Driving Blind

The Effects of Vision on Driving Safety and Performance

Final report

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Executive summary

Eyesight requirements for driver licensing in the UK need to be reviewed, suggests new research from Brunel University, sponsored by RSA. The number plate test, which only measures static visual acuity, does not correspond well to minimum requirements in EU legislation. More to the point, acuity itself is not necessarily a factor in driving performance. Other aspects of visual ability, such as field-of-view, should be taken into account, says the report.

The study of 19 drivers in a driving simulator found that on the whole, steering and speed control did not get worse when drivers were wearing specially constructed glasses to blur their vision. But drivers did stray off the road more often, and missed more road signs, even at the legal minimum levels of visual acuity. Drivers also found it more demanding when wearing the blurring glasses. Surprisingly, only just over two-thirds of the participants passed the number plate test at the legal minimum standard.

These findings suggest on the one hand that the current requirements are not stringent enough, with some elements of driving risk increasing even though these drivers would meet the standard. But on the other hand, the report argues that other tests of eyesight might be more appropriate for driver licensing. The study adds to a considerable body of existing knowledge calling for more evidence-based visual screening tests for driver licensing.

The reason for the confusion is that acuity is only one aspect of visual ability. In particular, field-of-view stands out as being especially related to driving performance. So the question may be asked as to why driver licensing regimes persist with tests of acuity to screen their drivers. In fact, moves are afoot to include tests of visual field as well as acuity in the driving test, and the current study supports such moves. Ultimately, though, the number plate test is popular because it is easy to administer – any alternative needs to be equally practical and reliable in screening the right drivers, while not disqualifying those who are capable.

Meanwhile, the report also recommends that a review of other standards for road sign design should be considered. If drivers are meeting the legal requirements for visual acuity, but still cannot read road signs, it suggests that the legibility of these signs is inadequate. Other researchers have suggested that road signs are designed for higher levels of visual acuity than the legislative standard for driving. The current report calls for these standards to be harmonised, so that drivers passing the visual screening test can also read road signs.

Visual requirements for driving

It has often been said most of the information drivers use for vehicle guidance has arrived through the visual modality (e.g., Evans, 2004; Hole, 2007; Kramer & Rohr, 1982). It is, therefore, intuitively appealing that standards for driver licensing should include some element of eyesight testing – which, in most regimes worldwide, means a test of static visual acuity (Higgins et al., 1998; Owsley & McGwin, 2010). European legislation lays down such requirements in Annex III of EU Directive 2006/126/EC, which states that drivers of private cars and motorcycles should have a minimum binocular visual acuity of 6/12[1] – that is, the ability to resolve detail at 6m that an average person could read at 12m.

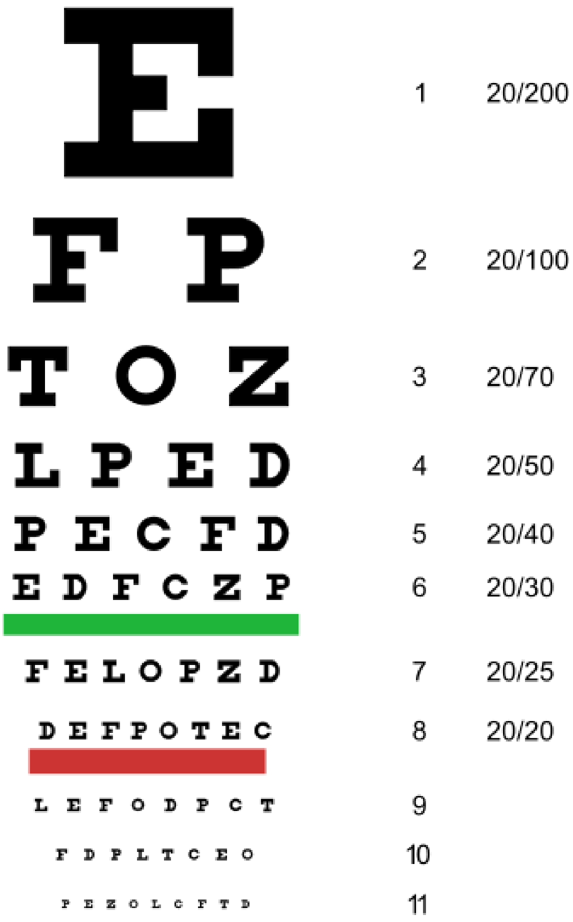

Figure 1: An example of a Snellen visual acuity chart, with imperial acuity indices for each line (Source: http://en.wikipedia.org/wiki/File:Snellen_chart.svg; accessed 14th June 2011).

[1] There are several ways of representing visual acuity – using imperial fractions (e.g., 20/20 – referring to feet), metric fractions (e.g., 6/6 – metres), or decimal fractions (e.g., 0.5, as specified in the EU Directive, equates to 6/12). In this report, metric fractions will be used throughout for consistency.

Measures of acuity are normally made with reference to a standardised Snellen chart (see e.g., Figure 1). In the UK, candidates for a driving test are required to read a standard number plate (with letters 79.4mm high) at a distance of 20.5m (or 20m for the new style number plates)[2]. This requirement has been in place since 1935 (Taylor, 2010), and remains as the UK's interpretation of the EU standard. The number plate test is not without criticism, though. For a start, there are many variables that can impact on readability – such as ambient lighting, dirt on the number plate etc. (Taylor, 2010). Moreover, it is not clear that the test as specified actually meets the EU requirements for visual acuity – geometrically, it is equivalent to a Snellen acuity of around 6/15 (Charman, 1997; Currie et al., 2000). Nor does it necessarily accord with other standards for road signs, which are variously designed based on visual acuity requirements from approximately 6/6.9 (Higgins & Wood, 2005) to 6/9 (Owsley & McGwin, 2010). Elsewhere, research has suggested that some drivers might pass the number plate test even though their visual acuity is at or below the EU standard, while others could have better vision and yet still fail the test. Drasdo & Haggerty (1981) compared a group of people who passed the number plate test with a similar group who had failed, and calculated that the level of visual acuity which would fail the same number of people as the number plate test is more like 6/10. Meanwhile, more than 1 in 20 people with a visual acuity of 6/18 would pass the test. Similarly, Currie et al. (2000) found that more than a quarter of patients with 6/9 visual acuity failed the number plate test, while 34% of those with 6/12 acuity passed it. The same authors suggest that a significant proportion of drivers on the roads would fail the number plate test, and consequently suggest that visual acuity is a "poor predictor of an individual's ability to meet the required visual standard for driving." (Currie et al., 2000; p.990).

It could be argued (e.g., Taylor, 2010) that if the number plate test does reflect a more stringent acuity criterion (in terms of pass rates), then it is erring on the side of caution. But these studies raise an important point regarding the sensitivity of any screening test for drivers – given the importance of mobility as a quality of life indicator, the stringency of the test must be balanced against the risk of disqualifying potentially capable drivers (Charman, 1997). Such tests therefore need to be evidence-based and accurate in predicting actual driving risk. Unfortunately, the evidence base to date remains inconclusive (Owsley & McGwin, 2010), leading some to argue that there is currently no better test suitable for accurately screening those at risk of accidents (Charman, 1997). Nevertheless, many experts feel that screening tests of static visual acuity such as the number plate test are "…of limited value in predicting safe driving" (Owens & Tyrrell, 1999; p. 126) and have called for their replacement (e.g., Taylor, 2010).

[2] http://www.direct.gov.uk/en/Motoring/LearnerAndNewDrivers/LearningToDriveOrRide/DG_4022529

Part of the problem is that it is unclear what aspects of vision relate to driving. Some (e.g., Hole, 2007) argue that detection is more important than identification (i.e., merely being able to see something is the minimum requirement; it is not necessary to know what that object is) – the latter only being important for reading road signs. But it is one thing to be able to see an object on the road; it is quite another to then do something about it (Burg, 1968; Taylor, 2010). In any case, visual acuity must be sufficient to allow time for the driver to detect and react to hazards when driving at the posted speed limits (Taylor, 2010).

The problem is compounded when we consider what aspects of driving we are concerned with. Driving metrics typically fall into two camps: those relating to safety (i.e., crashes), or those relating to performance (behaviour while driving) – and it is often difficult to link the two (Owsley & McGwin, 2010). Underpinning each of these is the driver's ability – which may include their visual ability, but performance and safety are also affected by a wide range of other individual capabilities, as well as external factors. Even if visual acuity does increase accident risk, it does not necessarily follow that the risk will translate into accidents. Thus whilst safety metrics might be appealing and are the most readily available data, they are also arguably the least relevant due to the rarity of accidents and the multiplicity of influencing factors other than vision (Burg, 1968).

It is perhaps because of these factors that there is virtually no substantive evidence of a relationship between visual acuity and accident risk (Evans, 2004; Hole, 2007), in spite of numerous studies investigating such. The research evidence is reviewed in the next two sections of this report, starting with the role of visual acuity in driving safety, before moving on to consider its relevance to driving performance.

Visual acuity and driving safety

Many researchers agree that there is little or no association between visual acuity and driving safety (e.g., Higgins & Wood, 2005; Higgins et al., 1998; Evans, 2004; Hole, 2007; Owsley & McGwin, 2010; Taylor, 2010). There is a handful of studies suggesting a link between visual acuity and accident rates, but in most cases there are issues with the analysis or interpretation of the results (cf. Charman, 1997; Burg, 1968). Small sample sizes cast doubt on some studies, whilst in other cases an exceptionally large sample can result in a statistically significant correlation even though the association is actually very weak, and therefore has little predictive value.

One EU report (CIECA, 1999) latched onto such correlations in support of visual acuity standards for driving, citing evidence from a cohort study (Lachenmayr et al., 1998) which showed that accident-involved drivers had reduced daylight acuity compared with accident-free drivers. Participants in this study were slightly older, with a mean age of 56-57 in each group. Whilst this may be a natural facet of investigating impaired vision (because visual problems increase with age), the results must be interpreted with caution since there may be other co-morbidities associated with age that cannot be ruled out (Charman, 1997; Owsley & McGwin, 2010). Indeed, it is notable that those studies reporting correlations (albeit weak ones) between acuity and accidents tend to be based on older drivers (e.g., Burg, 1968; Charman, 1997; Hole, 2007; Owsley et al., 1998).

