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Impact of vision disorders and vision impairment on motor vehicle crash risk and on-road driving performance: A systematic review

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ABSTRACT

Vision is important for safe driving, but there is limited understanding regarding the impact of vision disorders on driving ability and safety. This systematic review evaluated and summarised evidence on the impact of vision disorders and impairment on motor vehicle crash (MVC) risk and on-road driving performance across seven databases, was prospectively registered with PROSPERO (CRD42020180135), and study quality rated using a standard tool. Forty-eight studies met the inclusion criteria for MVC risk (N=36), on-road performance (N=9), and both MVC risk and on-road performance (N=3). Of these studies, less than half were rated 'good' quality. Due to the small number of studies and often conflicting findings, it was not possible to draw firm conclusions for most vision disorders. However, evidence from several 'good' and 'fair' quality studies suggested increased MVC risk with binocular visual field impairment. There was mixed evidence regarding the impact of cataract, glaucoma, age-related macular degeneration, and homonymous field loss on MVC risk and no evidence of increased MVC risk with mild VA impairment. This review highlights the need for future well-designed studies to further explore the impact of vision disorders and impairment on driving outcomes to inform evidence-based policy and fitness to drive guidelines.

KEYWORDS: Vision disorders, visual impairment, motor vehicle crash risk, driving safety on-road driving performance, driving ability

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INTRODUCTION

Vision is important for safe driving. Accordingly, numerous studies have explored the association between vision and driving, with a significant increase in the number of citations on vision and driving research indexed in PubMed since the 1980s (Owsley et al. 2015). This increase in interest is motivated both by a limited understanding of how different types of visual impairment impact on driving ability and safety, as well as a lack of clear research evidence for determining vision standards for fitness to drive. The issue of which vision tests should be included in licensing standards and the establishment of objective criteria to ensure adequate vision for safe driving remains unclear, and is the topic of continuing research (Owsley et al. 2015; Wood 2019). Much of this lack of clarity arises from the fact that driving is not a simple task but is complex and dynamic, relying on the integration of a diverse range of visual (Owsley & McGwin 2010), sensorimotor (Lacherez et al. 2014), and cognitive (Anstey & Wood 2011) skills, all of which can impact on driving ability and safety.

The issue of visual impairment and driving is also becoming increasingly important given the ageing population, where older drivers comprise one of the fastest growing sectors of the driving population (Federal Highway Administration 2018). As the number of older drivers increases, there will be a commensurate increase in the number of drivers with visual impairment, given that the prevalence of vision disorders increases with age (Wang et al. 2000; Foreman et al. 2018). Indeed, the world-wide prevalence of visual impairment is estimated to be 217 million, with cataracts, age-related macular degeneration (AMD), glaucoma and diabetic retinopathy being the leading causes, particularly in older adults (Flaxman et al. 2017). The increase in the number of older drivers also has relevance for road safety, as older drivers have high injurious motor vehicle crash (MVC) rates per distance travelled, compared with younger and middle-aged drivers, and experience more severe injury outcomes (Meuleners et al. 2006; Koppel et al. 2011). Additionally, older drivers have more MVCs that involve intersections, turns across traffic, failure to yield and are more commonly cited as being “at-fault” (Rakotonirainy et al. 2012). However, driving is important for maintaining independence, and driving cessation is linked with feelings of isolation and depression, and associated functional declines (Marottoli et al. 1997; Windsor et al. 2007).

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Policy makers rely on research literature and consensus-based practice resources to develop fitness to drive guidelines that are fair to drivers with visual impairment but do not compromise the safety of the driver, passengers, and other road users. Clinicians also depend on the research literature, consensus-based practice resources and government policies to conduct assessments and advise their patients regarding whether they meet the visual requirements for fitness to drive. It is therefore imperative that high quality evidence is available and synthesised to inform these practice resources, enabling consistent and appropriate decisions to be made regarding drivers with visual impairment, balancing risk against independence and public safety.

Visual acuity is the most common measure of visual function included in driver licensing standards, while visual fields are also considered important for safe driving and are included in the majority of driver licensing standards worldwide (Yan et al. 2019). However, the cut-off values adopted for each of these measures varies across countries, and even between states or regions within a given country, and are largely not evidence-based (Bro & Lindblom 2018; Wood 2019).

The aim of this systematic review was to determine the impact of a range of vision disorders and visual impairments, including but not limited to those that are most prevalent in the community, such as cataract, AMD, glaucoma, diabetic retinopathy and hemianopic field loss, on MVC risk and on-road driving performance.

