 (0.9)
Number of fixations	673 (89)	556 (114)	620 (80)	551 (148)	608 (96)	449 (155)
Mean fixation durations	413 (58)	519 (102)	424 (31)	539 (138)	457 (54)	644 (235)
Horizontal deviation (°)	11 (1.9)	6.2 (1.1)	10 (1.9)	5.9 (1.1)	11 (2.0)	6.6 (1.9)
Vertical deviation (°)	3.2 (0.6)	3.3 (0.7)	3.4 (0.6)	3.5 (0.4)	3.1 (0.5)	3.1 (0.7)
Pupil diameter (px)	45 (6.7)	56 (11.5)	55 (11)	69 (12.3)	46 (7.7)	57 (10.6)

follow the traffic regulations. Auditory directions were presented to guide participants along the route by arrows at the bottom of the screen and auditory instructions. The duration of each route was approximately 5 min. Participants were warned by a sign and a recorded message to slow down when exceeded 30 mph.

3. Results

Four eye movement measures are reported, number of fixations, mean fixation duration, standard deviations of the horizontal and vertical fixation locations (measured in degrees). Finally, the pupil diameter will be examined across the three visibility conditions. The means and standard deviations for all measurements can be seen in Table 1. In order to identify when key portions of the visual display were fixated, an area of interest (AOI) analysis was performed. The AOI were the left, right and rear view mirrors and the speedometer. This selection was made based on previous research findings (Underwood et al., 2002a) suggesting that group differences on vertical and horizontal spread of search is possibly due to mirror inspection. The means and standard deviations for the fixations on the AOI can be seen in Table 2.

In any analysis where Mauchly's test suggested that the assumption of sphericity was violated the Greenhouse-Geisser Epsilon was used to correct the degrees of freedom. Orthogonal pre-planned Helmert contrasts were performed for every significant main effect. In the first level "Day" condition was compared with the average of "Night" and "Rain", and "Night" was compared directly to the "Rain" condition.

3.1. Number of fixations

As participants had to encounter variable driving conditions the time of driving was not the same for everyone (e.g. some participants stopped at a red light while others encounter a green light at the same point). This could lead to methodological issues especially when concerning the number of fixations. For that reason an analysis was performed for driving time between groups and across visibility conditions. Mauchly's test showed that the assumption of sphericity was violated, χ^2 (2) = 15.5, $p < 0.05$; hence the more conservative Greenhouse-Geisser ($\varepsilon = 0.6$) was used to correct degrees of freedom. No main effect of visibility was found, F (1.3, 24.1) = 0.93, $MS_e = 0.39$, $p = 0.37$, and the group main effect was not significant, F (1, 19) = 0.01, $MS_e = 0.15$, $p = 0.99$. Finally no interaction between group and visibility was detected, F (1.3, 24.1) = 2.55, $MS_e = 0.39$, $p = 0.12$. This suggests there should be no systematic confounding of number of fixations due to driving time.

For the number of fixations all the fixations during the 5 min route were analysed. There was a main effect of visibility, F (2, 38) = 9.82, MS_e = 4 044, $p < 0.001$. Pre-planned contrasts showed that drivers had more fixations in the "Day" (mean = 614) route than in the other two routes (mean = 557, F (1, 19) = 16.97, MS_e = 4 046, $p < 0.01$) and also that they produced significantly greater number of fixations in "Night" (mean = 585) than "Rain" (mean = 529, F (1, 19) = 6.24, MS_e = 10 782, $p < 0.05$). There was a main effect for group, F (1, 19) = 6.07, MS_e = 11 376, $p < 0.05$ with DIs (mean = 634) having greater number of fixations than LDs (mean = 519). Finally no interaction was found between visibility and group for number of fixations, F (2, 38) = 2.62, MS_e = 4 044, $p = 0.09$.