Two separate studies from the 1970s sampled large numbers of drivers and compared their visual acuity with their accident records, to show some association with static acuity. Hofstetter (1976) ranked nearly 14,000 drivers according to their binocular visual acuity scores, and found that the lowest quarter of these were about twice as likely to have reported three or more accidents in the last 12 months as the top half of the list. Similarly, Burg (1971) compared the vision test performance of nearly 18,000 drivers with their three-year accident and conviction records, showing an association with static visual acuity. It should be borne in mind, though, that these studies involved people who had already passed their driving test – and hence their eyesight test – and so represent a segment of the population which has already been screened for good vision (cf. Burg, 1968). Nevertheless, there is some evidence that a small but significant proportion of the driving population would fail the current legislative requirements (e.g., Charman, 1997; CIECA, 1999), lending some support to these studies.

Evidence from commercial drivers also points towards a link between visual acuity and crash risk. Taylor (2010) reports on a German review of HGV drivers, noting that those with a visual acuity equivalent to around 6/9 or worse had more frequent accidents. Meanwhile, a study of 215 Nigerian commercial drivers by Oladehinde et al. (2007) found seven drivers with visual acuity of 6/18 or worse; these drivers were three and a half times more likely to have been involved in an accident. Again, though, these numbers are small (for the visually impaired group), and caution should be exercised in drawing more generalised conclusions.

Notwithstanding the outcomes of such studies, it is difficult to escape the overwhelming consensus that static visual acuity is not strongly associated with accident risk (e.g., Charman, 1997). On that basis, it has been suggested that the current standards may be too high, as drivers with Snellen scores of 6/15 present no more risk than those with better visual acuity; others going so far as to say that drivers with 6/60 acuity may be safe if they restrict their speeds (Charman, 1997). With this in mind, a number of studies have instead investigated the role of visual acuity on actual driving performance.

Visual acuity and driving performance

Two pairs of studies here have experimentally manipulated visual acuity by asking drivers to wear goggles with blurring lenses while driving – the first pair of studies in a real car, the second pair in a simulator. Higgins and colleagues (Higgins & Wood, 2005; Higgins et al., 1998) tested driving performance on a 5km closed-road circuit, consisting of a variety of hills, curves, straight sections, junctions and signage. Driving performance metrics included total driving time, sign recognition, hazard avoidance (using foam blocks in the road), gap perception, and steering (using a slalom course). Visual acuity was manipulated from 6/4.5 (the average normal acuity of the 24 participants), through 6/12, 6/30, up to 6/60 (a level of acuity considered to be legally blind in the US). Whilst gap perception or slalom performance was not affected at any level of acuity, sign recognition started to decline from 6/30 while hazard avoidance suffered from 6/12. Speeds also reduced according to total driving time, from around 52km/h (at 6/4.5) to 41km/h (6/60), suggesting some compensatory behaviour – although Higgins & Wood (2005) noted that such compensation did not go far enough given the level of visual degradation. The authors concluded that around 60% of the variance in sign-reading and hazard avoidance performance is accounted for by visual acuity.

Such results have been echoed in simulator studies. Owens & Tyrrell (1999) used a rudimentary steering simulator and presented participants with three levels of optical blur plus a baseline control condition. Although the sample size was small (nine participants – and data were lost for four of these), the authors still concluded that steering accuracy was not affected by blur. Despite the methodological limitations, these results are consistent with test track studies as well as the findings of a high fidelity simulator study by Brooks et al. (2005). Ten participants drove a fixed-base, full car simulator with a 150-degree forward horizontal field-of-view on a rural road at 55mph, with various curves, but no other traffic or junctions. Stationary pedestrians were presented at fixed points during the run for participants to detect. Four levels of blurring lenses were used (with maximum blur providing an equivalent Snellen acuity of 6/197), plus a baseline control condition. Pedestrian detection was fairly robust at low levels of blur, but decreased to 55% at the highest level of degradation. This relationship was statistically significant, with blur accounting for 76.9% of the variance in pedestrian detection. In terms of steering performance, standard deviation of lane position (a typical measure of steering consistency) was unaffected by blur, although there was a mild effect on drivers straying out of their lane.

Taken together, all of the research on static visual acuity and driving point to the conclusion that most driving tasks do not depend on good eyesight in this sense (cf. Hole, 2007) – it does not affect accident risk and hardly affects vehicle control (in terms of steering); only aspects of hazard detection and reading road signs are materially affected by acuity. Whilst the importance of these tasks in driving should not be understated, it does beg the question as to whether any other aspects of visual ability might be more relevant to driving.

Other visual abilities and driving

Visual acuity is only one aspect of vision. Good eyesight depends on a host of other factors with relevance to driving (see e.g., Charman, 1997; Taylor, 2010), such as luminance and retinal adaptation, contrast sensitivity, glare sensitivity, field-of-view, as well as more specific aspects of acuity. Although the legislative requirements are for static visual acuity, there is evidence that dynamic acuity is more closely associated with accident risk (Burg, 1971; Charman, 1997). Luminance also affects acuity, and whilst differences in daytime (photopic) and nighttime (scotopic) acuity are well researched, there is a poorly understood middle ground of twilight vision (mesopic acuity; Schieber et al., 2009). The cohort study of Lachenmayr et al. (1998) referred to earlier suggested that mesopic acuity was particularly related to accidents at night. In the same vein, Owens & Tyrrell (1999) noted that reducing luminance resulted in similar effects as reduced acuity – because luminance effectively restricts acuity. Thus steering performance was largely unaffected, even down to near absolute scotopic thresholds. This probably explains why driving speeds at night, being similar to daytime speeds, far exceed the theoretical limits of vehicle headlights (which should restrict speeds to 20mph) – an observation referred to by Owens & Tyrrell (1999) as 'overdriving' one's headlights.

Whilst there is clear potential in some of these other metrics to offer a more rigorous screening procedure for drivers, they are in many cases difficult to perform and less reliable, with little evidence to support an alternative single measure that can accurately predict driving risk (Charman, 1997; Taylor, 2010). However, there is one aspect of vision that stands out as being particularly relevant to driving performance, and can account for many of the findings already described in this review – field-of-view.

Focal vs. ambient vision

The human eye can only resolve fine detail in a very limited area of central vision – approximately one degree of visual angle, which is roughly equivalent to the width of a thumb at arm's length (Hole, 2007). Outside this zone, in peripheral vision, acuity rapidly falls away – but contrast and movement are much better detected. It follows that peripheral vision might be more important for those vehicle control tasks of steering assessed in the studies reviewed above – and there is good evidence that this is indeed the case.

Schieber et al. (2009) advocated a two-level model of steering according to the division between central and peripheral vision – or focal and ambient (respectively), in the terminology of the model. At a basic level, these can relate to 'what' (identification) and 'where' (navigation). More specifically in relation to steering, focal vision looks further ahead to see where the road is going for medium-term vehicular guidance, while ambient vision monitors the lane edges closer to the car for immediate steering corrections. This model explains why previous research into visual acuity (i.e., focal vision) and driving performance fails to find a notable effect on steering. Furthermore, related studies investigating restricted fields of view do show a relationship with lanekeeping performance.

Field-of-view and driving

Many of the studies on visual acuity reviewed earlier also included an investigation of visual field. The simulator studies by Brooks et al. (2005) and Owens & Tyrrell (1999) both demonstrated that steering performance was significantly affected by extreme visual field loss (below 11 degrees), while acuity had little or no effect. A more directed study by Coeckelbergh et al. (2002) assessed 87 patients with varying visual field defects in a high-fidelity simulator as well as during on-road driving. The simulator scenarios covered urban, rural and motorway driving, and metrics of longitudinal and lateral control were recorded. Participants with peripheral field defects showed more variability in their lane position across all scenarios, went out of lane more frequently, and tended to drive more towards the inside edge of curves. Meanwhile, those with central field defects were worse at longitudinal control, driving more slowly as well as closer to a lead vehicle. Coeckelbergh et al. (2002) then used the simulator data to predict performance during the on-road assessment.

The closed-road circuit used in studies by Higgins and colleagues (Higgins & Wood, 2005; Higgins et al., 1998) was also used by Wood & Troutbeck (1992) to assess the effects of visual field loss. In this study, restricting field-of-view to 40 degrees or less had a significant impact on speed, lateral position, reading road signs, hazard detection, and gap manoeuvring. Although some of these tasks are arguably focal (e.g., reading road signs, hazard detection), interestingly speed estimation – traditionally thought to be served by ambient vision (cf. Scheiber et al., 2009) – was not affected. Stopping distance was also unaffected, in line with the results of Coeckelbergh et al. (2002) suggesting that longitudinal driving tasks might be dependent on focal vision.

Taken together, these studies largely support the distinction between focal and ambient vision in terms of their relevance to driving performance. The key implication is that lateral control tasks are served by ambient vision, while longitudinal control and gathering detail information from the visual scene (e.g., road signs, hazards) appear to be dependent on focal vision – and thus will be affected by visual acuity. Such is the extent of this distinction that even very extreme levels of acuity degradation have little effect on ambient functions such as steering performance (Brooks et al., 2005; Higgins et al., 1998; Owens & Tyrrell, 1999). With regards to driving safety, the consensus of opinion is that field-of-view affects both safety and performance (Brooks et al., 2005; Evans, 2004), with visual field impairments apparently doubling accident risk (CIECA, 1999; Johnson & Keltner, 1983). More specifically, it is 'useful field-of-view' (UFOV) that is considered to be the most significant predictor of crash involvement (CIECA, 1999; Charman, 1997; Evans, 2004; Higgins & Wood, 2005; Owsley et al., 1998). Owsley et al. (1998) describe UFOV as a measure of sensory function, processing speed, and visual attention skills – thus it captures the essence of not just being able to see, but also making use of the information obtained. Their prospective three-year cohort study with nearly 300 drivers demonstrated that a 40% impairment on UFOV resulted in crash risk being more than doubled.