METHODS

Search strategy

This systematic review was planned, conducted and reported in accordance with PRISMA guidelines (www.prisma-statement.org). The systematic review protocol was prospectively registered with PROSPERO (registration number CRD42020180135). The objectives of the review were to determine the: 1) impact of vision disorders and/or visual impairment on MVC risk; and 2) impact of vision disorders and/or visual impairment on on-road driving test outcomes. A comprehensive search was performed in seven electronic databases (Cochrane Library, Ovid MEDLINE, PsycINFO via EbscoHost, EMBASE, CINAHL PLUS via EbscoHost, Ovid TRANSPORT and TRID: the TRIS and ITRD databases) to locate relevant studies up to 2 April 2020. The search strategy was developed by the research team and was

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guided by a subject matter expert librarian (CR) and the Cochrane Handbook for Systematic Reviews (Higgins et al. 2019), with the expert librarian subsequently conducting the electronic search.

Twenty-one relevant studies, that included both original research studies as well as reviews (so called *goldset studies*), were identified before the development of the search strategy by three expert vision researchers on the research team. These *goldset studies* were then used to identify and refine the relevant search terms and keywords, especially keywords and MeSH terms for vision disorders and visual impairment that impact on driving ability and safety (Supplementary File 1).

The search terms included MeSH terms and keywords that incorporated the following three key concepts: drivers of automobiles, vision disorders and vision impairment, and motor vehicle crash risk and on-road driving performance.

Study criteria

Articles that met the following criteria for inclusion were selected for full-text review and analysis: 1) original research published in a peer-reviewed journal; 2) English language and human studies; 3) full text available; 4) included drivers with vision disorders and/or visual impairment (assessed either by eye health professional and/or standardised vision measures); 5) included comparison or control drivers without vision disorders and/or visual impairment; 6) involved the assessment of either crash risk (self-reported or state-recorded through official crash records or recorded during naturalistic driving) and/or on-road driving test outcome (using a standardised criteria to assess fitness to drive, administered by driving instructor or driving occupational therapist or driving licensing authority); 7) used quantitative methods for data collection and reported quantitative results in the analysis.

Studies were excluded if they: 1) obtained results only from driving simulator methods; 2) included participants who were non-drivers; 3) only used qualitative methods for data collection and analysis; 4) were commentary manuscripts, literature or systematic reviews, case studies, conference abstracts and proceedings or dissertations.

Screening strategy and data extraction

From the database searches, a preliminary process of removal of articles that were duplicates or in the incorrect format (e.g. commentary, case studies, conference abstracts) was

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undertaken. Three of the authors worked independently and in duplicate to screen all of the remaining titles and abstracts for inclusion. Any queries raised were resolved by discussion with the team. For the full-text screening stage, three authors worked independently and in duplicate to include/exclude studies using the study criteria and coded the reasons for exclusion. Disagreements were resolved by consensus.

Information was extracted from each of the included studies: 1) study design (i.e. case control, cohort, cross-sectional); 2) methodological considerations (e.g. techniques employed to acquire MVC and implement on-road driving assessments); 3) participant characteristics (e.g. VI presence/type, diagnostic criteria, demographics, etc.); 4) comparison or control group characteristics; 5) results of specific outcome measures (e.g. percent of patients with visual impairment in all MVCs or at-fault MVCs, summarised on-road test scores); 6) key findings. The data extracted by one of the reviewers was independently verified by another reviewer to identify and rectify any errors.

Quality assessment

Risk of bias was assessed independently by two authors using The National Heart, Lung and Blood Institute Quality Assessment Tools (NHLBI 2014). Two reviewers assessed each study independently and in duplicate and did not assess the quality of their own studies. Each study was then assigned an overall quality rating ('good', 'fair' or 'poor'), where higher risk of bias equals lower quality rating. Discrepancies were resolved by a third author.

Evidence synthesis

A narrative review rather than a meta-analysis was undertaken due to the vastly different outcome measures, sample characteristics, and study designs included in the evidence synthesis. Where a study did not report any statistical findings relevant to the research question of this systematic review, the authors calculated a crude OR and 95%CI using online statistical tools (https://www.medcalc.org/calc/odds_ratio.php) where there was data reported in the article.

The evidence is reported according to the different vision disorders or vision impairments and summarised based on the available studies reporting MVC and/or on-road driving assessment outcomes. ~~No randomised control trials were found by the search strategy.~~

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RESULTS

Characteristics of included studies

The database searches resulted in the identification of 6,617 articles (Figure 1). After removal of duplicates, studies that did not meet the inclusion criteria (such as wrong publication type or not in English), and following screening of titles and abstracts, 159 articles remained where full text articles were available. These full text articles were screened on inclusion and exclusion criteria and assessed for eligibility, which resulted in 48 studies, of which 36 reported MVC risk outcomes only, nine reported on-road performance outcomes only, and three reported both MVC risk and on-road performance outcomes. Many of these studies were designed to determine the effect of a specific vision disorder or visual impairment on driving outcomes, while others had broader objectives but included data relevant to this review.

Of the studies reporting MVC risk, 11 (28%) were published in the last ten years (2010-2020). Most studies were retrospective cohort studies (N=29, 74%), five were prospective cohort studies and five were case-control studies. Conversely, of the studies reporting on-road performance outcomes, seven (58%) were published in the last ten years (2010-2020) and all were cross-sectional in design.