3.2. Mean fixation durations

Regarding mean fixation durations there was a main effect of visibility, F (1.3, 24) = 5.24, MS_e = 12 763, $p < 0.05$. Pre-planned comparisons showed that drivers had shorter fixation durations in the "Day" (mean = 466 ms) route than in the other two routes (mean = 516 ms, F (1, 19) = 5.63, $p < 0.05$) and also that they produced significantly shorter fixation durations in the "Night" (mean = 482 ms) route than the "Rain" route (mean = 550 ms, F (1, 19) = 4.99, $p < 0.05$). There was a main effect for group, F (1, 19) = 9.09, MS_e = 10 648, $p < 0.05$ with DIs (mean = 431 ms) having shorter fixation durations than LDs (mean = 567 ms). Finally no interaction was found between visibility and group for mean fixation durations, F (1.3, 24) = 1.27, MS_e = 12 763, $p = 0.28$.

3.3. Horizontal spread of search

No effect was found for visibility, F (1.5, 29) = 1.06, $MS_e = 0.96$, $p = 0.34$. There was a main effect for group, F (1, 19) = 40.27, $MS_e = 2.41$, $p < 0.001$ with DIs (mean = 10.6°) having broader spread of search in the horizontal axes than LDs (mean = 6.2°). An example of the spread of search along the horizontal axes for a DI and a LD is shown in Fig. 2. Finally no interaction was found between visibility and group for horizontal deviation of fixations, F (1.5, 29) = 0.59, $MS_e = 0.96$, $p = 0.52$.

3.4. Vertical spread of search

In regards to the vertical deviations there was a main effect of visibility, F (2, 38) = 3.50, $MS_e = 0.13$, $p < 0.05$. Pre-planned com-

Table 2
Means and standard deviations of the fixations on areas of interest.

Condition:	Day		Night		Rain	
Group:	DIs	LDs	DIs	LDs	DIs	LDs
Left mirror	3.1 (3.1)	0.1 (0.4)	1.8 (1.9)	0.1 (0.4)	2 (2)	0 (0)
Right mirror	12.1 (7.3)	1.6 (1.3)	11.2 (6.3)	3.1 (2.4)	12.3 (6.8)	1.5 (1.8)
Rear view Mirror	17.1 (9.7)	17.3 (4.5)	17.1 (8.6)	11 (4.8)	12.3 (8.2)	12.6 (7.6)
Speedometer	3.4 (7.3)	15.3 (16.2)	3.6 (6.6)	17.5 (17)	3 (7.1)	8.3 (6.4)

