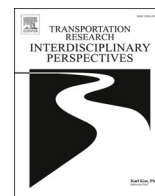


Contents lists available at [ScienceDirect](https://www.sciencedirect.com)

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives



Associations between vision impairment and driving performance and the effectiveness of vision-related interventions: A systematic review

Helen Nguyen^{a,*}, Gian Luca Di Tanna^b, Kristy Coxon^c, Julie Brown^b, Kerrie Ren^a,
Jacqueline Ramke^{d,e}, Matthew J. Burton^{d,f}, Iris Gordon^d, Justine H. Zhang^{d,g},
João M. Furtado^h, Shaffi Mdalaⁱ, Gatera Fiston Kitema^j, Lisa Keay^{a,b}

^a School of Optometry and Vision Science, Faculty of Medicine and Health, The University of New South Wales, NSW, Australia

^b The George Institute for Global Health, Faculty of Medicine and Health, University of New South Wales, NSW, Australia

^c School of Health Sciences, and the Translational Health Research Institute, Western Sydney University, NSW, Australia

^d International Centre for Eye Health, London School of Hygiene & Tropical Medicine, London WC1 E7HT, United Kingdom

^e School of Optometry and Vision Science, University of Auckland, Auckland, New Zealand

^f National Institute for Health Research Biomedical Research Centre for Ophthalmology at Moorfields Eye Hospital NHS Foundation Trust and UCL Institute of Ophthalmology, London, United Kingdom

^g Royal Free Hospital, London, United Kingdom

^h Division of Ophthalmology, Ribeirão Preto Medical School, University of São Paulo, Ribeirão Preto, São Paulo, Brazil

ⁱ Ophthalmology Department, Queen Elizabeth Central Hospital, Blantyre, Malawi

^j Ophthalmology Department, School of Health Sciences, University of Rwanda, Kigali, Rwanda

ARTICLE INFO

Keywords:

Vision impairment
Driving performance
Driving errors
Road safety
Systematic review

ABSTRACT

Introduction: This systematic review aims to (1) investigate the associations between vision impairment and driving performance, and (2) evaluate the effectiveness of vision-related interventions to improve driving performance.

Method: Medline (Ovid), EMBASE and Global Health electronic databases were searched from their inception to March 2022 for observational and interventional English-language studies. The population of focus were licensed drivers of all ages of four-wheeled motorised vehicles. The primary outcome was measures of driving performance from naturalistic driving and/or on-road closed circuits. All screening, data extraction and critical appraisals were completed independently by two authors.

Results: 27 studies (n = 6358 participants) from the 4281 identified in the search were included in this review. All but one study, an RCT, were observational. Only 2 cross-sectional studies were rated as high risk of bias. The majority of papers (80 %) were limited to older drivers. There were 33 different performance measures reported. Poor driving performance was associated with glaucoma, AMD and monocularly, and measures of vision function including contrast sensitivity, visual acuity and visual fields. From the vision-related interventions identified only cataract surgery and toric refractive correction for astigmatism were shown to improve driving performance on selected measures.

Conclusion: Despite differences in outcome measures, there is consistent evidence for associations between vision impairments and poor driving performance. This review highlights the importance vision has on an individual's ability to safely drive and complete common manoeuvres. Early detection and management of eye conditions may help decrease the likelihood of crashing and road traffic injuries.

Introduction

Poor vision including impairments in visual acuity, contrast sensitivity and visual fields, caused by either age-related declines or specific

eye diseases, have been shown to worsen different measures of driving performance. (Owsley and McGwin, 2010) These measures attempt to capture how a driver can safely operate a vehicle and include specific driving manoeuvres, such as lane changing and hazard avoidance, and

* Corresponding author.

E-mail address: helen.nguyen1@unsw.edu.au (H. Nguyen).

<https://doi.org/10.1016/j.trip.2022.100753>

Received 13 July 2022; Received in revised form 15 December 2022; Accepted 30 December 2022

Available online 6 January 2023

2590-1982/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

can be combined into overall driving scores or error counts. (Owsley and McGwin, 2010) When drivers make performance errors, crash risk can increase by 18.2 times. (Dingus et al., 2016) These surrogate measures of driving safety can be investigated through on-road driving circuits with a trained driving instructor or more recently, “naturalistic” driving using in-vehicle monitoring systems which provide insight into everyday driving behaviour. The associations of deficits in vision with driving performance worldwide for drivers of all ages has not been systematically reviewed.

The United Nations’ (UN) Sustainable Development Goals (SDGS) aim to halve road deaths by 2020 (Target 3.6) and provide safe and sustainable transport systems for vulnerable road users (Target 11.2). (UN. #Envision, 2015) A greater understanding of the associations between vision and driving performance across all ages can inform policy and direct investment in eye health services. As part of the *Lancet Global Health Commission* on Global Eye Health, this systematic review aimed to (1) investigate the associations between vision impairment and driving performance, and (2) evaluate the effectiveness of vision-related interventions to improve driving performance.

Material and methods

This systematic review is reported using the PRISMA guidelines (Appendix A) and its protocol has been published. (Nguyen et al., 2020) Briefly, an electronic database search on Medline (Ovid), EMBASE and Global Health was conducted from their inception to March 2022 with no geographic restrictions. The search terms included terms for motor vehicle crash involvement and driving cessation as a review on these outcomes measures was conducted in parallel to this review (Appendix B). Table 1 describes the inclusion and exclusion criteria for studies included in this review.

The population of focus was all four-wheeled licensed drivers of all ages. The outcome of interest was driving performance which included overall driving scores and errors, and other measures of driving performance such as lane keeping, braking, and speed control. These outcomes were assessed using on-road driving tests or “naturalistic” driving with in-vehicle monitoring. Studies which used driving simulators were omitted to restrict the scope of the study to direct measures of driving and associations with habitual vision. Further, studies investigating self-regulatory driving behaviours (e.g. night driving avoidance) were excluded.

All titles, abstracts, and full-texts were reviewed independently by

Table 1
Study inclusion and exclusion criteria.