Note that this systematic review excluded studies evaluating driving interventions, therefore no pre-post or randomised control trials are presented.

Participants included in studies

Tables 1 and 2 provide details of the demographic and clinical characteristics of participants in the MVC and on-road driving studies that were included in the evidence synthesis.

Of the 39 studies reporting MVC risk outcomes, three included drivers with cataract, five with AMD, nine with glaucoma, one with homonymous hemianopia and quadrantanopia and three with genetic retinal diseases. There were three studies that included drivers with different eye conditions, two of which provided a breakdown across the different eye conditions (McCloskey et al. 1994; McGwin et al. 1998) and one that provided data that was

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combined across all eye conditions (which are termed 'combined eye diseases' for the purpose of this review). Regarding those studies that reported on drivers with impairments in visual function, 11 studies included visual acuity (VA) impairment alone, five included visual field (VF) impairment alone, and six had VA and/or visual field (VF) impairment from a range of conditions. The sample size of drivers with visual impairment in these studies ranged from ten (Szlyk et al. 1995) to 2,071 (Hofstetter 1976). The age of the drivers with visual impairment was predominantly older (65 years and over); however, some studies investigated younger and middle-aged drivers (homonymous hemianopia and quadrantanopia, genetic retinal diseases), while others included a wide age range (16-79 years, (Davison 1985); 15 years and over (Hofstetter 1976) and 16 years and over (Johnson & Keltner 1983; Decina & Staplin 1993)). Overall, there was a wide range of gender distribution, from 0% to 100% male; however, in some studies, the gender of drivers was not reported (Hofstetter 1976).

Of the 12 studies reporting on-road outcomes, two included drivers with AMD, four with glaucoma, two with homonymous hemianopia/quadrantanopia, and four included drivers with various eye conditions. The sample size of drivers with vision disorders ranged from ten (Szlyk et al. 1995) to 75 (Wood et al. 2016). ~~As for the MVC studies,~~ The age of the drivers with visual impairment in these on-road studies was predominantly older (65 years and over), with some younger and middle-aged drivers, particularly those drivers with homonymous hemianopia and quadrantanopia (Wood et al. 2009; Elgin et al. 2010) and those using bioptic telescopes (Wood et al. 2013). Overall, there was a wide range of gender distribution, ranging from 36% to 100% male.

Information about the severity of vision disorders varied across both the MVC and on-road studies, ranging from mild to advanced disease, while some studies failed to report disease severity. The measures used to determine disease severity, and whether they were standardised instruments, varied between different vision disorders, which included clinical measures of disease severity that are specific to a particular disease, for example, the AREDS scale for AMD (McGwin et al. 2013; Wood et al. 2018), and functional measures of vision loss, such as VA for conditions causing central vision loss (AMD, cataract), and a range of different VF indices for conditions causing VF loss (glaucoma, homonymous hemianopia and quadrantanopia). All studies included a comparison or control group with no eye disease, most of which were age-matched to the drivers with visual impairment.

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Outcome measures of included studies

Table 1 provides an overview of the outcome measures used in the 39 studies that included MVC risk. Studies assessed state-recorded MVC outcomes (N=16), self-reported outcomes (N=15), or both (N=6). One study used MVC data generated from in-vehicle sensors (Huisingh et al. 2017), while another used data collected from a company MVC database (Humphriss 1987). Most studies reported 'any' MVCs, while some reported more specific categories, such as 'at-fault' or 'injurious' MVCs.

The time over which MVCs were measured varied widely between studies. Studies using retrospective data ranged from MVCs occurring in the previous one-year to ten-year period. Several studies did not report any specific timeframe for the recall of previous self-reported MVCs (Adeoti et al. 2007; Oladehinde et al. 2007; Adekoya et al. 2009). In prospective studies, drivers were followed for up to ten years (Margolis et al. 2002), with most having shorter durations of follow-up. For example, the follow-up period for one prospective study was as short as 14 days and up to 1,567 days for some participants (Rubin et al. 2007). The shorter duration of follow-up in many of these prospective studies arose from factors such as time of study enrolment, time of diagnosis, cessation of driving, or consideration of only the time to the first crash.

The way in which the MVC outcome measures were reported also varied considerably and included the number of MVCs within a defined period, the proportion of participants with any MVC within a defined period, or the rate of MVCs adjusted for time (per person-time) or adjusted for driving exposure (per person-miles), with the latter two rates commonly used in prospective studies. In some instances, the MVC data was not reported separately for drivers with different types of vision disorders or visual impairment, particularly in the larger case-control or population-based cohort studies.