Summary and study rationale

In spite of the intuitive appeal of a visual acuity test for screening drivers (cf. Owsley & McGwin, 2010; Taylor, 2010), there is little evidence to suggest it actually predicts accident risk; furthermore, acuity has only limited effects on some aspects of driving performance. Whilst some experts (e.g., Charman, 1997) maintain that there is no better option for a practical and reliable screening test, several other aspects of vision have been related to driving safety and performance. Perhaps most promising amongst these is field-of-view, particularly 'useful field-of-view'. Some states in the US already have legal requirements for drivers' visual field, and a recent EU Directive (2009/113/EC) amended the existing legislation to include visual field requirements. Indeed, moves are afoot to try and include a formal assessment of visual field in the UK driving test (e.g., Taylor, 2010).

So the question could be asked as to why many driver licensing regimes persist with an outdated and arguably redundant test of static visual acuity (cf. Charman, 1997). The problem remains that there is no clear case for or against such screening, based on current data. The relationship between acuity and accidents is statistically weak, and in any case is fraught with numerous confounding variables. In terms of driving performance, some studies have found an effect on specific aspects of driving, but there are still limitations with these studies, leaving gaps in our knowledge. Closed-road studies have typically been conducted at low speeds and with limited data collection, while simulator studies have used small sample sizes (with the exception of Coeckelbergh et al., who investigated visual field rather than acuity).

Thus a rigorous and robust investigation of visual acuity and driving performance is needed. Following the precedent set by previous research in this field (e.g., Brooks et al., 2005; Coeckelbergh et al., 2002; Owens & Tyrrell, 1999) and the increasing popularity of simulator studies for vision research (Owsley & McGwin, 2010; Taylor, 2010), an empirical investigation of visual acuity in the Brunel University Driving Simulator (BUDS) was conducted and is reported here. BUDS is a fixed-base, high-fidelity simulator not dissimilar to the facilities used by Brooks et al. (2005) and Coeckelbergh et al. (2002). Simulators offer several advantages for research of this nature, providing a fully controllable, repeatable, and safe environment with rich data collection on a range of driving performance variables.

Given the reliance of many driving tests on an assessment of acuity, coupled with the lack of clear evidence regarding static visual acuity and driving performance, the study was designed to investigate the effects of visual acuity on a wider range of driving performance variables than has previously been investigated.

Method

Design

A repeated-measures design was used, with visual acuity manipulated at two levels of blur ('weak' and 'strong' – Snellen equivalents of 6/12, and 6/18), plus a baseline ('normal') control condition at normal levels of acuity (i.e., 6/6). This was achieved using specially constructed spectacles with positive dioptre lenses at varying strengths (+0.75, +1.00, +1.50, and +2.00; plain lenses were also used for the control condition); participants were asked to don a pair of glasses and their acuity was then checked using a computerised version of the Snellen chart, in order to reach the desired acuity for each condition. Thus the independent variable was based on measured acuity, rather than strength of the lenses. The computerised Snellen chart was calibrated against a standardised Snellen chart in the lab, but offered the advantage of randomised letters on each presentation, preventing learning of the chart. Once the desired Snellen acuity had been confirmed, participants were presented with the UK number plate test, using cars in the University car park at the measured distance of 20.5m (a different car was used for each condition, again to prevent learning). The order of presentation of the blurring conditions was counterbalanced throughout, although normal acuity was always presented last to prevent learning of the simulated route (following Higgins & Wood, 2005).

The driving route was modelled on previous studies in this field, with a two-lane single-carriageway inter-urban route comprising a mix of curves and straight sections, for a total distance of approximately 6.6 miles (10.7km). Each lane was 12 feet (3.66m) wide, and the subject vehicle was five feet (1.52m) wide. Participants were asked to drive in the left hand lane (as a UK study) at 45mph (72.4km/h) appropriate to the route (cf. Brooks et al., 2005); this speed was chosen in particular based on the conclusions of Higgins & Wood (2005), who suggested that the lack of a steering effect may have been due to the slower speeds in their study. Moreover, most previous studies have allowed self-paced driving, and this has led to compensatory behaviour (i.e., slowing down) in degraded vision conditions (cf. Higgins & Wood, 2005). In the present study, a 'follow-that-car' paradigm using a fixed-speed lead vehicle was used to discourage compensatory behaviours. Thus there were no junctions, nor requirements for overtaking or stopping in the scenarios.

Two scripted critical events were presented during each trial to investigate hazard detection and response. One of these events comprised of the lead car braking, a firm deceleration from the set speed of 45mph (72.4km/h) to 7.5mph (12.1km/h) over a period of five seconds. This represents a comfortable deceleration rate, but necessitates a braking intervention by the participant in order to avoid a collision. The second hazard was varied across conditions, being either a car pulling out from a driveway or a pedestrian walking into the road. Again, the participant had to intervene in these cases in order to avoid a collision. The dependent variable for these critical hazards was brake reaction time. In addition, three cyclists were presented on the route at two feet (0.61m) from the left lane edge, to determine negotiation of a non-critical hazard; the dependent variable in this case was lateral lane position, as an indicator of safety margin to the cyclist. The timing and order of presentation for all of these hazards was varied across each condition to prevent learning effects.

Six speed limit road signs were presented on each route (again varied according to location and sign content), specifically to measure sign reading ability although this task also serves as an indication of driver situation awareness (a similar task is used in the Institute of Advanced Motorists' coaching and assessment programme). A few seconds after each sign was passed, a recorded verbal instruction was presented through the simulator speakers: "What was the last road sign you passed?" Total number of correct responses in each condition was recorded as the dependent variable.

In terms of other dependent variables, where previous studies have largely concentrated on standard measures of lateral control (steering), sign reading and hazard detection, the present study also assessed longitudinal control. It has been suggested that speed maintenance is a focal task (e.g., Schieber et al., 2009), and therefore may be affected by acuity. Thus metrics of speed and headway maintenance were recorded as per Coeckelbergh et al. (2002). In the present study, these metrics were derived measures of lateral and longitudinal instability, as advocated by Bloomfield & Carroll (1996) and successfully applied in several studies by Young and his colleagues (e.g., Young et al., 2008; Young & Stanton, 2007a, 2007b). Instability represents the standard error of the regression line for each of the variables, and reflects the drivers' relative consistency in their own performance, rather than deviation from an absolute measure (as with standard deviation). This metric is especially useful for lane position, since good driving practice (e.g., IAM, 2007) does not necessarily recommend maintaining a central position in the lane on a curved route. Nevertheless, one can assume that safe driving does normally imply staying inside one's driving lane, and for this reason the number and duration of lane excursions was also recorded as a measure of lateral control. Furthermore, minimum distance headway and minimum time-to-contact (TTC) were also recorded as indicators of safe longitudinal performance.

As well as these continuous measures of driving performance, collisions with other vehicles, pedestrians, and off-road objects were also recorded. Finally, mental workload was assessed using the NASA-TLX subjective workload rating scale (Hart & Staveland, 1988).

Participants

There were several criteria for participation in the study. Participants must have held a UK driving licence for a minimum of three years, and record an average annual mileage of at least 6000 miles. Age was also controlled; although there is a clearer relationship between visual acuity and driving safety for older drivers (e.g., Burg, 1968; Owens & Tyrrell, 1999; Owsley et al., 1998), age also acts as a confounding variable with both visual and driving ability (cf. CIECA, 1999; Owsley & McGwin, 2010; Scheiber et al., 2009). Therefore it was deemed prudent to control this variable by only recruiting younger participants. A conservative estimate of the age at which visual performance starts to decline is 45, and bearing in mind the increased accident risk of younger drivers (e.g., McGwin & Brown, 1999), the age limits for the study were 25-45 years. Finally, in order to maintain control over visual acuity using the blurring spectacles, only participants with contact lenses or 6/6 visual acuity (as confirmed by an eye test in the previous 12 months) were recruited. Gender was balanced as far as practicable within these constraints.

Thus there were 19 participants in the present study (13 male), whose average age was 28.1 years (SD = 3.70). They had held a UK driving licence for an average of 8.47 years (SD = 4.51), and drove an average of 9421 miles per year (SD = 2795). Three participants reported having had a single accident in the last five years; no participants reported having more than one accident.

Apparatus

BUDS is a fixed-base, fully interactive immersive simulator based on a 2006 Jaguar S-Type full vehicle body (see figure 2). The driving simulator software is provided by STISim (Systems Technology Inc, Hawthorne, CA; Build 2.08.04), which has state-of-the-art graphics hardware enabling a real-time, fully-textured, anti-aliased, 3-D graphical scene of the projected virtual world. The images are projected via three

Toshiba TDP-T95 digital projectors onto three 2.4 m x 2.0 m (viewable area) screens at a resolution of 1280 x 1084 pixels, thus giving the forward facing scene plus the left and right peripheral scenes. In total from the driver's seat the projection covers a 150˚ horizontal and 45˚ vertical field-of-view. Simulated images of the dashboard instrumentation as well as rear view and side mirrors are projected onto the viewing screens. The simulator is controlled by a Logitech multimedia driving unit (G25 Racing Wheel) consisting of steering wheel, gear lever and pedal block (including clutch pedal), fitted in the car as a UK-standard right-hand drive vehicle. The Logitech driving unit allows for simulation of manual or automatic transmission, with six-speed manual being used in the present study. The simulator automatically recorded all driving performance variables at a rate of 10Hz.