Inclusion	Exclusion
<ul style="list-style-type: none"> Interventional (RCTs) and observational (cohort, cross-sectional, case-control and case series) studies. Systematic reviews with meta-analyses Studies on drivers of four-wheeled motorised vehicles of all ages. Studies looking at the following exposures of interest: impairment in measures of vision (visual acuity (VA), contrast sensitivity (CS), visual field (VF), and glare sensitivity (GS)) or specific eye conditions including but not limited to glaucoma, cataracts, age-related macular degeneration (AMD), diabetic retinopathy (DR), stereopsis disorders and colour vision deficiencies. Studies on interventions such as vision screening, refractive correction, cataract surgery, anti-VEGF injections and other treatments to improve vision. 	<ul style="list-style-type: none"> Literature reviews and narrative systematic reviews. Commentary articles, dissertations, abstracts, editorials and conference presentations. Studies using simulators or investigated either self-regulatory driving behaviours (e.g. night driving avoidance), or self-reported measures of driving safety. Studies on populations with specific medical conditions (e.g. dementia, epilepsy, stroke and history of medical events such as syncope), low vision or vision difficulties caused by other medical conditions (e.g. hemianopia caused by brain damage).

two investigators using Covidence systematic review management software (Covidence non-profit SaaS Enterprise, Melbourne, Australia). All discrepancies were resolved via consultation with a third investigator. Similarly, data extraction was completed independently by two investigators using data extraction forms adapted from the Joanna Briggs Institute (JBI) templates for observational and systematic review study designs, and Cochrane templates for interventional studies. Data extracted from the studies included design, participant and setting characteristics, exposure type and definition, intervention details (if any), outcome measures, and relevant effect measures.

Overall risk of bias for all included studies was completed by two investigators independently with conflicts resolved by a third investigator. All quality assessments were conducted using the relevant JBI critical appraisal tools. (Adelaide Uo, xxxx) Each question on the relevant tools were categorised into either selection, detection, confounding, validity, performance, attrition, or allocation bias. Each study was given an overall “score” for bias depending on how each question was answered (Yes = 1, No = 0, Unsure or N/A = 0). The final scores were used to assign each study as low, medium, or high risk of bias, with lower scores indicating higher risk of bias.

Statistical analysis

Associations between vision impairment and vision-related interventions with driving performance were summarised with appropriate effect measures (relative risk (RR), hazard ratio (HR) and odds ratio (OR) for binary data, and standardised mean differences for continuous data. As there were many measures of driving performance, measures validated against crash risk were prioritised in synthesis of results. Reporting of the narrative summaries were guided by the SWiM guidelines. (Campbell et al).

Results

From the electronic database search, 5111 studies were identified after the removal of 4868 duplicates. After title and abstract screening, 242 studies remained for full-text review after which 217 studies were excluded leaving 26 studies. An additional study not picked up in the search was identified by authors, thus the final review includes 27 studies for data extraction (n = 6358 participants) (Fig. 1). There were 19 studies which reported on multiple measures of driving performance together and eight studies that only looked at one. There were 14 cross-sectional studies, 8 case-control studies, 4 cohort studies, and 1 randomised control trial (RCT). All but four studies had sample sizes < 200 participants and only three studies had participants of mean age < 50 years. All studies were from high-income countries (HICs). Risk of bias for each study is shown in (Appendix C). Overall, only two studies, both cross-sectional, were rated as high risk of bias, with the remaining rated as either medium or low risk of bias.

Across the 27 studies there were 87 combinations of independent variables (measures of vision impairment or vision related interventions) and outcome measures (Fig. 2) and most results were for single studies. All measures of vision impairment had measurable impact on at least one measure of driving performance.

Overall driving Errors, scores and counts

Overall driving scores were lower for drivers with glaucoma, (Bhorade et al., 2016; Haymes et al., 2008; Lee et al., 2018; Wood et al., 2016) age-related macular degeneration (AMD) (Szlyk et al., 1960). 1995.; Wood et al., 2018) and self-reported eye disease, (Wood, 2002) with greater impact with severe disease. All four studies on glaucoma (n = 267 participants) found drivers with glaucoma made more than double the rate of critical errors needing driving instructor intervention than drivers without glaucoma, (Wood et al., 2016) had lower mean driving performance scores, (Lee et al., 2018) and were four times more

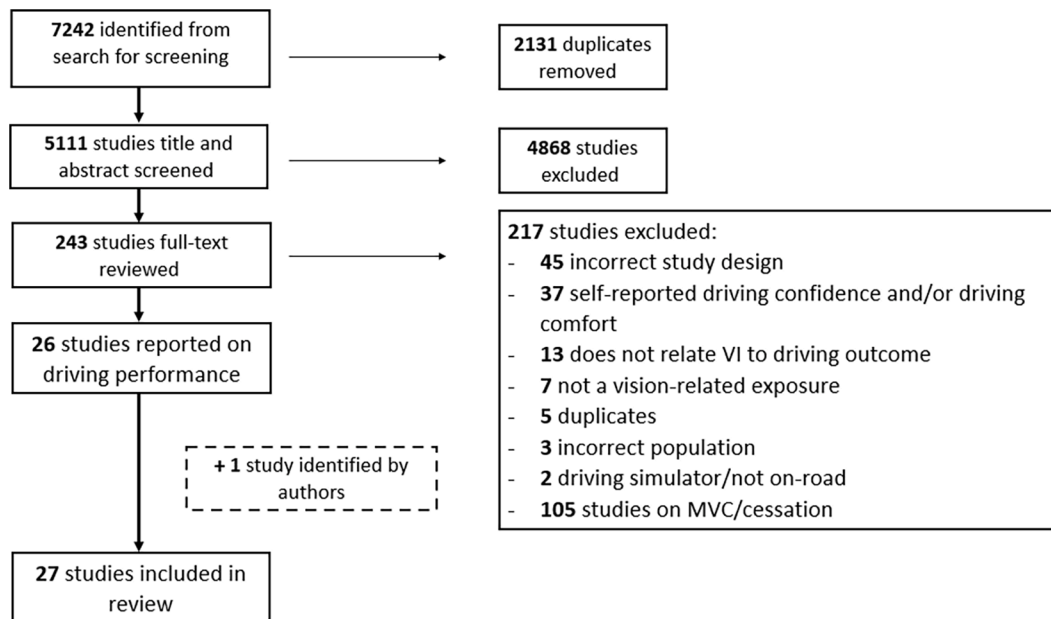


Fig. 1. Flow chart of search with papers reporting on driving performance.

likely to receive a marginal/fail score for the driving assessment. (Bhorade et al., 2016) Only one study found no difference between the median driving score of drivers with glaucoma and drivers without. (Haymes et al., 2008).