Table 2 provides an overview of the outcome measures used in the 12 studies that included on-road assessments, where standardised criteria were used to assess fitness to drive and the test was administered by a driving instructor, driving occupational therapist, or driving licensing authority. All assessments were administered with a qualified driving instructor or driver-trained therapist (occupational therapist or rehabilitation therapist), seated in the front passenger seat, often in a dual-controlled vehicle. The length of the route was generally reported either in terms of distance, ranging from 10 km (Haymes et al. 2008) to 23.5 km (Wood et al. 2013), or by duration, ranging from 20-mins (Silveira et al. 2007) to 45-mins

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(Devos et al. 2018). One study reported a drive consisting of a four block radius (Szlyk et al. 1995), where the distance or time was not reported. The driving routes also varied in complexity, all including suburban and urban sections, with some including more challenging interstate or highway sections (Wood et al. 2009; Devos et al. 2018).

Assessment of performance was undertaken by either the front seat instructor or therapist (N=2), or by one or more therapists or trained examiners seated in the back-seat (N=9), while in one study, rating was by a rehabilitation therapist, but their seating position was not stated (Szlyk et al. 1995). In the majority of studies, the evaluator was masked to the visual status of the driver, but in two instances, the driving instructor or assessor was unmasked (Elgin et al. 2010; Bhorade et al. 2016). Various performance outcomes were used, including numerical safety ratings, pass/fail criteria, or a combination of both, and ratings of specific driving behaviours, such as lane position, scanning, gap judgements, speed, and braking. Seven of the on-road studies included additional metrics relating to the number of critical errors where the driving instructor intervened, such as steering wheel and brake interventions.

Quality of included studies

Tables 1 and 2 summarise the methodological quality of included studies, based on the National Heart, Lung and Blood Institute Quality Assessment tools for observational cohort and cross-sectional studies and case-control studies (NHLBI 2014). Of the 39 studies reporting MVC outcomes, 34 were observational cohort studies and five were case-control studies. For the cohort studies, 11 were rated as 'good', 17 rated as 'fair', and six rated as 'poor' quality. For the case-control studies, four were rated as 'good' and one was rated as 'poor' quality. Of the 12 studies reporting on-road performance outcomes, five were rated as 'good' and seven were rated as 'fair' quality. Studies rated as 'poor' quality failed to meet more than 50% of the quality assessment criteria. Although results are presented for all studies regardless of their quality ratings, the discussion and conclusions are based only on those studies rated as 'good' or 'fair' quality.

Impact of vision disorders on driving

The data from the studies included in this systematic review are presented separately for each vision disorder or visual impairment. Studies of state-recorded MVC risk are generally reported first, as they present data that is less prone to bias than that derived from self-reported crash data (McGwin et al. 1998), which are presented next for each of the visual

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conditions. Studies of on-road driving performance are presented separately at the end of each section. For each of these driving outcomes, higher quality studies (rated as 'good' or 'fair') are presented before those of lower quality ('poor').

Cataract

The impact of cataract on state-recorded MVC risk relative to controls has been explored in three studies, all rated as 'good' quality (McCloskey et al. 1994; McGwin et al. 1998; Owsley et al. 1999). One retrospective cohort study that focused specifically on drivers with cataract, reported that those with cataract in one or both eyes, were 2.5 times more likely to have a history of at-fault state-recorded MVCs in the previous five years than drivers without cataract (adjusted rate ratio (RR)=2.48, 95%CI 1.00-6.14) (Owsley et al. 1999). However, there were no differences in the number of self-reported MVCs between drivers with cataract and controls. Conversely, two other studies of state-recorded MVCs reported no significant difference in MVC risk in those with cataracts compared to controls, with a population-based study showing no significant association of cataract with involvement in any MVCs (McGwin et al. 1998), and a case-control study reporting that cataract was not associated with increased injurious MVC risk (McCloskey et al. 1994). There have been no studies of on-road driving performance in drivers with cataract compared to controls.

Age-related macular degeneration

Five studies have reported data on the MVC risk of drivers with AMD compared to those without AMD, all rated as 'good' or 'fair' quality. However, although three of these studies reported the risk for state-recorded MVCs in AMD (McCloskey et al. 1994; McGwin et al. 1998; McGwin et al. 2013), only one focussed entirely on drivers with AMD (McGwin et al. 2013). In this retrospective cohort study (McGwin et al. 2013), which pooled samples from four different studies, at-fault state-recorded MVC risk in terms of person miles was significantly lower in those with intermediate AMD compared to controls (RR=0.35, 95%CI 0.13-0.91), while the risk of MVCs in those with early and advanced AMD was equivalent to that of controls. The authors suggested that the lower MVC risk of those with intermediate AMD reflected self-regulation of driving, through avoiding challenging situations and exercising greater caution on the road (McGwin et al. 2013). Two case-control studies also investigated state-recorded MVCs, with one showing no significant association of AMD with involvement in any MVC (McGwin et al. 1998), and the other reporting that AMD was not associated with increased injurious MVC risk (McCloskey et al. 1994). Both of these case-

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control studies included drivers with a range of different visual disorders and visual impairments and were limited by small numbers of drivers with AMD.