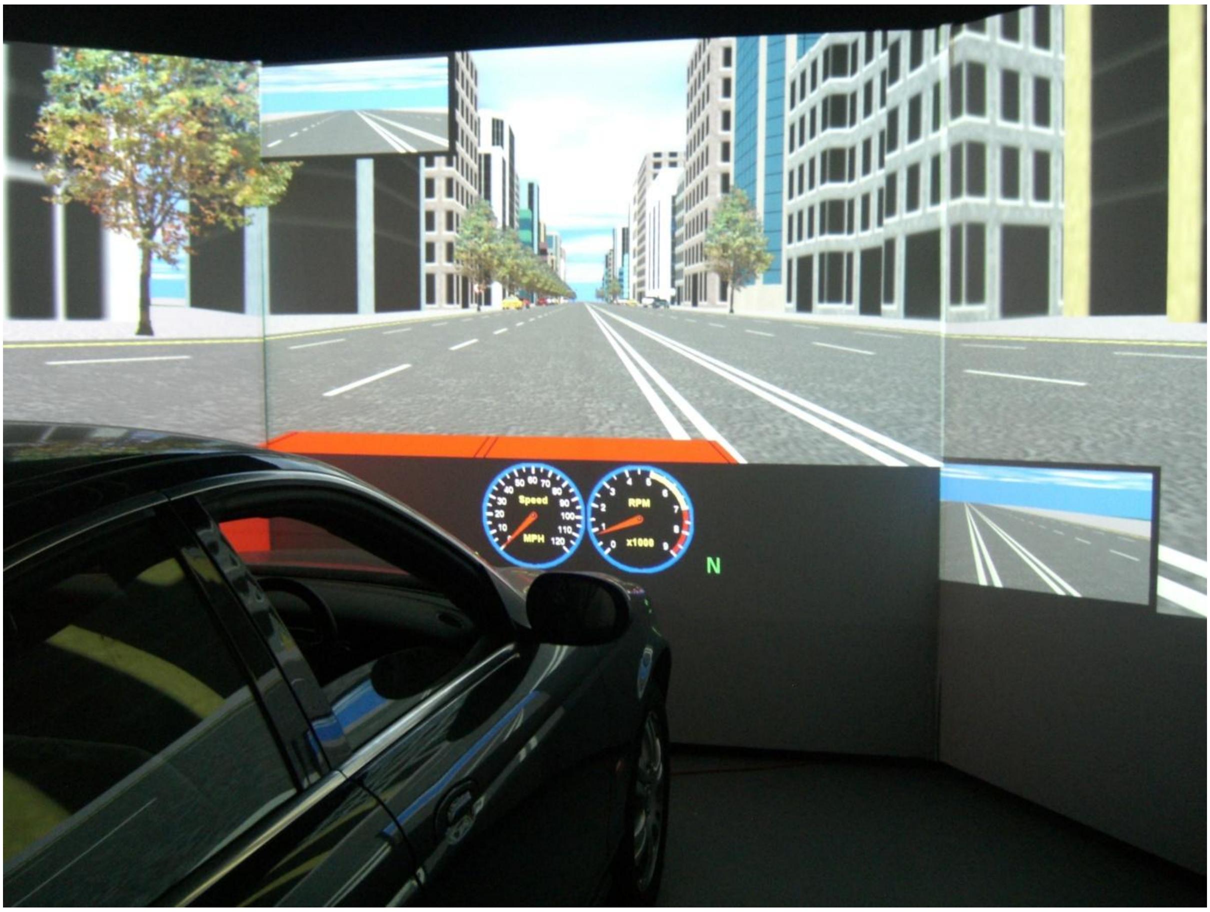

Figure 2: The Brunel University Driving Simulator (BUDS)

Procedure

On entering the lab, participants were briefed about the study and asked to sign an informed consent form (in accordance with ethics procedures), and basic demographic data were collected at this point. Then they were introduced to the simulator, and given a minimum five-minute practice run to acclimatise to the controls. Following the practice run, the first experimental trial was set up.

Participants were offered an appropriate pair of spectacles, and were given a few minutes to acclimatise before their acuity was checked on the computerised Snellen chart. During this time, the experimental instructions were read to the participant, particularly emphasising the required speed (regardless of speed limit signs) and the follow-that-car task. The sign-reading task was also explained, with the instruction to give a verbal response to each challenge. After the Snellen acuity check, participants were taken into the car park outside the lab to conduct the number plate test. They then returned to the simulator to start the first experimental trial. The duration of each trial was approximately eight minutes. At the end of the run, participants were asked to complete the NASA-TLX workload scales.

The same procedure was followed for the remaining experimental trials, with participants being offered a break and water if necessary. At the end of all the experimental trials, participants were debriefed and offered £15 for their time. The total procedure lasted around one hour. The study design and procedure were approved by the Research Ethics Committee of the School of Engineering and Design at Brunel University.

Data reduction and analysis

As a within-subjects study, the dependent variables were treated with repeated-measures analyses of variance (ANOVAs), using planned contrasts to determine the nature of any significant effect. Where appropriate (e.g., for frequency data), nonparametric equivalents were used (Friedman), coupled with post-hoc (Wilcoxon) tests. All data were filtered for outliers and extreme values before the analyses.

Results

Driving performance

Lateral control

In terms of steering control, acuity had a significant effect on lateral instability ($F_{2,28}$ = 10.0, p < 0.005). Pairwise comparisons revealed a difference between normal and weak conditions (p < 0.005), and between weak and strong conditions (p < 0.01); there was also a suggestion of an effect between normal and strong conditions (p = 0.070). Descriptive data (see figure 3) show that instability was actually lowest in the weak condition (mean = 1.48, *SD* = 0.253), followed by the strong condition (mean = 1.65, *SD* = 0.236), and highest in the normal condition (mean = 1.80, *SD* = 0.313).

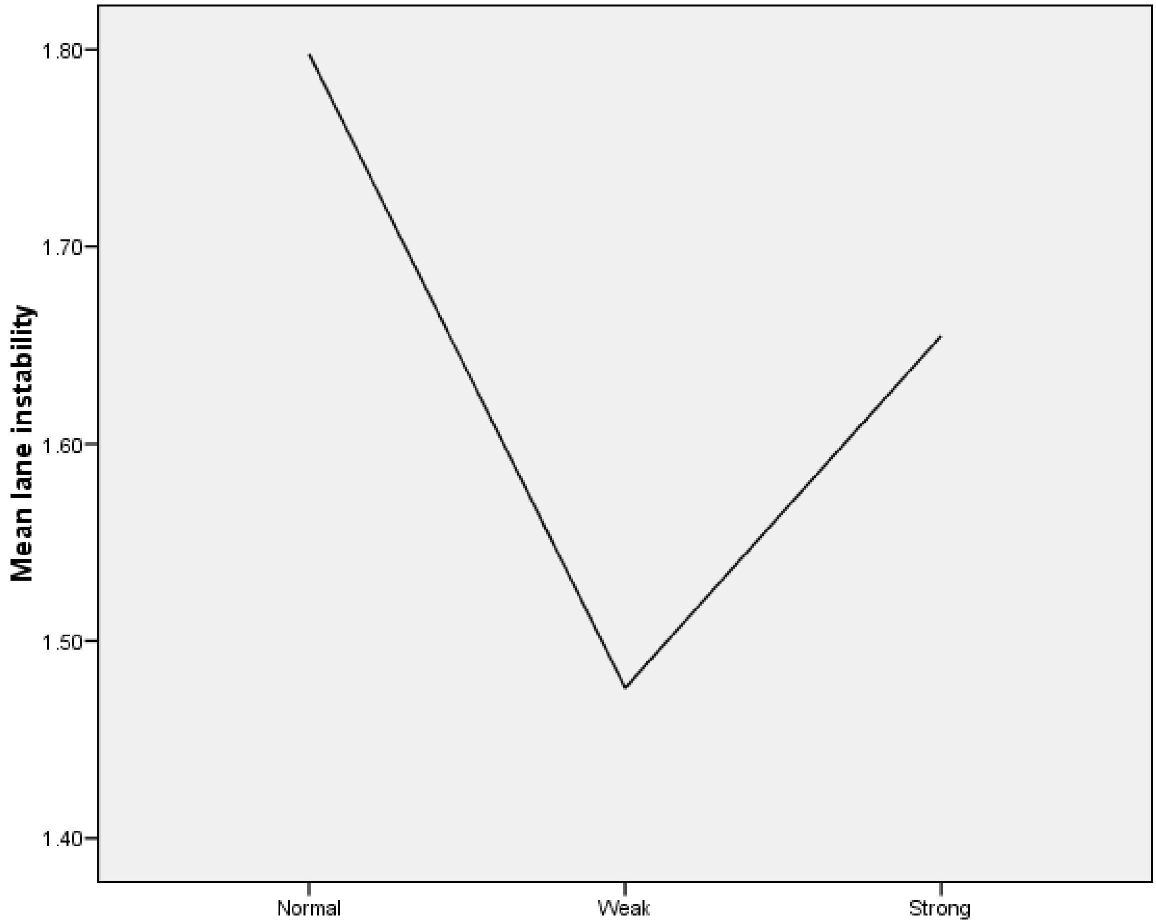

Figure 3: Mean lane instability in each condition

As well as stability, an additional measure of lateral control is how accurately drivers stay in their lane. Although reductions in acuity appeared to increase the percentage distance of the run drivers spent out of lane, this was statistically nonsignificant ($F_{2,28}$ = 1.92, p = 0.166). However, the number of lane excursions did show an effect of acuity. Left edge excursions were treated separately from centreline crossings, since these are substantively different events. A Friedman test revealed a significant effect of acuity on left edge excursions ($\chi^2_{(2)}$ = 14.8, p < 0.005). Post-hoc Wilcoxon signed ranks tests showed that there were significantly fewer lane excursions in the normal condition compared to both the weak (Z = -2.96, p < 0.005) and the strong (Z = -2.99, p < 0.005) conditions; there was no difference between weak and strong conditions (Z = -0.343, p = 0.732). Average number of lane excursions in the normal, weak and strong conditions were 4.53 (*SD* = 5.06), 7.35 (*SD* = 5.00) and 8.35 (*SD* = 8.71) respectively (see figure 4).