Two studies ($n = 104$) compared drivers with and without AMD, and one study found drivers with AMD to have a three times greater rate of making driving errors; with this rate increasing to four and ten times in drivers with intermediate and severe AMD, respectively. (Wood et al., 2018) The proportion of terminated driving assessments due to safety concerns was also three times higher in drivers with AMD compared to drivers without AMD. However, a 1995 study found no significant differences between the overall road test score for drivers with and without AMD ($p \leq 0.07$). (Szlyk et al., 1960). 1995).

A final study comparing the on-road driving performance of older drivers with either mild or moderate/severe self-reported ocular disease ($n = 46$) to drivers without vision impairment across all age groups ($n = 93$), found drivers with self-reported ocular disease made significantly more errors ($p < 0.001$). (Wood, 2002).

All four studies ($n = 375$) evaluating visual acuity found associations with overall driving performance scores and number of errors made whilst driving on an on-road circuit. (Szlyk et al., 1960). 1995.; Dawson et al., 2010; Kimlin et al., 2020; Wood and Mallon, 2001) Better visual acuity was positively correlated with better scores in driving performance, with decreases in visual acuity additionally linked to poorer night-driving performance. (Szlyk et al., 1960). 1995) One study found older drivers with greater near visual acuity loss made more driving errors during the day, however another study reported impairments in distance visual acuity when driving at night to be responsible for greater safety errors. (Dawson et al., 2010; Kimlin et al., 2020) Older drivers with vision impairment were also found to make more errors, judged by both a driving instructor and an occupational therapist, than the younger, middle-aged and older drivers without vision impairment. (Wood and Mallon, 2001).

Six studies ($n = 543$), all using on-road driving circuits, looked at the effect of contrast sensitivity loss on overall driving performance scores and errors committed. (Haymes et al., 2008; Lee et al., 2018; Szlyk et al., 1960). 1995.; Wood, 2002; Dawson et al., 2010; Carr et al., 2016) All but two studies found poor contrast sensitivity to significantly predict worse driving scores. (Dawson et al., 2010; Carr et al., 2016).

The results concerning visual field impairments and overall driving

performance assessed using on-road driving routes were mixed (three studies, $n = 163$). (Haymes et al., 2008; Lee et al., 2018; Coeckelbergh et al., 2004) Two studies involved drivers with glaucoma but only one found poor driving scores to be associated with visual field defects. (Haymes et al., 2008; Lee et al., 2018) The third study which included drivers with either AMD, glaucoma or retinitis pigmentosa, found overall visual field defects to not be correlated with overall driving scores (Spearman's $p = -0.150$), however drivers with either peripheral or central field defect were more likely to fail the driving test compared to those with only mild field defect ($p < 0.05$). Further, more participants with peripheral visual field defects, attributed to a diagnoses of glaucoma, failed the driving test compared to drivers with central field defects all diagnosed with AMD. (Coeckelbergh et al., 2004).

The only study ($n = 162$) looking at vision screening for visual acuity and contrast sensitivity as a tool to predict driving performance found no correlation between failing screening and driving ability. (Spreng et al., 2018).

Another looked at the overall night-time driving score of participants wearing different contact lenses (spherical or toric) on an on-road circuit. (Black et al., 2019) All participants ($n = 10$) in this RCT were diagnosed with low to moderate bilateral astigmatism. After adjusting for lap time and run order, correction of astigmatism using toric lenses resulted in significantly better overall driving scores ($p = 0.003$) than spherical lenses.

Driving performance measures

Glaucoma was found to worsen driving performance on all eight manoeuvres related to safe driving: speed, braking, lane-changing and lane-position control, gap selection and judgement, blind spot checking, vehicle manoeuvring/control, hazard recognition and avoidance and sign recognition (Fig. 2). Drivers with bilateral moderate and/or advanced glaucoma were found to be twice as likely to require more than one brake intervention on an on-road driving test from an instructor compared to drivers without glaucoma. (Bhorade et al., 2016) The number of braking errors, however, were not significantly different between drivers with glaucoma with mild to moderate visual field loss and the control group of drivers without glaucoma ($p = 0.28$). (Wood et al., 2016) Drivers with glaucoma were found to have poorer lane control than drivers without glaucoma in two thirds of studies, (Lee

Driving Performance Measure	Eye Diseases or Conditions (Binary Measures)						Measures of Vision Function (Continuous Measures)				Vision-related Interventions		
	Glaucoma	AMD	Stereopsis	Monocularity	Visual Dysfunction	Self-reported ocular disease	Visual Acuity Loss	Contrast Sensitivity Loss	Glare Sensitivity Loss	Visual Field Loss	Vision screening	Corrective Lenses (toric vs spherical)	Cataract Surgery
Overall Errors/Counts/Scores	Yellow	Yellow				Green*	Green	Yellow		Yellow	Red*	Green*	Green*
Braking errors	Red*	Red*	Red*		Red*		Green*						
Lane changing/control errors	Yellow	Yellow		Green*			Yellow	Yellow	Green*	Red*		Red	
Speed control errors	Red*	Green*			Green*		Yellow	Green*	Green*				
Gap judgement errors	Red*	Green*		Red*		Green*	Green*		Green*				Red*
Blind spot checking errors	Red*	Yellow					Green*						
Vehicle manoeuvring/control errors	Red*	Red*				Green*	Green*	Green*					
Hazard recognition and avoidance errors	Green*					Green*					Yellow	Green*	
Signage recognition errors	Red*			Green*		Green*					Yellow	Green*	
Reversing			Red*										
Slalom			Green*										
Estimating relative position			Green*										
Wheel interventions by instructor	Green*												
Circuit completion time	Red*					Green*					Yellow	Red*	
Manoeuvring time													Red*
Critical interventions	Green*												
Head and shoulder movements	Green*								Green*				
Divided attention													Red*
Overall safety rating	Green*	Green*					Green						
Observation errors	Green*	Green*					Green*						
Indicator use errors	Red*	Red*					Green*						
Approach errors	Green*	Red*					Green*						
Traffic light situations	Green*	Green*							Green*				
One-way driving errors	Red*	Red*											
Two-way driving errors	Red*	Red*											
Give-way errors	Green*	Red*											
Left turn manoeuvres								Red*		Green*			
Failure to stop at stop sign							Red*	Red*		Green*			
Mirror checking errors							Green*						
Turning errors							Red*						
Defensive driving							Red*						
Vehicle sympathy							Red*						
Reversing time						Green*							
Total no. of LEDs seen						Green*							
Reverse angle park						Red*							