Two AMD-specific studies reported on the risk of self-reported MVCs, with mixed findings (Szlyk et al. 1995; Wood et al. 2018). In one study, self-reported MVC risk over the previous one and five years, was not associated with AMD status in older drivers with early and intermediate AMD (Wood et al. 2018), while in the other study, self-reported MVC risk was reported to be lower in drivers with AMD compared to controls (Szlyk et al. 1995). However, the latter study was limited by very small numbers of participants in both the AMD (N=10) and control group (N=11).

Two studies also assessed the on-road driving performance of drivers with AMD, both reporting inferior performance on some outcome measures compared to drivers without AMD (Szlyk et al. 1995; Wood et al. 2018). In the larger of these two studies (N=33 with AMD, N=50 for controls), Wood et al. (2018) reported that drivers with early and intermediate AMD were less safe than age-matched controls ($p=0.012$), with driving instructor interventions being significantly higher than for controls, but only for drivers with intermediate rather than early AMD (RR=3.05, 95%CI 1.47-6.36). Szlyk et al. (1995) also reported a reduction in overall on-road performance scores in drivers with AMD, compared to controls, however, the difference failed to reach significance ($p=0.07$), possibly due to the small sample size of this study (N=10 drivers with AMD, N=11 controls).

Glaucoma

Nine studies investigated the MVC risk of drivers with glaucoma, all rated as 'good' or 'fair' quality. Five reported the risk for state-recorded MVCs (McCloskey et al. 1994; McGwin et al. 1998; McGwin et al. 2004; Haymes et al. 2007; Kwon et al. 2016), three of which were retrospective cohort studies focussing on glaucoma (McGwin et al. 2004; Haymes et al. 2007; Kwon et al. 2016). In the earliest of the three glaucoma-specific studies (McGwin et al. 2004), drivers aged 50 years and older with glaucoma were less likely to be involved in MVCs than controls without glaucoma (RR=0.51, 95%CI 0.33-0.80), although, there was no statistically significant difference in at-fault MVCs. The suggestion that these findings might have been due to increased avoidance of challenging driving situations by those with glaucoma was found not to be the case in post-hoc analyses. However, the severity of glaucoma among participants was not reported. In a more recent study of older drivers (aged 70 years and older) with a range of visual field impairment from glaucoma (Kwon et al.

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2016), the at-fault MVC rate among drivers with glaucoma was significantly higher than controls (RR=1.65, 95%CI 1.20-2.28). In a smaller study, Haymes et al. (2007) found a non-significant increase in risk for state-recorded at-fault MVCs (OR=7.21, 95%CI 0.46-113.40), as well as any MVCs; however, the confidence intervals were wide. Two earlier case-control studies of older drivers also reported state-recorded MVC risk, with conflicting findings (McCloskey et al. 1994; McGwin et al. 1998). McCloskey et al. (1994) reported no evidence that glaucoma increased injurious MVC risk (RR=1.5, 95%CI 0.8-2.9). In contrast, McGwin et al. (1998) reported that glaucoma significantly increased the risk for involvement in any MVCs (OR=2.9), however, confidence intervals and significance values were only given for the multivariable model and not for the effect of glaucoma alone. The number of cases with glaucoma was relatively small in both case-control glaucoma studies (N≤43).

Five glaucoma-specific retrospective cohort studies investigated self-reported MVC risk (Szlyk et al. 2002; Szlyk et al. 2005; Haymes et al. 2007; Tanabe et al. 2011; Devos et al. 2018). Haymes et al. (2007) found a significantly increased risk for at-fault MVCs (OR=12.4, 95%CI 1.1-144.0) and any involvement in MVCs among drivers with glaucoma compared to drivers with no glaucoma, noting wide confidence intervals and a small sample size (N=20 with glaucoma). In a study of drivers with a wide range of glaucomatous visual field impairment in Japan, where there was a relatively low MVC rate (Tanabe et al. 2011), there was evidence of increased MVC risk for those with severe glaucomatous visual field sensitivity loss (expressed as mean deviation -10 dB or worse in the worse eye) compared to control drivers with no glaucoma, but no increase in risk for those with mild or moderate glaucoma. In another small study (Szlyk et al. 2002), there was no significant difference in MVC risk among drivers with mild to moderate glaucoma compared to control drivers with no glaucoma. However, a later study of glaucoma participants with a slightly wider range of visual field impairment by the same research group (Szlyk et al. 2005) found a significantly increased MVC risk for drivers with glaucoma compared with controls (calculated OR 21.0, 95%CI 1.17 - 378.25), noting wide confidence intervals and a small sample size (N=35 with glaucoma). In a recent pilot study of on-road driving performance, neither the drivers with glaucoma (n=17) nor the control group of drivers (n=11) reported any MVCs in the previous five years (Devos et al. 2018).