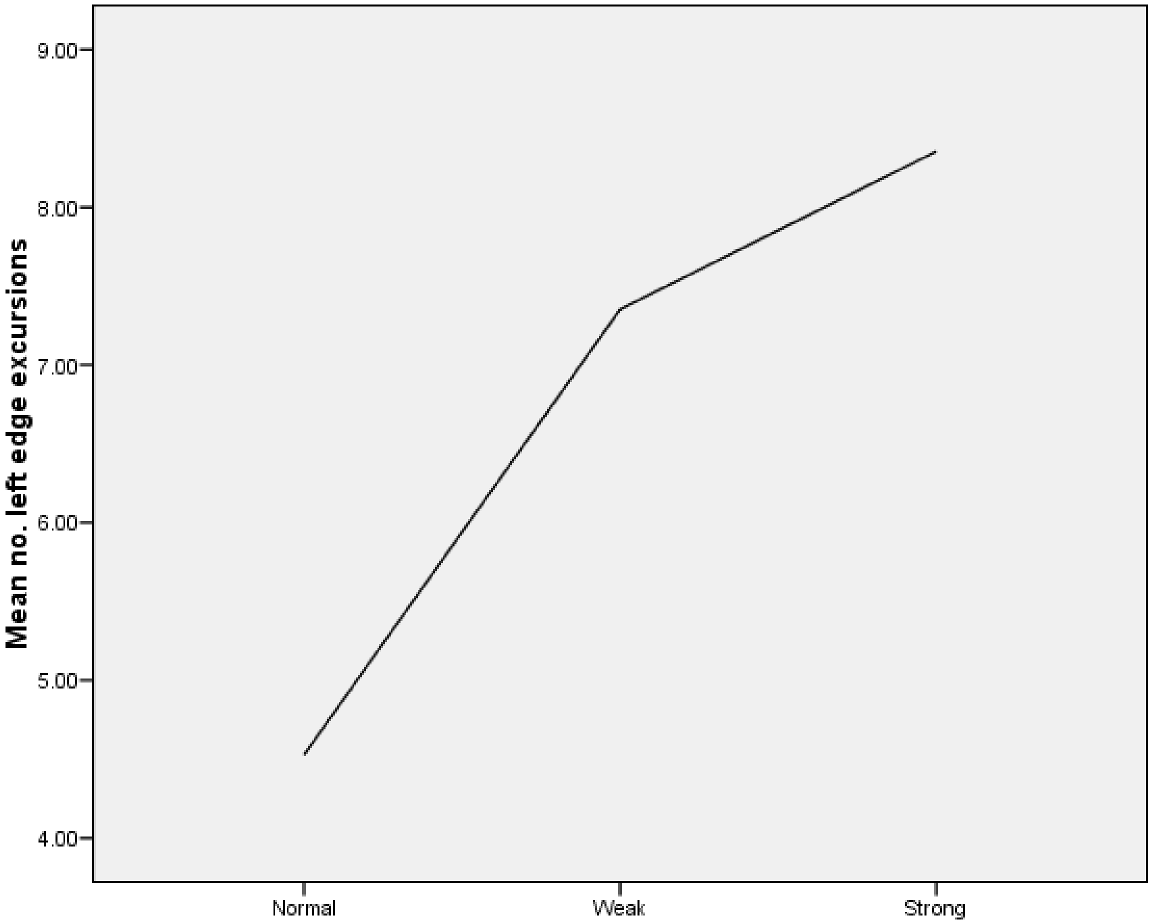

Figure 4: Mean number of left edge lane excursions in each condition

The number of centreline crossings showed a tendency towards a significant result ($\chi^2_{(2)} = 5.40$, $p = 0.067$). Although we must interpret this with caution, post-hoc Wilcoxon tests suggested a significant difference between the normal and strong conditions ($Z = -2.04$, $p < 0.05$). Other post-hoc contrasts were nonsignificant (normal vs. weak: $Z = -1.07$, $p = 0.285$; weak vs. strong: $Z = -0.359$, $p = 0.719$). Average number of centreline crossings in each condition, as represented in figure 5, are 2.87 ($SD = 1.60$), 2.00 ($SD = 1.69$), and 1.73 ($SD = 1.03$) for the normal, weak, and strong conditions respectively.

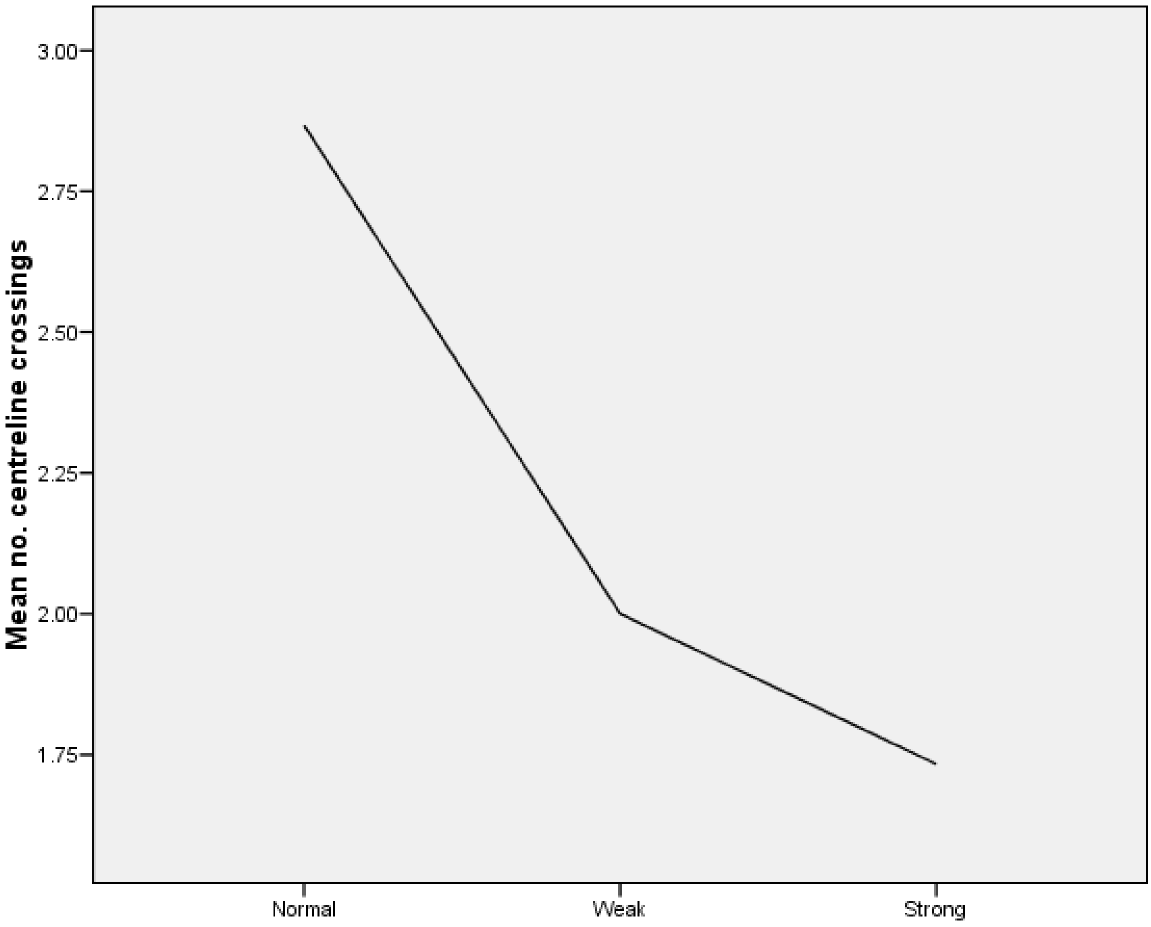

Figure 5: Mean number of centreline crossings in each condition

Longitudinal control

Acuity had a pronounced effect on speed instability ($F_{2,30} = 13.2$, $p < 0.001$), with pairwise comparisons showing differences between normal and weak ($p < 0.05$), normal and strong ($p < 0.05$), and between weak and strong ($p < 0.001$). Again, instability appeared to be lowest in the weak condition (mean = 8.14, *SD* = 1.88), followed by the normal condition (mean = 9.12, *SD* = 1.77), and highest in the strong condition (mean = 10.4, *SD* = 1.93; see figure 6).