Fig. 2. Matrix illustrating the relationship between vision impairment and vision-related interventions on driving performance measures. Red = vision condition is not associated with driving error and or driving performance measure; Yellow = vision condition is not consistently associated with driving error and or driving performance measure; Green = vision condition is associated with driving error and or driving performance measure* outcome only reported by one paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al., 2018; Wood et al., 2016) specifically those with binocular field loss ($p \leq 0.05$). (Kasneji et al., 2014) Even though there were no differences in performance when time spent unsafely lane-crossing was used as a measure of poor lane control ($p = 0.16$), (Lee et al., 2018) drivers with glaucoma were found to make significantly more lane position errors ($p = 0.01$) when assessed using on-road circuits than drivers without glaucoma. (Wood et al., 2016) Drivers with glaucoma also hit significantly more hazards on an on-road driving circuit compared to drivers without glaucoma ($p = 0.04$). (Lee et al., 2018) Further, gap judgement performance was worse in drivers with glaucoma and worse binocular VF than those with sufficient field of vision. (Kasneji et al., 2014) Errors in speed control, blind spot checking, vehicle manoeuvring and signage recognition were not affected by the presence of glaucoma in these three studies.

Drivers with AMD (two studies; $n = 104$) were found to make significantly more errors in lane positioning, observance, and merging manoeuvres than control drivers without AMD. (Szlyk et al., 1960). 1995; Wood et al., 2018) They were also found to have more points deducted for driving too slow (defined as 5mph below the speed limit) on an on-road driving circuit than drivers without AMD ($p \leq 0.02$). (Szlyk et al., 1960). 1995) Significantly more errors in gap selection were made by drivers with AMD compared to those without ($p = 0.036$). (Wood et al., 2018) Only one 1995 study found drivers with AMD ($n = 21$) made significantly more errors when checking blind spots ($p \leq 0.02$). Further, the same study found both better visual acuity and binocular contrast sensitivity in both AMD and non-AMD drivers to be significantly associated with better speed control ($p < 0.05$). (Szlyk et al., 1960). 1995) AMD presence did not affect braking control or vehicle manoeuvring errors (Fig. 2). (Wood et al., 2018).

Monocularity was investigated by one study (Fig. 2) comparing the driving performance of 40 monocular to 40 binocular truck drivers. (McKnight et al., 1991) Only signage recognition was found to be impacted, with recognition distances in monocular drivers significantly shorter in both day and night conditions ($p < 0.05$). Monocularity did not worsen lane keeping and gap selection and judgement performances.

The impact of self-reported vision loss, referred to in Fig. 2 as either visual dysfunction or self-reported ocular disease, on driving performance was investigated in two studies ($n = 216$). (Wood, 2002; Merickel et al., 2019) One study found drivers aged 65 years and older with poorer self-reported vision loss to have more erratic braking behaviours, errors in braking control and worse vehicle control whilst accelerating compared to drivers with milder self-reported vision loss; specifically on high-speed interstate highways at night ($p < 0.0001$). (Merickel et al., 2019) The other study found drivers with self-reported vision loss, when compared to drivers without vision loss, made more gap judgement errors ($p = 0.001$), took significantly longer to complete driving manoeuvres ($p = 0.001$), hit more on-road driving cones ($p = 0.025$), were worse at recognising on-road hazards ($p = 0.001$) and signs ($p < 0.001$), and hit more hazards ($p < 0.001$). (Wood, 2002).

Stereopsis impairment was found to only impact how fast a driver can move the vehicle in and out of cones (slalom) and relative position estimation performances. (Bauer et al., 2001).

Studies on the impact of specific measures of vision on driving performance reported mixed results (Fig. 2). A cross-sectional study found drivers with poor visual acuity to make more braking ($p = 0.03$), gap selection ($p = 0.02$), blind-spot checking ($p = 0.001$), and vehicle manoeuvring ($p = 0.004$) errors than drivers with normal vision. (Wood and Mallon, 2001) A prospective study found a strong correlation between total satisfactory driving manoeuvre and skills execution with contrast sensitivity in the better eye ($r = 0.6$; $p = 0.005$). (Haymes et al., 2008) The impact of measure of vision on lane changing abilities (two studies) was mixed. Even though one study reported visual acuity, contrast sensitivity and bilateral visual field loss to not be predictors of lane changing errors in drivers aged above 65 years, (Munro et al., 2010) the other found better VA ($p \leq 0.01$), CS ($p \leq 0.01$) and glare sensitivity ($p \leq 0.05$) to be strongly correlated with better scores in lane position

and observance when merging or turning left or right. (Szlyk et al., 1960). 1995) Worse speed control and increasing errors in speed of approach have been linked to worse glare sensitivity ($p < 0.05$) (Szlyk et al., 1960). 1995) and CS ($p < 0.01$), (Baldock et al., 2008) respectively. Another study investigating contrast sensitivity, visual field and visual acuity through naturalistic driving with in-vehicle monitoring, found both contrast sensitivity and visual field loss to predict higher rates of deceleration events but only on low mileage drivers. (Keay et al., 2013).