Four studies investigated on-road driving performance in drivers with glaucoma compared to controls, reporting inferior performance on some outcome measures (Haymes et al. 2008; Bhorade et al. 2016; Wood et al. 2016; Devos et al. 2018). In one of the first studies to assess

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on-road driving performance in glaucoma, the overall rating of driving performance of drivers with early to moderate glaucoma (N=20) was not significantly different to that of controls (N=20) with no glaucoma (Haymes et al. 2008). However, the drivers with glaucoma had ten times more driving instructor interventions than controls (OR=10.62, 95%CI 1.46-77.35). In a larger study by Wood et al. (2016), the safety of drivers with mild to moderate glaucoma (N=75) was rated as significantly worse than controls (N=70) (p=0.028), and the number of critical errors (requiring driving instructor intervention) for the drivers with glaucoma was twice that of controls (RR=2.06, 95%CI 1.17-3.62). Likewise, in a study where the driving instructor was unmasked (Bhorade et al. 2016), drivers with bilateral moderate or advanced glaucoma (mean deviation -6.01 dB or worse in both eyes) were significantly more likely to receive a marginal/fail score on the on-road test than controls, and over four times more likely to require a steering wheel intervention by the driving instructor (OR=4.7, 95%CI 1.03-21.17); however, there was no evidence of increased likelihood of brake interventions (OR=1.94, 95%CI 0.36-10.63). In another small study, on-road driving performance scores were not significantly different for drivers with glaucoma (N=17) compared to controls (N=11) without glaucoma (Devos et al. 2018).

Homonymous hemianopia and quadrantanopia

Only one study has reported on the state-recorded MVC risk of drivers with hemianopic and quadrantanopic field loss compared to controls (McGwin et al. 2016). In this retrospective cohort study, drivers with hemianopia (N=20) or quadrantanopia (N=7) had a significantly higher history of at-fault MVC crashes (RR=2.64, 95%CI 1.03-6.80) than age-matched controls (N=27). However, this study was limited by small participant numbers.

The on-road driving performance of the drivers included in the study described above was also reported in two papers that provided safety ratings from masked backseat assessors (Wood et al. 2009), as well as independent ratings from a clinical driving rehabilitation specialist seated in the front passenger seat who was unmasked to the visual status of the drivers (Elgin et al. 2010). Wood et al. (2009) reported that drivers with hemianopia were significantly more likely to fail the driving assessment compared to controls (p=0.027), while the performance of drivers with quadrantanopia was not significantly different to controls (Wood et al. 2009). Data from the clinical driving rehabilitation specialist included the numbers of verbal and physical interventions required, which were significantly higher for those with hemianopia compared to controls ($p<0.05$), but were only significantly higher for drivers with quadrantanopic field loss compared to controls for verbal interventions ($p<0.05$)

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(Elgin et al. 2010). While this was the first study to evaluate the on-driving performance of drivers with hemianopic and quadrantanopic field loss, it was limited by small numbers, as suggested by the wide confidence intervals.

Genetic retinal diseases

Evidence for MVC risk in genetic retinal diseases is limited to a few small, older studies, and there are no studies of on-road driving performance. One study of MVC risk in young to middle-aged drivers with central vision loss resulting from juvenile macular dystrophy (Stargardt's N=7 and cone-rod dystrophy N=13), found no evidence for either increased state-recorded or self-reported MVC risk compared to controls (Szlyk et al. 1993). Two retrospective cohort studies compared self-reported MVC risk in the previous five years in drivers with Retinitis Pigmentosa (RP) (Fishman et al. 1981; Szlyk et al. 1992) with that of controls. Both studies reported increased risk of self-reported MVC in drivers with RP compared to controls, with Fishman et al. (1981) reporting that drivers with RP (N=42) had more than twice the risk (OR 2.48, 95% CI 1.16-5.32) compared to controls (N=87) and Szlyk et al. (1992) reporting that drivers with RP (N=21) had five times the risk (OR 5.07, 95%CI 1.47-17.46) compared to controls (N=32). Importantly, in both RP studies, several participants had moderate to severely constricted visual fields, as measured using kinetic Goldmann visual field testing.

Combined eye diseases

One study assessed the MVC risk of younger and older drivers with visual impairment from a range of eye diseases compared to controls, and included both state-recorded and self-reported MVCs (Szlyk et al. 1995). In this retrospective cohort study, neither state-recorded nor self-reported MVC risk over the previous five years were significantly different to that of age-matched normal control drivers. However, the MVC risk for different eye diseases was not reported separately, making direct comparison with other studies of MVC risk in eye disease impossible.