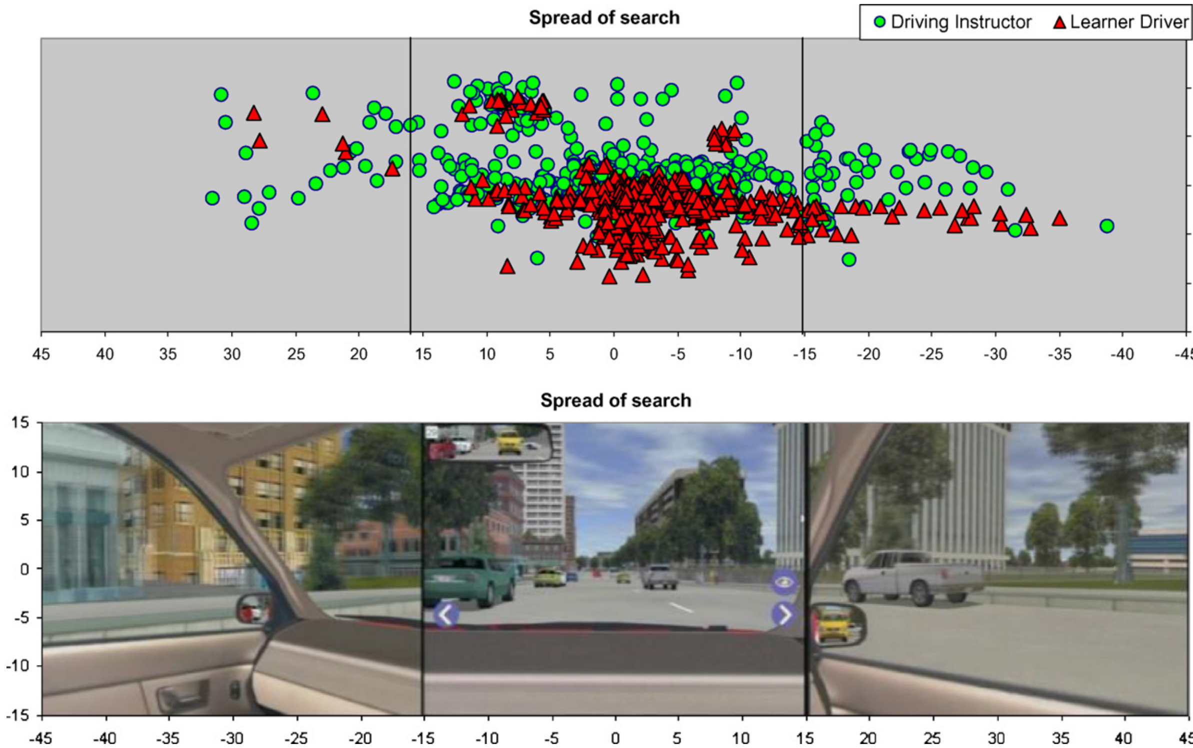

Fig. 2. Upper image represents an example of spread of search between one driving instructor and one learner driver during "Day" driving. Both axes represent visual angle measure in degrees. Lower picture is for demonstration purposes to indicate where the illustrated fixations might be allocated in the driving scene. Despite the fact that the fixation patterns look similar there are actual statistical differences at horizontal spread of search with DIs having broader spread and less fixations than LDs. Also DIs fixated more time on side mirrors than LDs.

parisons showed that drivers did not have significantly different vertical spread of search between "Day" (mean = 3.2°) and the average of the other two routes (mean = 3.3°, $F(1, 19) = 0.25$, $MS_e = 0.23$, $p = 0.62$). However, drivers had broader vertical scanning in the "Night" (mean = 3.4°) route than during "Rain" (mean = 3.1°, $F(1, 19) = 8.44$, $MS_e = 0.20$, $p < 0.05$). There was no group effect, $F(1, 19) = 0.07$, $MS_e = 0.27$, $p = 0.80$. Finally no interaction was found between visibility and group for vertical deviation of fixations, $F(2, 38) = 0.13$, $MS_e = 0.13$, $p = 0.88$.

3.5. Pupil diameter

For the pupil diameter there was a main effect of visibility, $F(1.3, 24) = 141$, $MS_e = 9.57$, $p < 0.001$. Pre-planned comparisons showed that participants had smaller pupil diameter during the "Day" (mean = 51 px) route than the other two routes (mean = 57 px, $F(1, 19) = 82.66$, $MS_e = 9.20$, $p < 0.001$). In addition contrasts revealed that participants' pupil diameter was significantly higher during the "Night" route (mean 62 px) than "Rain" (mean = 51, $F(1, 19) = 200.63$, $MS_e = 12.00$, $p < 0.001$). There was a group effect, $F(1, 19) = 7.91$, $MS_e = 100.95$, $p < 0.05$ with DIs (mean = 48 px) having smaller diameter than LDs (mean = 61 px).

3.6. Areas of interest analysis

No effect of visibility was found, $F(1.4, 20.7) = 1.6$, $MS_e = 2.1$, $p = 0.2$, and no significant interaction, $F(1.4, 20.7) = 1.4$, $MS_e = 2.1$, $p = 0.3$. A group effect was found, $F(1, 15) = 10.2$, $MS_e = 2$, $p < 0.05$, with DIs having significantly more fixations (mean = 2.3) than LDs (mean = 0.1) on the left mirror.

For the fixations on the right mirror no effect of visibility was found, $F(2, 30) = 0.1$, $MS_e = 7.5$, $p = 0.9$, nor a significant interaction, $F(2, 30) = 1.2$, $MS_e = 7.5$, $p = 0.3$. A group effect was again found, $F(1, 15) = 19.2$, $MS_e = 2$, $p = 0.001$, with DIs having significantly more fixations (mean = 11.9) than LDs (mean = 2.1) on the right mirror.

For the fixations on the rear view mirror a visibility effect was found, $F(2, 30) = 6.3$, $MS_e = 15.3$, $p < 0.05$. Pre-planned contrasts showed that participants fixated the rear view mirror significantly more on the day route (mean = 17.2) compared to the average of the night and rain routes (mean = 13), $F(1, 15) = 13.5$, $MS_e = 19.2$, $p < 0.05$. No group effect was found for this analysis, $F(1, 15) = 0.3$, $MS_e = 47.4$, $p = 0.6$. Finally a significant interaction was found, $F(2, 30) = 3.7$, $MS_e = 15.3$, $p < 0.05$, and pre-planned contrasts showed that the interaction occurred between night and rain levels with DIs decreasing their rear view mirror fixations in the rain condition (mean = 12.3) relative to the night condition (mean = 17) while LDs had relatively similar night and rain rear view inspection pattern during night (mean = 11) and rain (mean = 12.6).