Vision-related interventions and their impact on specific driving performance measures were investigated by four studies (Fig. 2). The only study ($n = 162$) looking at vision screening used the traditional measure of visual acuity with the addition of contrast sensitivity, as a tool to predict driving performance. The drivers in this study were 70 years and older and 21 % had moderate to severe deficits in contrast sensitivity. The combination of visual acuity and contrast sensitivity was not predictive of daytime driving ability. (Spreng et al., 2018) Two studies looked at the use of corrective lenses. One study was an RCT on drivers with uncorrected astigmatism given either toric or spherical lenses. (Black et al., 2019) This study found toric lenses to be better at reducing the number of hazards hit ($p = 0.022$) and increasing the number of signs recognised ($p = 0.021$) than spherical lenses. The difference in lane-keeping time between the two types of lenses, however, was not significant. The other study on corrective lenses looked at drivers with presbyopia corrected by either single-vision lenses, progressive-addition spectacle lenses, monovision contact lenses, and multifocal contact lenses. (Chu et al., 2010) Overall, there were no significant differences in either the number of road hazards hit, the number of signs recognised, or the lane-crossing times between the types of lens worn. The remaining study investigated whether cataract surgery could improve on-road driving performance and found post-op driving scores to improve for overall driving score ($p = 0.001$), road sign recognition ($p < 0.001$), road hazard recognition ($p = 0.001$) and avoidance ($p < 0.001$). (Wood and Carberry, 2006).

Raw data summary of all driving performance measures can be found in Appendix D. (Haymes et al., 2008; Lee et al., 2018; Wood et al., 2016; Szlyk et al., 1960). 1995; Wood et al., 2018; Wood, 2002; Wood and Mallon, 2001; Coeckelbergh et al., 2004; Spreng et al., 2018; Black et al., 2019; Kasneji et al., 2014; McKnight et al., 1991; Merickel et al., 2019; Bauer et al., 2001; Baldock et al., 2008; Keay et al., 2013; Chu et al., 2010; Wood and Carberry, 2006; Keay et al., 2009; Eramudugolla et al., 2022; Swain et al., 2021; Wang et al., 2021).

Discussion

This paper synthesises global data on the associations of vision impairment and vision-related interventions on driving performance. Both glaucoma and AMD, alongside declines in measures of vision function, were found to be associated with poor driving performance. These results support the findings of a complementary systematic review (Nguyen et al., 2020) which also found these vision impairments to be associated with either crash involvement and or driving cessation. Early detection and management of eye conditions is therefore an important strategy to promote road safety. As disease severity worsens, driving performance and timely treatment is critical. Licensing and healthcare systems are needed to ensure drivers have access to eye-care services including diagnosis and management of ocular disease, particularly older drivers where eye diseases are more common. Though there was limited evidence from interventional studies, corrective lenses are a relatively simple intervention to maintain and optimise vision for driving.

Despite vision being commonly assessed during licensure, only one study identified in this review examined vision screening and its association with driving performance. Despite no predictive value found in this study, other studies focusing on sole measures of vision function still consistently found poor visual acuity and contrast sensitivity to

negatively impact driving performance, thus supporting the rationale for vision screening. A recent big data study found the likelihood of failing the visual acuity standards for driving to increase with age, particularly for those aged over 80 years whose fail rates increase every 2 years after 80. (Moore et al., 2022) Vision screening policies may have an impact in low- and middle-income countries (LMICs) where many drivers are licensed with vision loss that is treatable, such as refractive errors. (Dotse et al., 2019) It is estimated that more than 90 % of all persons with uncorrected refractive error are from LMICs and rural areas who, due to economic, social and health service barriers, are unable to access adequate eye- care services. (Ehrlich et al., 2019; Naidoo and Jaggernath, 2012) This is of concern as corrective lenses, as illustrated in this review, do help improve select driving performance measures. As LMICs also suffer from the highest crash involvement and road traffic injury rates, strategies are needed to improve accessibility of eye health services in order to complement vision screening for licensure and keep all road users safe.

Vision screening as a fitness-to-drive tool, however, should not be considered alone, with previous studies finding screening not accurate at predicting on-road driving performance. (Higgins and Wood, 2005; Silveira et al., 2007) Instead, combining vision assessments alongside psychometric tests may be better at evaluating on-road driving skills. (Grundler et al., 2020; Wood et al., 2013) For example, the “multi-D test”, a computer-based test on colour reaction, vision motion sensitivity, and balance and postural sway, has high specificity and sensitivity for people with a vision impairment. (Anstey et al., 2020) Further, higher scores in useful field of view assessments, and poorer scores in hazard perception tests and multi-D battery tests have all been shown to be good at predicting the risk of failing on-road driving assessments. (Anstey et al., 2020; Jones Ross et al., 2014; Myers et al., 2000) Inclusion of many of these additional assessments during license renewal, however, is not feasible. Future policies surrounding licensing and fitness-to-drive may instead aim to include selected parts of these assessments on indication alongside vision screening, specifically for older drivers and those with vision difficulties. Programs to support independent mobility beyond driving are also needed.

There were no studies identified looking at cataract and driving performance despite this review finding one paper showing cataract surgery to improve driving performance. There was however substantial evidence about the negative impact of reduced contrast and glare sensitivity on driving performance, both common symptoms of cataract. Cataract surgery can decrease these driving difficulties by 88 %, (Subzwari et al., 2008) but driving at night or in low contrast visual acuity conditions can still remain difficult. (Mönestam and Lundqvist, 2006) Further, a driving simulation study on older drivers comparing their driving performance scores from before first eye to after second eye surgery only found significant improvements to the time spent speeding but not lane and speed deviations. (Meuleners et al., 2021) Others have proposed that improvements to driving may be due to the type of intraocular lens implanted and its blue light filtering feature may impact how much driving improves but research on this area is currently inconclusive. (Beiko, 2015; Espindle et al., 2005; Gray et al., 2012; Wright et al., 2017).

This review found 33 different ways driving errors and performance can be measured on on-road driving circuits, thus making it difficult to determine which measure impacts driving safety, particularly crash involvement. Reporting the number of driving errors was the most commonly used measure. This makes sense as naturalistic driving data has shown driver errors, impairment, fatigue and distraction, to be responsible for almost 90 % of crashes. (Dingus et al., 2016) A study on the naturalistic driving habits of older drivers found impaired contrast sensitivity or moderate and severe slowing of visual processing speed to increase crash risk by 2.7, 2.3 and 5 times, respectively. (Swain et al., 2021) A recent study combining naturalistic driving data and on-road driving performance of older drivers found those with worse scores on the on-road circuit to be 2.8 times more likely to get into both at-fault

and near-crashes than those with better scores after adjusting for age. (Swain et al., 2021) However other surrogate measures of performance such as course completion time and reversing time have yet to be connected with crash involvement. Future research looking into the harmonisation of outcome measures could be of benefit to the field. One such example is the “P-drive” assessment tool which tests a range of skills from vehicle position to stimuli responses, and has been used clinically and validated by occupational therapists. (Patomella and Bundy, 2015).