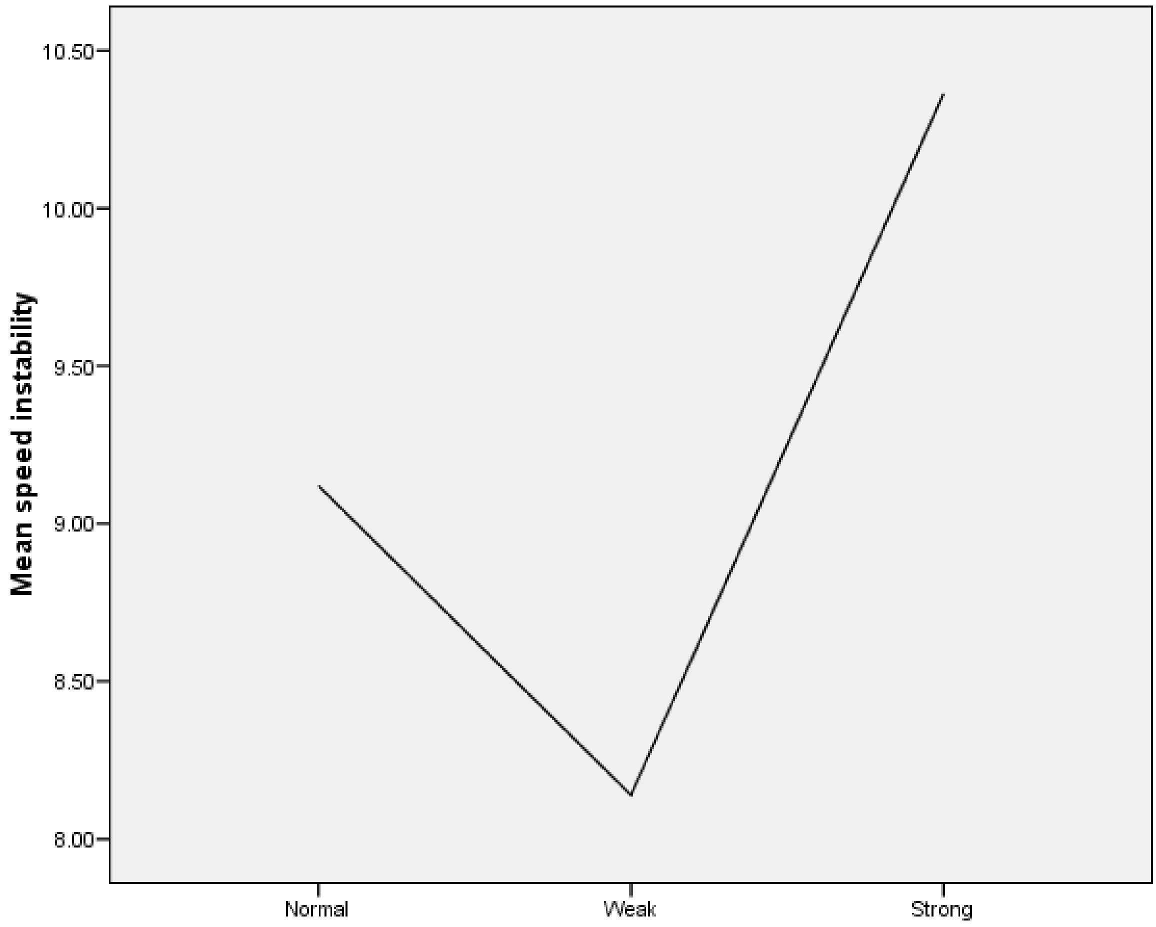

Figure 6: Mean speed instability in each condition

Distance headway (i.e., distance to the lead vehicle) was also subjected to an analysis of instability. However, the repeated-measures ANOVA did not find a significant effect ($F_{2,28}$ = 1.61, p = 0.218). In addition, two measures of risk-related longitudinal behaviour were recorded in each condition: minimum distance headway, and minimum time-to-contact. Both variables returned nonsignificant results (minimum distance headway: $F_{2,36}$ = 0.72, p = 0.494; minimum time-to-contact: $F_{2,34}$ = 0.802, p = 0.457).

Dealing with hazards

The three types of hazards were treated separately for statistical analysis; reaction times (RT) for the two scripted critical events (lead car braking and car pulling out / pedestrian walking into road), and lane position on passing the cyclists (with three cyclists in each run, lane position was averaged across these events to arrive at one data point for each condition). The sampling rate of the simulator allowed the RT data to be captured to an accuracy of 0.1s. Unfortunately, a technical error with the simulator program meant that RT data for the first four participants were lost; these analyses were thus conducted on the remaining 15 participants. Due to the reduced sample size resulting from further listwise filtering for outliers and extreme values, nonparametric analyses were conducted on these RT data.

Brake reaction time (BRT) to the lead car braking was measured from the point of onset of the event (i.e., when the lead car started to brake) to the first pressure on the brake pedal. If the participant did not brake, this was noted as a 'miss' and was therefore treated as a missing value in the analysis. A Friedman analysis returned a significant result ($\chi^2_{(2)} = 7.00$, $p < 0.05$). Post-hoc Wilcoxon tests revealed the source of this effect to be due to a significant difference between weak and strong conditions ($Z = -2.52$, $p < 0.05$). The comparisons for normal vs. weak ($Z = -1.12$, $p = 0.263$) and normal vs. strong ($Z = -0.421$, $p = 0.674$) were nonsignificant. As represented in figure 7, BRT was longest in the weak condition (mean = 3.27s, *SD* = 1.18), followed by the normal condition (mean = 2.97s, *SD* = 2.15), and shortest in the strong condition (mean = 2.61s, *SD* = 1.18).

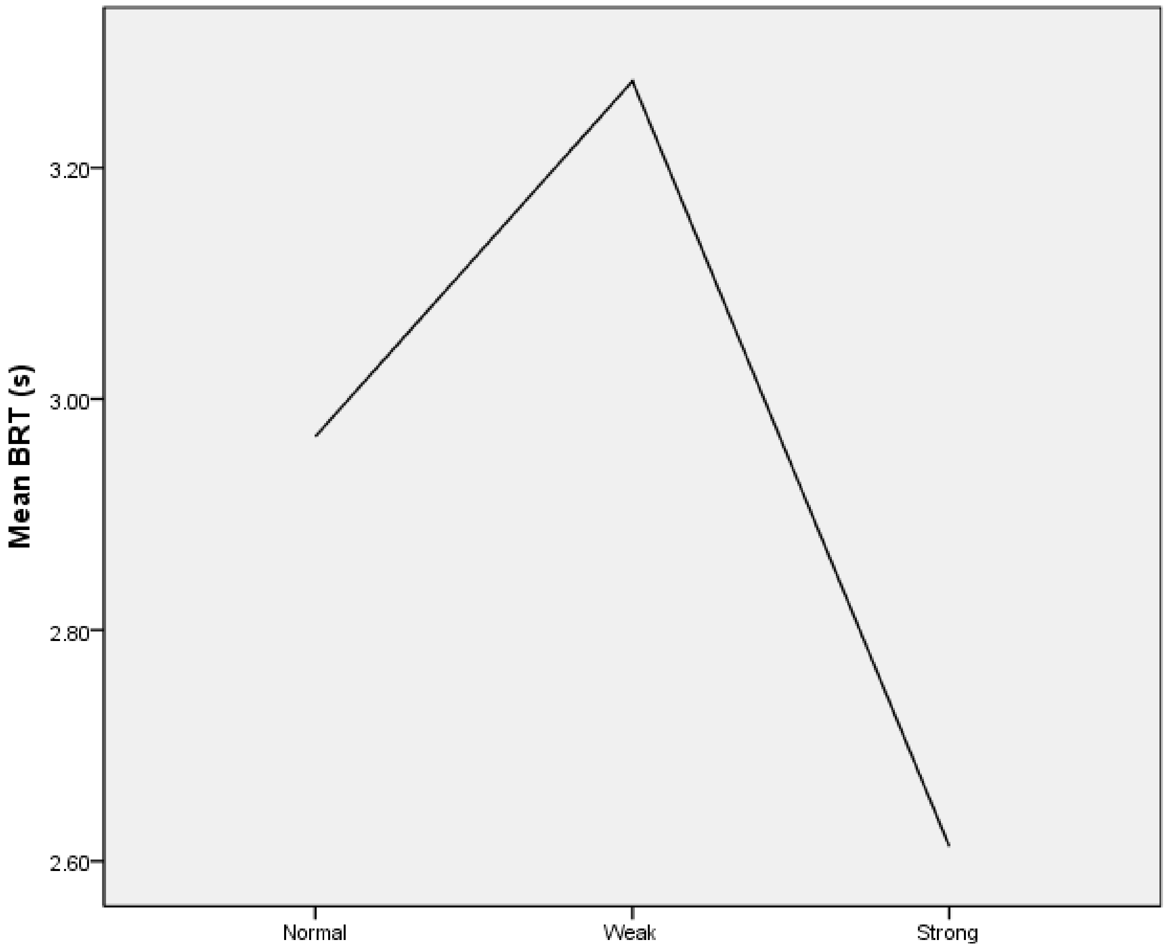

Figure 7: Mean brake reaction time to lead car braking (s) in each condition

The other critical event was coded in the same way – RT from onset of the hazard to the first detection of brake pressure. Again there appeared to be reduced RT in the strong condition, although this time the Friedman analysis proved nonsignificant ($\chi^2_{(2)}$ = 1.75, p = 0.417).

Lane position on passing the cyclist was used as a measure of clearance or safety margin. A repeated-measures ANOVA revealed a significant result ($F_{2,32}$ = 24.6, p < 0.001). Pairwise comparisons were all significant, showing a difference between normal and weak (p < 0.001), normal and strong (p < 0.001), and weak and strong (p < 0.005). As can be seen in figure 8, average lane position in the normal condition was -6.96 (SD = 0.658), in the weak condition this moved to the right for an average of -6.13 (SD = 0.801), and even further right in the strong condition for an average of -4.62 (SD = 1.59).