The analysis of speedometer fixations showed an effect of visibility, $F(2, 40) = 3.5$, $MS_e = 40.5$, $p < 0.05$. Pre-planned comparisons showed that participants made more speedometer inspections during night (mean = 10.6) than the rain condition (mean = 5.7). A group effect was found, $F(1, 20) = 5.6$, $MS_e = 104.8$, $p < 0.05$, with DIs (mean = 3.3) fixating the speedometer significantly less than LDs (mean = 13.7). No significant interaction was found, $F(2, 40) = 2.7$, $MS_e = 40.5$, $p = 0.08$.

4. Discussion

The purpose of the experiment was to identify how drivers' visual attention is affected by both driving experience and different visibility conditions. Two groups with different driving experience (DIs and LDs) participated in this experiment. Also in order to generate and manipulate different visibility conditions (day, rain, night) a driving simulator was used. Eye movements were used as the behavioural aspect of visual attention and the fixation allocation on certain areas of interest (mirrors, speedometer) was used as indication of visual search.

4.1. Driving experience

The hypothesis that DIs will differ significantly from LDs was supported for all eye movement measures apart from vertical deviation of fixations. In general DIs had a greater number of shorter fixations distributed more widely across the driving scene. DIs had a higher sampling rate of the driving scene across all three visibility conditions. This results shows that DIs were able to collect more information of the scene by employing more fixations. This result confirms previous findings (Chapman and Underwood, 1998; Crundall and Underwood, 1998) which showed similar pattern of results.

Moreover DIs needed less processing time as indicated by shorter mean fixation durations. DIs were able to move their locus of attention quicker than LDs independently of the visibility condition. The present findings are consistent with previous results since it has been found that more experienced drivers' need less processing time (Chapman and Underwood, 1998) as demonstrated by shorter mean fixation durations. DIs' strategy of deploying frequent short fixations can be considered crucial in hazardous situations when the driver has to be able to anticipate dangerous on-road behaviours by maintaining awareness of many potential sources of hazard without becoming overly focused in any one source.

DIs spread their fixations on the horizontal axis significantly wider than LDs irrespectively the visibility of driving conditions. This result could be attributed to the significantly higher number of fixations to both side mirrors that DIs had in relation to LDs. Fig. 2 shows a representative example of the spread of fixations for a DI and a LD on which we can see that DI has wider spread of fixations than the LD. Similar findings come from previous analysis of on-road driving (Underwood et al., 2002a) which found that experienced drivers inspect their side mirrors more than novices. It seems that LDs have restricted their fixation allocation to the scene more directly in front of them which results in a significantly narrower allocation of fixations than DIs. Konstantopoulos and Crundall (2008) showed that novice drivers' infrequent inspection of side mirrors might not be due the demands of the driving situation but due to different prioritisation strategies that novices have in relation to DIs. Finally, in agreement with previous research (Crundall and Underwood, 1998) no group differences were found for vertical deviation. The lack of group differences in vertical deviation might be explained by the fact that groups did not differ in their frequency of fixations on the rear view mirror. In contrast there was a significant group difference for the speedometer but this difference was not enough to reveal any variability between groups at the vertical spread of fixations.

4.2. Visibility conditions

In general, visibility conditions affected drivers' eye movements. Drivers had lower sampling rates and longer fixations when driving a route with decreased visibility in comparison to day driving. Both low visibility conditions resulted in reduced fixations with rain condition producing the fewer fixations overall. A similar pattern of results was found for the mean fixation durations. Drivers' had longer fixation durations when driving at night and rain in comparison with the day route on which drivers' had the shortest fixation durations. Hence the decreased visibility conditions resulted in increased processing time and lower sampling rate. For LDs the results are not so surprising since they are expected to have decreased performance in such situations since they might not have the experience under those conditions. Surprisingly DIs were also affected by rain and were not be able to maintain their high day-time sampling rate across all conditions. Also, DIs needed longer to process information in the driving scene under decreased visibility conditions, especially in the rain condition.