There are a few limitations in this review that need to be acknowledged. Firstly, this review only includes 27 studies despite searching from three, large electronic databases. This might be because the scope was restricted to on-road driving. It is also a limitation that there are few studies from LMICs. Further, due to the variability in driving performance measures, meta-analysis was not feasible. Narrative summaries were used instead however these summaries are restricted by the studies’ methodological limitations. Sample sizes in the included studies were small as individuals with a vision impairment may deem participation to be too risky. Studies also used different on-road circuits and scoring of performance measures varied from relying on either a driving instructor, a driver-trained occupational therapist or both. As there were no studies from LMICs identified, the results from this review may hold limited relevance in these countries. This is of concern as, despite legislation promoting safe driving in these countries, the practice-knowledge gap amongst drivers contribute to high crash and road injury rates in LMICs. (Anebonam et al., 2019; Chen, 2010; Chen et al., 2016; Damsere-Derry et al., 2017; Jothula and Sreeharshika, 2021; Mohamad et al., 2019; Ngueutsa and Kouabenan, 2017; Staton et al., 2016) Research is needed to understand this gap and the factors surrounding how drivers in LMICs interact with the road system. Nonetheless, the strengths of this review includes the breadth of different eye diseases and vision-related interventions on numerous different driving performance measures. There were also no restrictions on age which therefore allowed the evidence on the driving ability of younger and or middle-aged drivers with a vision impairment to be documented. With all but two of the studies being published within the past two decades, this review nonetheless provides a comprehensive overview of this growing area of research.

Conclusions

In conclusion, this review summarises the global literature on the impact of vision and vision-related interventions on driving performance as part of the *Lancet Global Health Commission* on Global Eye Health. Glaucoma, AMD, monocularly, self-reported vision loss and declines in contrast sensitivity, visual acuity, glare sensitivity and visual field were shown to negatively impact a variety of driving performance measures, while cataract surgery or appropriate corrective lenses can improve driving scores and reduce errors on hazard and signage recognition. Current literature, however, is highly heterogeneous, and contains few interventional studies and no studies from LMICs. Future studies should aim to address these gaps in order to inform investments in health care services directed at eye care to help reach the UN’s SDGs on creating a safer driving environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

None.

Data sharing

All data collected for the study have been provided in the submitted supplementary tables and will be made available at the time of publication with the journal. The study protocol was previously published and is publicly available ([10.1136/bmjopen-2020-040881](https://doi.org/10.1136/bmjopen-2020-040881)).

Funding statement

HN is supported by the Australian Government Research Training Program (RTP) Scholarship. MJB is supported by the Wellcome Trust (207472/Z/17/Z). JR's appointment at the University of Auckland is funded by the Buchanan Charitable Foundation, New Zealand. The Lancet Global Health Commission on Global Eye Health was supported by grants from The Queen Elizabeth Diamond Jubilee Trust, Moorfields Eye Charity (GR001061), NIHR Moorfields Biomedical Research Centre, The Wellcome Trust (20190426.PH2), Sightsavers, The Fred Hollows Foundation, SEVA Foundation, British Council for the Prevention of Blindness, and the Christian Blind Mission.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.trip.2022.100753>.