Two studies explored the on-road driving performance of drivers with visual impairment resulting from a range of eye diseases (Wood & Mallon 2001; Wood et al. 2013). Wood and Mallon (2001) assessed overall driving safety of older drivers with visual impairment from a range of vision diseases (including cataracts, glaucoma and AMD) compared to visually normal controls. While driving safety was rated as poorer for drivers with visual impairment, these differences did not reach statistical significance ($p>0.05$), and there was no significant

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difference in the number of drivers with visual impairment who failed the driving assessment compared to the controls (Wood & Mallon 2001). However, this study did not report separate results for the different eye diseases, thus direct comparison with other eye disease studies is not possible. Wood et al. (2013) assessed the on-road driving safety of a group of young to middle aged drivers with central vision loss from a range of eye diseases who used bioptic telescopes for driving, demonstrating no significant difference in overall driving safety of bioptic drivers to that of control drivers with normal vision. These devices are permitted for driving in some countries including the US and the Netherlands and allow drivers with reduced central visual acuity (6/60 or better depending on the jurisdiction), to drive with the assistance of the device (VA through the telescope must be 6/18 or better) that provides a magnified view of the driving scene and is used to briefly view road signs and traffic lights.

Visual acuity impairment

Eight studies with a quality rating of 'fair' or 'good' reported on the state-recorded MVC risk of drivers with VA impairment compared to those drivers without VA impairment, including large population-based cohort studies (Margolis et al. 2002; Cross et al. 2009; Green et al. 2013), as well as case control studies, many of which had only small numbers of drivers with VA impairment (Gresset & Meyer 1994; McCloskey et al. 1994; McGwin et al. 1998; Owsley et al. 1998; Owsley et al. 1998).

Of the three large population-based cohort studies, two reported on prospective MVC risk (Margolis et al. 2002; Cross et al. 2009) and the other reported on retrospective MVC risk (Green et al. 2013). Increased prospective MVC risk was not associated with VA of 6/12 or worse over a mean follow-up period of 5.7 years (Margolis et al. 2002), although this study only included older women and it is not stated whether VA was assessed binocularly or monocularly. In another study of prospective MVC risk that included two to six years follow-up and combined data from four different US cohort studies, there was no association between binocular VA of 6/12 or worse and increased MVC risk, regardless of whether the MVCs were categorised as any, at-fault or injurious (Cross et al. 2009). The large population-based retrospective cohort study also found that MVC risk (any or at-fault in the previous five years) of drivers with binocular VA worse than 6/12 was not significantly different to those with no VA impairment (Green et al. 2013).

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In the population-based case-control study by McCloskey et al (1994), injurious MVC risk was not increased for those drivers with VA impairment, regardless of the definition of impairment (6/7.5 to 6/9; 6/12; 6/15 to 6/18; 6/21 or worse), compared to VA of 6/6 or better. Indeed, for drivers with corrected VA of 6/15-6/18, MVC risk was reduced rather than increased compared to those with VA of 6/6 or better (RR=0.3, 95%CI 0.1-0.9). Another case-control study also showed that VA impairment (binocular VA worse than 6/12) was not a significant risk factor for either state-recorded or self-reported MVCs (previous five years) compared to those with VA 6/12 or better (McGwin et al., 1998). In a prospective cohort study of older drivers with three years of follow-up (Owsley, Ball, et al., 1998), there was no significant difference in MVC risk among drivers with binocular VA impairment (worse than 6/12) compared to controls (binocular VA 6/12 or better). Two case-control studies also demonstrated that VA impairment was not associated with increased MVC risk (Gresset et al., 1994; Owsley, McGwin, et al 1998). Gresset and Meyer (1994) found that male drivers aged 70 years with VA impairment (better eye VA 6/12 or 6/15) did not have increased MVC risk compared to a group without VA impairment. Similarly, Owsley et al. (1998) found that binocular VA impairment (worse than 6/12) was not associated with an increased risk of either injurious or non-injurious MVCs over the previous 5 year period.

A naturalistic prospective study of older drivers using in-vehicle monitoring devices collected across six states, also reported that binocular VA impairment (worse than 6/12) was not associated with prospective MVC risk (any, severe or at-fault) over a 3 year monitoring period (Huisingh et al. 2017). An advantage of in-vehicle monitoring devices is that they also record driving exposure, which is typically determined using self-reported data, and there is also video and sensor data to identify crashes, including minor crashes. This might explain the higher MVC rates reported in this study compared with those typically found in studies of state-recorded MVC rates in older drivers.

Seven studies evaluated the self-reported MVC risk of drivers with VA impairment compared to those with no VA impairment (Hofstetter 1976; Davison 1985; Ivers et al. 1999; Keeffe et al. 2002; Adeoti et al. 2007; Oladehinde et al. 2007; Adekoya et al. 2009) with mixed results. However, over half of these studies were rated as being of 'poor' quality.