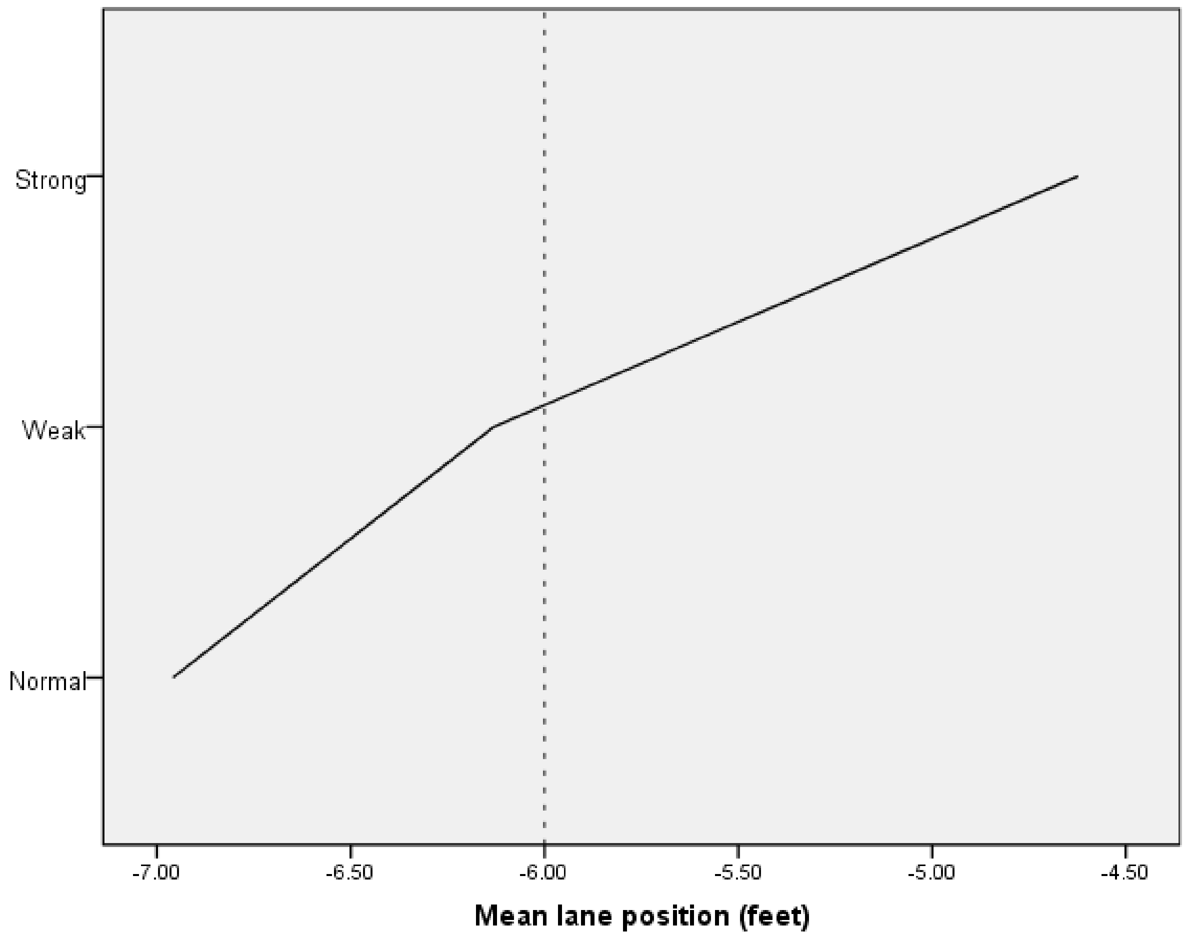

Figure 8: Mean lane position (feet) in each condition. Lane position is measured relative to the road centre, negative values to the left, positive to the right. The reference line at -6.00 denotes the centre of the left-hand lane.

Finally, the total number of crashes was recorded in each condition. The simulator records several variants of crash – off road crash, collision with other vehicles (including cyclists), or hit pedestrians. Given the relatively low frequency counts for each of these variables, the dependent variable treated to analyses was the sum total of all these events in each condition. Nevertheless, a Friedman analysis proved nonsignificant ($\chi^2_{(2)}$ = 1.03, p = 0.598).

Driver attention and mental workload

Participants were asked to recall the speed limit posted on roadside signs at six points during each run. The dependent variable was number of correct responses. A Friedman test revealed a significant difference across the conditions ($\chi^2_{(2)}$ = 13.8, $p < 0.05$). Post-hoc Wilcoxon analyses demonstrated that there were significant differences between normal and weak (Z = -2.97, $p < 0.005$) and between normal and strong (Z = -2.69, $p < 0.01$), but not between weak and strong (Z = -0.160, p = 0.873). Average numbers of correct responses in the normal, weak and strong conditions were 6.00 (SD = 0.00), 4.65 (SD = 1.41) and 4.65 (SD = 1.80) respectively (see figure 9).

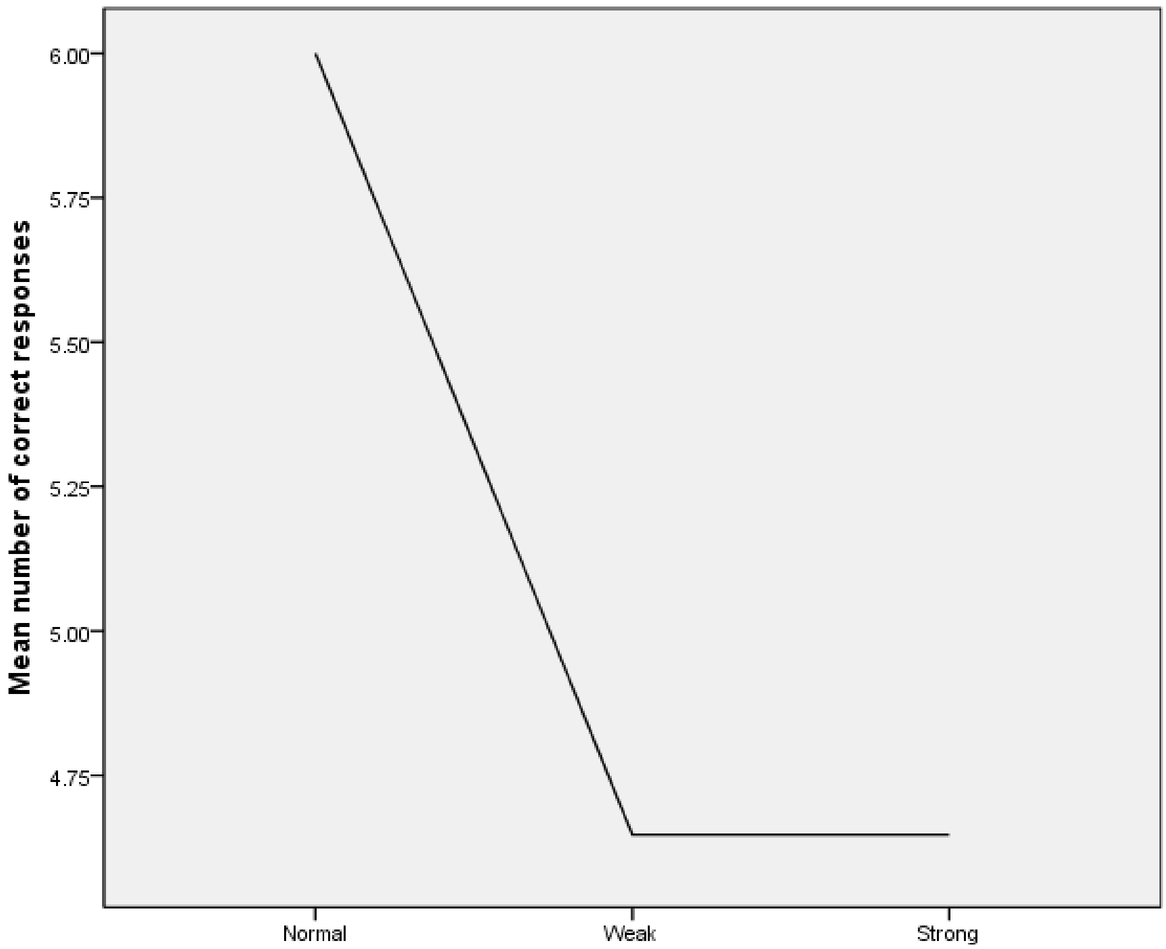

Figure 9: Mean number of correct responses to the sign recall questions in each condition

Subjective mental workload was measured using the NASA-TLX scales after each condition. There are six subscales to the TLX, and these combine to produce an Overall Workload (OWL) result. Following Hill et al. (1992), the raw scores of the TLX subscales were used, with OWL reflecting the arithmetic mean. A repeated-measures ANOVA on the OWL scores returned a significant result ($F_{2,32} = 19.7$, $p < 0.001$). Pairwise comparisons revealed differences between normal and weak conditions ($p < 0.05$), between normal and strong ($p < 0.001$), and between weak and strong ($p < 0.01$). Evidently, OWL increased from normal (mean = 27.3, *SD* = 12.6), through weak (mean = 41.3, *SD* = 16.7) to strong (mean = 54.9, *SD* = 14.0), as seen in figure 10.