References

- Adelaide Uo. Critical Appraisal Tools N/A [Available from: <https://joannabriggs.org/ebp/critical appraisal tools>].
- Anebonam, U., Okoli, C., Ossai, P., Ilesanmi, O., Nguku, P., Nsubuga, P., Abubakar, A., Oyemakinde, A., 2019. Trends in road traffic accidents in Anambra State, South Eastern Nigeria: need for targeted sensitization on safe roads. *Pan Afr. Med. J.* 32.
- Anstey, K.J., Eramudugolla, R., Huque, M.H., Horswill, M., Kiely, K., Black, A., Wood, J., 2020. Validation of Brief Screening Tools to Identify Impaired Driving Among Older Adults in Australia. *JAMA Netw. Open* 3 (6).
- Baldock, M.R.J., Berndt, A., Mathias, J.L., 2008. The functional correlates of older drivers' on-road driving test errors. *Top. Geriatr. Rehabil.* 24 (3), 204–223.
- Bauer, A., Dietz, K., Kolling, G., Hart, W., Schiefer, U., 2001. The relevance of stereopsis for motorists: a pilot study. *Graefes's Archiv. Clin. Experiment. Ophthalmol. Albrecht von Graefes Archiv für klinische und experimentelle Ophthalmologie.* 239 (6), 400–406.
- Beiko, G.H., 2015. A pilot study to determine if intraocular lens choice at the time of cataract surgery has an impact on patient-reported driving habits. *Clin. Ophthalmol. (Auckland, NZ).* 9, 1573–1579.
- Bhorade, A.M., Yom, V.H., Barco, P., Wilson, B., Gordon, M., Carr, D., 2016. On-road driving performance of patients with bilateral moderate and advanced glaucoma (30q, 0370500). *Am. J. Ophthalmol.* 166, 43–51.
- Black, A.A., Wood, J.M., Colorado, L.H., Collins, M.J., 2019. The impact of uncorrected astigmatism on night driving performance. *Ophthalm. Physiol. Opt.* 39 (5), 350–357.
- Campbell, M., McKenzie, J.E., Sowden, A., Katikireddi, S.V., Brennan, S.E., Ellis, S., et al., 2020. Synthesis without meta-analysis (SWiM) in systematic reviews: reporting guideline. *BMJ* 368.
- Carr, D.B., Barco, P.P., Babulal, G.M., Stout, S.H., Johnson, A.M., Xiong, C., Morris, J.C., Roe, C.M., Ginsberg, S.D., 2016. Association of Functional Impairments and Co-Morbid Conditions with Driving Performance among Cognitively Normal Older Adults. *PLoS One* 11 (12).
- Chen, G., 2010. Road traffic safety in African countries - status, trend, contributing factors, countermeasures and challenges. *Int. J. Inj. Contr. Saf. Promot.* 17 (4), 247–255.
- Chen, Y., Li, Y., King, M., Shi, Q., Wang, C., Li, P., 2016. Identification methods of key contributing factors in crashes with high numbers of fatalities and injuries in China. *Traffic Inj. Prev.* 17 (8), 878–883.
- Chu, B.S., Wood, J.M., Collins, M.J., 2010. The effect of presbyopic vision corrections on nighttime driving performance. *Invest. Ophthalmol. Vis. Sci.* 51 (9), 4861–4866.
- Coeckelbergh, T.R.M., Brouwer, W.H., Cornelissen, F.W., Kooijman, A.C., 2004. Predicting practical fitness to drive in drivers with visual field defects caused by ocular pathology. *Hum. Factors* 46 (4), 748–760.
- Damsere-Derry, J., Palk, G., King, M., 2017. Road accident fatality risks for "vulnerable" versus "protected" road users in northern Ghana. *Traffic Inj. Prev.* 18 (7), 736–743.
- Dawson, J.D., Uc, E.Y., Anderson, S.W., Johnson, A.M., Rizzo, M., 2010. Neuropsychological predictors of driving errors in older adults. *J. Am. Geriatr. Soc.* 58 (6), 1090–1096.
- Dingus, T.A., Guo, F., Lee, S., Antin, J.F., Perez, M., Buchanan-King, M., Hankey, J., 2016. Driver crash risk factors and prevalence evaluation using naturalistic driving data. *PNAS* 113 (10), 2636–2641.
- Dotse, J., Nicolson, R., Rowe, R., 2019. Behavioral influences on driver crash risks in Ghana: A qualitative study of commercial passenger drivers. *Traffic Inj. Prev.* 20 (2), 134–139.
- Ehrlich, J.R., Stagg, B.C., Andrews, C., Kumagai, A., Musch, D.C., 2019. Vision Impairment and Receipt of Eye Care Among Older Adults in Low- and Middle-Income Countries. *JAMA ophthalmology.* 137 (2), 146–158.
- Eramudugolla, R., Laird, M., Black, A.A., Cameron, L.D., Wood, J.M., Anstey, K.J., 2022. Inability of the Mini-Mental State Exam (MMSE) and high-contrast visual acuity to identify unsafe drivers. *Accid. Anal. Prev.* 168, 106595.
- Espindle, D., Crawford, B., Maxwell, A., Rajagopalan, K., Barnes, R., Harris, B., et al., 2005. Quality-of-life improvements in cataract patients with bilateral blue light-filtering intraocular lenses: clinical trial. *J. Cataract Refract Surg* 31 (10), 1952–1959.
- Gray, R., Hill, W., Neuman, B., Houtman, D., Potvin, R., 2012. Effects of a blue light-filtering intraocular lens on driving safety in glare conditions. *J. Cataract Refract Surg* 38 (5), 816–822.
- Grundler, W., Strasburger, H., Useche, S.A., 2020. Visual attention outperforms visual-perceptual parameters required by law as an indicator of on-road driving performance. *PLoS One* 15 (8).
- Haymes, S.A., LeBlanc, R.P., Nicoleta, M.T., Chiasson, L.A., Chauhan, B.C., 2008. Glaucoma and on-road driving performance. *Invest. Ophthalmol. Vis. Sci.* 49 (7), 3035–3041.
- Higgins, K.E., Wood, J.M., 2005. Predicting components of closed road driving performance from vision tests. *Optometry Vision Sci.* 82 (8), 647–656.
- Jones Ross, R.W., Cordazzo, S.T., Scialfa, C.T., 2014. Predicting on-road driving performance and safety in healthy older adults. *J. Saf. Res.* 51, 73–80.
- Jothula, K.Y., Sreeharshika, D., 2021. Knowledge, attitude, and practice toward road safety regulations among college students in Telangana state. *J. Educat. Health Promot.* 10 (1), 25.
- Kasneji, E., Sippel, K., Aehling, K., Heister, M., Rosenstiel, W., Schiefer, U., Papageorgiou, E., Bex, P., 2014. Driving with binocular visual field loss? A study on a supervised on-road parcours with simultaneous eye and head tracking. *PLoS One* 9 (2).
- Keay, L., Jasti, S., Munoz, B., Turano, K.A., Munro, C.A., Duncan, D.D., Baldwin, K., Bandeen-Roche, K.J., Gower, E.W., West, S.K., 2009. Urban and rural differences in older drivers' failure to stop at stop signs. *Accid. Anal. Prev.* 41 (5), 995–1000.
- Keay, L., Munoz, B., Duncan, D.D., Hahn, D., Baldwin, K., Turano, K.A., et al., 2013. Older drivers and rapid deceleration events: Salisbury Eye Evaluation Driving Study. *Accid. Anal. Prev.* 58, 279–285.
- Kimlin, J.A., Black, A.A., Wood, J.M., 2020. Older drivers' self-reported vision-related night-driving difficulties and night-driving performance. *Acta Ophthalmol.* 98 (4).
- Lee, S.-S.-Y., Black, A.A., Wood, J.M., 2018. Scanning behavior and daytime driving performance of older adults with glaucoma. *J. Glaucoma* 27 (6), 558–565.
- McKnight, A.J., Shinar, D., Hilburn, B., 1991. The visual and driving performance of monocular and binocular heavy-duty truck drivers. *Accid. Anal. Prev.* 23 (4), 225–237.
- Merickel, J., High, R., Dawson, J., Rizzo, M., 2019. Real-world risk exposure in older drivers with cognitive and visual dysfunction. *Traffic Inj. Prev.* 20 (sup2), S110–S115.
- Meuleners, L.B., Ng, J.Q., Fraser, M.L., Tjia, D., Feng, Y.R., Morlet, N., 2021. Changes in driving performance after first and second eye cataract surgery: A driving simulator study. *J. Saf. Res.* 78, 146–154.
- Mohamad, F.F., Abdullah, A.S., Mohamad, J., 2019. Are sociodemographic characteristics and attitude good predictors of speeding behavior among drivers on Malaysia federal roads? *Traffic Inj. Prev.* 20 (5), 478–483.
- Mönstam, E., Lundqvist, B., 2006. Long-time results and associations between subjective visual difficulties with car driving and objective visual function 5 years after cataract surgery. *J. Cataract Refract Surg* 32 (1), 50–55.
- Moore, M., Butler, J.S., Flitcroft, D.I., Loughman, J., 2022. Big Data analysis of vision screening standards used to evaluate fitness to drive. *Curr. Eye Res.* 47 (6), 953–962.
- Munro, C.A., Jefferys, J., Gower, E.W., Muñoz, B.E., Lyketos, C.G., Keay, L., Turano, K.A., Bandeen-Roche, K., West, S.K., 2010. Predictors of lane-change errors in older drivers. *J. Am. Geriatr. Soc.* 58 (3), 457–464.
- Myers, R.S., Ball, K.K., Kalina, T.D., Roth, D.L., Goode, K.T., 2000. Relation of useful field of view and other screening tests to on-road driving performance. *Percept. Mot. Skills* 91 (1), 279–290.
- Naidoo, K.S., Jaggernath, J., 2012. Uncorrected refractive errors. *Indian J. Ophthalmol.* 60 (5), 432–437.
- Ngueutsa, R., Kouabenan, D.R., 2017. Accident history, risk perception and traffic safe behaviour. *Ergonomics* 60 (9), 1273–1282.
- Nguyen, H., Di Tanna, G.L., Coxon, K., Brown, J., Ren, K., Ramke, J., Burton, M.J., Gordon, I., Zhang, J.H., Furtado, J.M., Mdala, S., Kitema, G.F., Keay, L., 2020. Associations between vision impairment and driving and the effectiveness of vision-related interventions: protocol for a systematic review and meta-analysis. *BMJ Open* 10 (11).
- Owsley, C., McGwin Jr., G., 2010. Vision and driving. *Vision Res.* 50 (23), 2348–2361.
- Patomella AH, Bundy A. P-Drive: Implementing an Assessment of On-Road Driving in Clinical Settings and Investigating Its Internal and Predictive Validity. *The American journal of occupational therapy : official publication of the American Occupational Therapy Association.* 2015;69(4):6904290010.
- Silveira, S., Jolly, N., Heard, R., Clunas, N.J., Kay, L., 2007. Current licensing authority standards for peripheral visual field and safe on-road senior aged automobile driving performance. *Clin. Experiment. Ophthalmol.* 35 (7), 612–620.