In regards to horizontal spread of search no effect of visibility was detected. It seems that both DIs and LDs did not change their horizontal allocation of fixations according to visibility conditions (although DIs had significantly broader horizontal scanning than LDs). If the spread of search was partly dictated by peripheral stimuli attracting attention one might expect poor visibility to reduce the possibility that such cues might be spotted and therefore reduce the spread of search. The fact that this does not happen suggests that drivers' horizontal spread of search could be influenced by top-down strategies. In addition, another interesting finding is that the number of fixations and mean fixation durations are affected by visibility while horizontal spread of search is not. So processing time and sampling rate are affected by degradation of bottom-up information while the deployment of visual attention in the horizontal axis, is not affected by such bottom-up influences to such an extent. These findings might generate some questions about top-down and bottom-up influences upon different parameters of eye movements, however, such speculation needs further investigation.

Finally vertical deviation of fixations was affected by the visibility of the driving route. The orthogonal pre-planned contrasts showed that both DIs and LDs on the night route had significantly increased vertical deviation of fixations compared to the rain route. One possible explanation for these results is that speedometer was inspected at night more often because this condition removed peripheral information vital for speed estimation.

4.3. Interaction between driving experience and visibility

Interestingly, and contrary to our hypothesis, no interaction was found between driving experience and visibility, apart from the number of fixations to the rear view mirror. The results showed that group differences remained constant despite visibility conditions. One explanation might be the relatively small sample size, however since there was a lack of interaction in nearly all the statistical tests, it is reasonable to seek alternative explanations. Since certain aspects of eye movements for both driving groups were affected by visibility it seems possible to suggest that some elements of visual search are developed through general driving experience independently of the driving condition. The present results might provide additional support for the efficacy of graduated driver licensing (GDL) since it does not allow novices to drive in risky driving conditions (Hedlund, 2007) while at the same time it is possible for novices to develop some essential visual search skills by driving in less demanding situations. Hence GDL might allow a less risky transition from novice to more experienced driver without any restrictions on the development of general visual search strategies.

4.4. Simulator validity

The relative validity of the simulator can be examined by comparing the eye movement results of the present studies with similar results from other environments. Regarding the experiential differences it was found that DIs had more effective visual search strategies (e.g. more frequent and shorter fixations, broader horizontal spread of fixations) than LDs which replicate previous results (Chapman and Underwood, 1998; Crundall and Underwood, 1998; Mourant and Rockwell, 1972). Although it has been suggested that there is a possibility that driving simulators exaggerate experiential differences (Blaauw, 1982) there is no reason to believe that DIs would be more comfortable in a simulated environment than LDs. So it is reasonable to suggest that the driving simulator has relative validity as a research tool to investigate experiential differences in driving.

In regards to the visibility effects the issue of validation is less clear. Day driving in this particular simulator could be considered having relative validity since the outcome in day driving is comparable to on-road studies such as the Crundall and Underwood (1998) study that mentioned above. Regarding night driving one question that someone might ask is if the night driving really simulates night driving conditions. In absolute terms this issue is unknown since no luminance measurements were taken and there was not calibration of the screen or of the stimuli due to dynamic nature of the simulator. However we have indirect evidence from pupil diameter that night driving was relatively darker than the other conditions. Pupillary light reflex will adjust its diameter according to available illumination (Wyatt and Musselman, 1981), with the pupil becoming larger when there is less light available in order to accommodate for the low luminance conditions. The present results indicate pupil diameter was significantly larger in night condition than the other two. In regards to the group effect in pupil size that we found it can be explained by the age difference of the groups. It has been found that age affects pupil size and older adults have smaller pupil size than younger individuals (Winn et al., 1994). Hence our results regarding pupil dilation fit with previous findings and indicate that the night route was darker in comparison to other two routes. However, it has been suggested (Recarte and Nunes, 2000) that pupil diameter is linked to attentional workload hence the results regarding pupil diameter might have been affected by the workload in the night condition. Nonetheless, it seems that the present findings are affected more by light reflex than mental workload due to large decrease in pupil diameter in the night condition only.