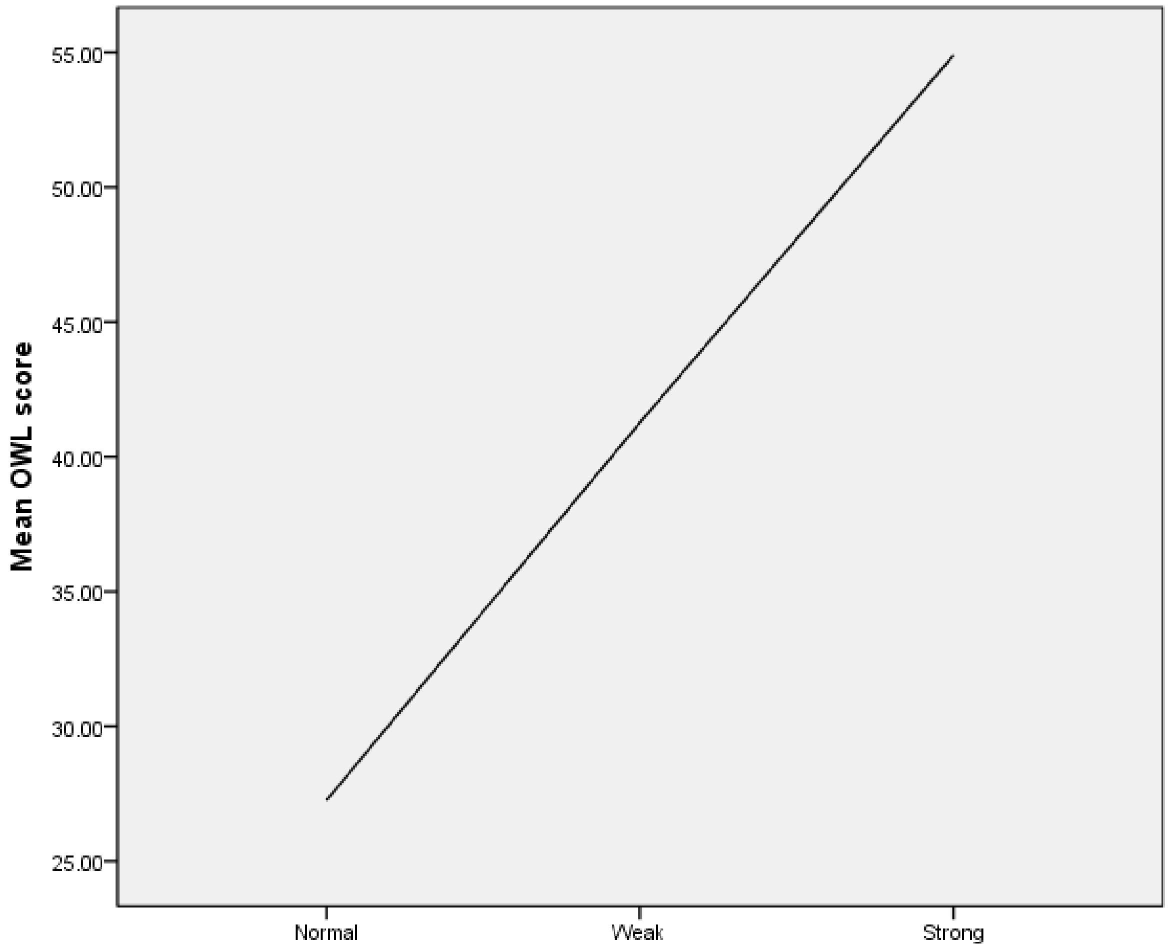

Figure 10: Mean overall workload score in each condition

Discussion

The principal aim of this study was to determine, through a rigorous empirical investigation, the effects of visual acuity on driving performance. To summarise the main results, reduced acuity affected steering control, although surprisingly drivers in the weak condition (i.e., 6/12 acuity) showed more consistency in lane-keeping than those in the normal and strong conditions. Perhaps more in line with expectations, both of the reduced acuity conditions resulted in more left edge excursions than the normal condition. Consistency in speed control was also surprisingly best in the weak condition, but worst in the strong blur (6/18 acuity) condition. None of the other measures of longitudinal control were affected by acuity.

Drivers in the strong condition also reacted more quickly to the lead car braking event when compared to those in the weak condition – again an unexpected result. When it came to passing the cyclists, drivers gave more of a safety margin as their vision deteriorated. However, there were no differences in crashes between the conditions. Finally, driver attention and workload were clearly affected by acuity, as drivers in both blur conditions recalled fewer road signs than with normal vision; furthermore, perceived workload increased with reductions in acuity.

On the whole, the results of this study are consistent with previous research which suggests static visual acuity has little effect on crash risk (e.g., Charman, 1997) nor driving performance (e.g., Brooks et al., 2005). In particular, Brooks et al. (2005) found no effect of blur on steering performance, although they did report that drivers strayed out of their lane more with reduced acuity. The present study largely supports these findings, and the associated conclusion that steering control is more dependent on visual field than acuity.

The exception is in terms of lane position instability – a metric of steering consistency, which was actually most stable in the weak blur condition (6/12 acuity). A similar result emerged for speed instability. Counterintuitive though these results might be, they could be explained by drivers attempting to compensate for the degraded conditions. Similar compensatory mechanisms have been found in studies of mobile phone use when driving, where drivers slow down and increase headway when phoning (Haigney et al., 2000; Strayer et al., 2003). Indeed, a phone conversation has also been specifically observed to reduce variability in lane-keeping (Törnros & Bolling, 2005), while Young et al. (2008) reported the same effect as a result of eating and drinking while driving. Thus whilst a more consistent drive might appear on the face of it to reflect better performance, it could actually be indicative of increased effort by the driver. That said, such consistency could clearly not be maintained in the strong blur condition – although only speed instability saw this get worse than the normal condition. Thus we may tentatively conclude, again in line with previous research, that focal vision affects speed control, while lateral control is dependent on ambient vision.

Higher demands were certainly experienced by drivers in the blurring conditions, with an almost perfect linear relationship between reduced acuity and increased mental workload. Clearly, then, degradations in visual acuity mean that drivers have to concentrate harder on the road ahead. Whilst this may be sustainable in the shortterm scenarios of the present study, on a longer drive this could increase the chances of acute fatigue – and hence increase accident risk (cf. Arnedt et al., 2001).

Further evidence of overcompensation due to reduced acuity was observed in dealing with the scripted hazards. Drivers were certainly erring on the side of caution when passing the cyclist – it could even be argued that more risky behaviours were observed in the normal condition. Taking into account the position of the cyclist, and the width of the subject vehicle, the data indicate that on average, drivers in the normal condition allowed about 6.5 inches (16.5cm) clearance when overtaking the cyclist. In contrast, in the strong condition this increased to 34.6 inches (87.8cm), while in the weak condition the average clearance was 16.4 inches (41.8cm). Whilst none of these would satisfy the UK Highway Code advice for treating a cyclist as if it were a small car when overtaking (it is notable that none of these figures involved using the right-hand lane, even though the simulator script ensured that there were no oncoming vehicles when encountering the cyclist), the extremely low safety margin in the normal condition is particularly shocking.

Nevertheless, it is the effects of acuity which are of concern here, and the inescapable conclusion is that drivers overcompensate when encountering hazards with degraded vision. A similar phenomenon occurred with the lead car braking event, since drivers in the strong blur condition actually responded more quickly than those in the weak condition. Although previous research has suggested that hazard detection and avoidance is affected by the levels of acuity investigated here (e.g., Higgins & Wood, 2005; Higgins et al., 1998), other studies have only found an effect at extreme levels of blur (Brooks et al., 2005). Possibly, then, hazard responses would only be affected by more severe acuity degradations than 6/18, suggesting that mere detection of an object is sufficient to initiate a response, regardless of whether the driver can actually see what that object is (cf. Hole, 2007). That said, it is also important for drivers to respond in an appropriate manner to hazards (cf. Taylor, 2010), implying that actual recognition would be important in certain circumstances. It is not possible to be conclusive on the basis of the results here, but it may be that a wider range of hazards would elicit different responses under the range of acuity conditions investigated in the present study.

Finally, an important aspect of focal vision for driving is in sign reading ability, which is dependent on static visual acuity. Previous research has found that sign recognition is affected at higher levels of degradation (6/30 acuity – Higgins & Wood, 2005; Higgins et al., 1998); in the present study, sign recall performance was at ceiling in the normal condition, but declined even from the legal minimum acuity requirement for drivers (i.e., 6/12). This seems to accord with the suggestion that road signs are designed on the basis of much better levels of acuity (e.g., Owsley & McGwin, 2010). Signs are an important source of information when driving, and missing such information can adversely affect drivers' situation awareness for hazards, as well as potentially causing them not to comply with instructions (such as posted speed limits) – all of which can increase risk on the roads.

Limitations and future research

Although empirically robust, the current study was not necessarily exhaustive with respect to exploring all of the issues surrounding vision and driving. It was designed purely to evaluate static visual acuity; future studies could seek to extend this by investigating field-of-view (or, indeed, other relevant visual abilities), in replication of previous research. Furthermore, a wider range of acuity levels would provide more information on the relationship between acuity and driving performance variables, while an extended driving scenario could be used explore any effects of fatigue as implied in the workload results here.

More adventurously, eye-tracking equipment could be used to monitor the driver's direction of gaze, as an indicator of their hazard perception and attention to other relevant aspects of the road scene. For instance, the impaired ability for road sign recognition could be due to drivers not seeing the signs, or because they were looking at the signs but could not read the actual numbers. Future research investigating any of these factors would help to contribute to the evidence base in this field.

Conclusions and implications

Earlier in this report, it was argued that a more evidence-based approach was needed to determine the appropriateness of any visual screening test for driver licensing. The lack of any clear relationship between static visual acuity and driving safety has led many to call for a review, with moves towards a test of field-of-view being more promising. The current study contributes to that debate, and to the evidence base, by confirming that acuity is not a particularly important factor in many aspects of driving performance. At the EU minimum requirement for static acuity (6/12), most driving performance measures did not show significant degradation compared to driving with 6/6 vision – and, in fact, there was evidence of drivers compensating for the reduced acuity with more cautious driving.

However, such compensation came at a price, with drivers experiencing higher workload as a result of reduced acuity. If sustained over longer-term scenarios than were investigated here, this could impact on risk as drivers struggle to maintain performance. Moreover, reduced acuity resulted in more frequent left-edge lane excursions, even at the legal minimum for driving. It is fair to assume that driving off the road represents a safety risk in any environment. Thus, although the current legal standards for visual acuity are not necessarily related to driving performance, there are implications for road safety – which may, in fact, suggest that the standard needs to be more stringent.

Consistent with this view is the fact that anything other than normal visual acuity has a significant impact on drivers' ability to recall road signs. This report has argued that failure to observe road signs can also indirectly affect driving risk and rule compliance. But it has also been noted that standards for road sign design are based on assumptions of better visual acuity than the EU minimum requirement. Therefore, as well as reconsidering the legal requirements for acuity, there is also a strong argument for ensuring that other standards for road and signage design are consistent with those requirements.

In terms of driver screening for visual requirements, the UK number plate test has also attracted criticism for various reasons. Some have suggested that the equivalent acuity required for the number plate test falls short of the 6/12 standard laid down in legislation, while at the same time only a minority of drivers with 6/12 visual acuity pass the number plate test (Currie et al., 2000). In the current study, 68% of participants (13 out of 19) passed the number plate test with 6/12 acuity. Although this is a higher proportion than previously observed, it adds weight to the argument that the number plate test is not a sensitive measure of the legislative acuity threshold, despite its practicality.

In conclusion, this study suggests, as with others before it, that static visual acuity is only part of the story when it comes to the relationship between vision and driving. Whilst there were some direct and indirect implications of acuity for driving risk (which, in fact, implied that the acuity requirements need to be more stringent), other aspects of driving performance remained unaffected by acuity. Taken together with the growing body of evidence in this field, this reinforces calls for a review of legislation surrounding the visual requirements for driver licensing.

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