- Spreng, L., Favrat, B., Borruat, F.-X., Vaucher, P., 2018. Cross-sectional study assessing the addition of contrast sensitivity to visual acuity when testing for fitness to drive. *BMJ Open* 8 (1).
- Staton, C., Vissoci, J., Gong, E., Toomey, N., Wafula, R., Abdelgadir, J., Zhou, Y.I., Liu, C., Pei, F., Zick, B., Ratliff, C.D., Rotich, C., Jadue, N., de Andrade, L., von Isenburg, M., Hocker, M., Olivier, J., 2016. Road Traffic Injury Prevention Initiatives: A Systematic Review and Metasummary of Effectiveness in Low and Middle Income Countries. *PLoS One* 11 (1).
- Subzwari, S., Desapriya, E., Scime, G., Babul, S., Jivani, K., Pike, I., 2008. Effectiveness of cataract surgery in reducing driving-related difficulties: a systematic review and meta-analysis. *Injury Prevent.* 14 (5), 324–328.
- Swain, T.A., McGwin Jr., G., Wood, J.M., Antin, J.F., Owsley, C., 2021. Naturalistic driving techniques and association of visual risk factors with at-fault crashes and near crashes by older drivers with vision impairment. *JAMA Ophthalmol.* 139 (6), 639–645.
- Swain, T.A., McGwin Jr., G., Antin, J.F., Owsley, C., 2021. Driving specialist's ratings of on-road performance and naturalistic driving crashes and near-crashes. *J. Am. Geriatr. Soc.* 69 (11), 3186–3193.
- Swain, T.A., McGwin, G., Antin, J.F., Wood, J.M., Owsley, C., Pak, R., 2021. Left turns by older drivers with vision impairment: A naturalistic driving study. *Innov. Aging* 5 (3).
- Szlyk JP, Pizzimenti CE, Fishman GA, Kelsch R, Wetzel LC, Kagan S, et al. A comparison of driving in older subjects with and without age-related macular degeneration. *Archives of ophthalmology* (Chicago, Ill : 1960). 1995;113(8):1033-40.
- UN. #Envision2030: 17 goals to transform the world for persons with disabilities 2015 [Available from: <https://www.un.org/development/desa/disabilities/envision2030.html>].
- Wang, S., Sharma, A., Dawson, J., Rizzo, M., Merickel, J., 2021. Visual and Cognitive Impairments Differentially Affect Speed Limit Compliance in Older Drivers. *J. Am. Geriatr. Soc.* 69 (5), 1300–1308.
- Wood, J.M., 2002. Age and visual impairment decrease driving performance as measured on a closed-road circuit. *Hum. Factors* 44 (3), 482–494.
- Wood, J.M., Carberry, T.P., 2006. Bilateral cataract surgery and driving performance. *Br. J. Ophthalmol.* 90 (10), 1277–1280.
- Wood, J.M., Horswill, M.S., Lacherez, P.F., Anstey, K.J., 2013. Evaluation of screening tests for predicting older driver performance and safety assessed by an on-road test. *Accid. Anal. Prev.* 50, 1161–1168.
- Wood, J.M., Black, A.A., Mallon, K., Thomas, R., Owsley, C., Anderson, A., 2016. Glaucoma and Driving: On-Road Driving Characteristics. *PLoS One* 11 (7).
- Wood, J.M., Black, A.A., Mallon, K., Kwan, A.S., Owsley, C., 2018. Effects of age-related macular degeneration on driving performance. *Invest. Ophthalmol. Vis. Sci.* 59 (1), 273–279.
- Wood, J.M., Mallon, K., 2001. Comparison of driving performance of young and old drivers (with and without visual impairment) measured during in-traffic conditions. *Optometry Vision Sci.* 78 (5), 343–349.
- Wright, A.J., Singh, M.K., Henriksen, B.S., McFadden, M., Olson, R.J., 2017. Two single-piece acrylic intraocular lens choices and their effect on patient-reported driving habits. *J Cataract Refract Surg* 43 (2), 239–245.