Driving under rain conditions also had an effect on drivers' visual search patterns. Whether this effect is simulator-specific finding is not clear. Kemeny and Panerai (2003) have suggested that for visibility testing it is necessary to have absolute fidelity of the simulator. However, due to the novelty of the results, not only is it not possible to test absolute validity, but furthermore it is very difficult to examine the relative validity because there are no similar studies available to compare the results to. While it is acknowledged that simulating rain is very difficult (Rokita, 1997) since it was shown that the other two conditions have relative validity it is more likely that the rain condition has satisfied the relative validity criterion. Despite that indication further research on this topic is necessary.

4.5. Theoretical explanations

There are some possible explanations that can explain both group and visibility results. One reason that might explain part of the present results is the visual properties of the stimuli. Plainis and Murray (2002) have shown that stimuli that simulate night driving (low luminance) result in slower reaction times. Consequently it could be argued that visual properties of night and rain driving might have affected visual search of the drivers. However, with such a simplistic explanation it is difficult to explain why the rain route had a greater effect than the night condition on visual search and why in some instances night performance did not differ from day. Nevertheless it seems that rain driving affected visual search. So probably, in addition to risky driving or wet road conditions there are some visual aspects to rain driving that may contribute to the risk. This could be supported by the finding that there is increased accident risk during rainfall but this risk returns to normal after rain has stopped despite the continuing wet road conditions (Andrey and Yagar, 1993). It is possible that the combination of wipers and raindrops reduce the visibility of the driver considerably and lead to increased accident risk. In fact one possible explanation might come from the field of change blindness (Rensink et al., 2000). Rensink et al. found that achromatic "patches" that were presented on-screen affected participants' reaction times to identify changes. Applying this finding to the present results it could be argued that virtual rain disturbed participants' visual search. Also it could be said that after the wipers cleaned the windscreen the new raindrops affected the visual search pattern of the drivers. This sound possible since it has been found that new objects attract attention even if there is no luminance change (Yantis, 1993).

Other possible explanations for the results come from mental workload research. Previous studies (Lee et al., 2007; Recarte and Nunes, 2003) have demonstrated that mental workload affects driving performance. Applying that to our results it could be said that the driving task is very demanding for the LDs because of the novelty of the task. Following the same rationale it could be said that driving under rain increased the workload of all the participants hence it increased their processing time. Despite the fact that mental workload undoubtedly plays a role in driving performance it does not entirely explain the processes that underlie driving. It has been shown that experiential differences in visual search patterns are present even when drivers are watching driving videos which consist of considerable less workload than actual or simulated driving (Underwood et al., 2002b)

5. General conclusions—future research

The previous findings in the literature which show that driving experience influences visual search is replicated in this experiment. Furthermore the present study offers new insight into the effects of visibility and how it is moderated (or not) by driving experience. In particular rain driving was found to significantly affect the sampling rate and the processing time of participants. The lack of interaction between driving experience and visibility conditions showed that experiential differences on visual search strategies are not affected by low visibility conditions. Also the possibility that some eye movements parameters (horizontal spread of search) are affected less by bottom-up influences than others (number and duration of fixations) should be taken into account.

An additional point of interest, that future replications should consider, might be the frequency of traffic violations while driving at different visibility conditions. Another future research question might be the identification of the differences in behavioural data, such as speed and steering deviation, during different visibility conditions. All the findings in the present study derive from a methodology that used a driving simulator and in general the driving simulator used here showed relative validity when compared with similar studies. However, there are some specific issues, like rain driving, that require further validation.

Some additional practical implications of the present findings might include the development of training interventions for more efficient visual search strategies. In the past training interventions about eye movements of learner drivers have been successful but time-limited (Chapman et al., 2002). One of the reasons that such training might be short lived could be the general nature of any instruction. Future training should consider the fragmentation and adoption of different visual allocation under different conditions such as rain and night driving. This expansion could be achieved by creating training interventions that take into account the fact that drivers have different sampling rate and processing time under different visibility conditions hence try to accommodate that knowledge when delivering training intervention to train eye movements. Future studies that aim to train drivers' eye movements should take into account the present findings and consider the attentional allocation of drivers as a function of both driving experience and visibility.

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