Hofstetter (1976), in one of the earliest studies of VA impairment and self-reported MVC risk, conducted a large retrospective cohort study, and found that twice as many drivers (aged 20 years and above) with poor binocular VA reported three or more MVCs compared to drivers with good vision (Hofstetter 1976). However, the categorisation of VA was defined as

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being in the top quartile of the sample (good VA) vs. the lower two quartiles (poor VA), rather than a pre-defined VA level used in licensing standards. Overall, the study was rated as being of 'poor' quality. A large population-based retrospective cohort study (Ivers et al. 1999), reported that a 2-line difference in VA between eyes was associated with increased MVC risk (adjusted Prevalence Ratio [PR]=1.6, 95%CI 1.0-2.4), as was VA worse than 6/18 in the right eye (adjusted PR=2.0, 95%CI 1.3-3.5). However, MVC risk was not associated with VA impairment in the left eye or in the better eye. Conversely, in a large retrospective cohort study, MVC risk (in the previous 5 years) was not significantly different between those with poor VA (VA worse than 6/12) and better VA (VA 6/12 or better) (Keeffe et al. 2002), regardless of whether MVCs were attributed to poor vision or not by participants. In a smaller retrospective cohort study (Davison 1985), VA impairment (VA 6/6.5 or worse) was associated with increased MVC risk for drivers of all ages (χ^2=6.25, p<0.01 one tailed), while for drivers 55 years and above, VA impairment (binocular VA of 6/9 or worse) was associated with significantly increased MVC risk (χ^2=5.30, p<0.025 one tailed; calculated OR=14.36, 95%CI 1.84-111.92). However, the criterion for VA impairment was determined using optimum cut-off scores based on the data collected, rather than a pre-defined level used in licensing standards, and the self-reported MVC data was collected by police officers, thus it was suggested that drivers may have reported only more serious crashes.

Three retrospective cohort studies, all rated as being of 'poor' quality, reported the MVC risk of commercial drivers in Nigeria, where the rates of MVCs and fatalities are relatively high, as is the case for many low-to middle-income countries (Ihueze & Onwurah 2018). In one study, MVC risk was higher for drivers with VA impairment (VA in the better eye worse than 6/18) compared to those with normal vision (RR=3.5, 95%CI 2.38-5.14) (Oladehinde et al. 2007). In the other two studies there was no significant difference in MVC risk for drivers with VA impairment (binocular VA 6/18 or worse) (Adeoti et al. 2007), or (better eye VA less than 6/9) (Adekoya et al. 2009) compared to drivers with normal vision. These studies were all limited by relatively small sample sizes of drivers with VA impairment and the fact that the time period over which drivers self-reported their MVCs was not defined; all of these studies were rated as 'poor' quality. Finally, in a case-control study of construction workers, employer-recorded MVC risk was significantly higher in those with VA impairment (monocular or binocular VA worse than 6/12, or one eye worse than 6/12 and the second eye worse than 6/6) compared to controls (OR=2.34, 95% CI 1.09-5.02) (Humphriss 1987). However, like the studies of commercial drivers, this study was limited by a small sample

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size and that the time period over which MVC risk was reported was not defined and was rated as 'poor' quality.

Visual field impairment

Ten studies examined MVC risk and two studies assessed on-road performance in drivers with visual field (VF) impairment, using a range of different methods to measure and classify VF impairment. Of the 10 MVC risk studies, seven had a quality rating of 'good' or 'fair' while three were rated as 'poor' quality (Oladehinde et al. 2007; Adekoya et al. 2009; Woolnough et al. 2013), with eight reporting the risk for state-recorded MVCs (Johnson & Keltner 1983; McGwin et al. 1998; Owsley et al. 1998; Owsley et al. 1998; Rubin et al. 2007; Woolnough et al. 2013; Huisingh et al. 2015; Okamura et al. 2019) and four reporting self-reported MVC risk (McGwin et al. 1998; Oladehinde et al. 2007; Adekoya et al. 2009; Okamura et al. 2019).

The earliest of the studies of state-recorded MVC risk was a large population-based retrospective cohort study of driving and VF impairment (Johnson & Keltner 1983). This study reported that MVC rates among drivers with VF impairment in both eyes (measured with a modified automated Fieldmaster 78-point screening test spanning 60 degrees temporally; criteria for impairment not clearly specified) was twice that of controls with no VF impairment ($p<0.005$), but there was no significant difference in MVC risk among individuals with VF impairment in one eye compared to controls. Rubin et al. (2007) investigated MVCs among older drivers in a population-based prospective cohort study and found that binocular field loss was a significant predictor of MVC involvement, with the strength of association varying by level of visual field loss. More severe binocular VF impairment (Humphrey Field Analyzer [HFA] 81-point single intensity screening test spanning 60 degree radius; 20 or more points missed) was associated with 30% increased risk for MVCs compared with controls (HR=1.31, 95%CI 1.13-4.27); whereas, milder VF impairment (fewer than 20 points missed) was associated with a paradoxical decrease in MVC risk (HR=0.59, 95%CI 0.34-1.00), even after adjustment for driving exposure and other potential confounders. More recently, two population-based retrospective cohort studies focussed on drivers with VF impairment (Huisingh et al. 2015; Okamura et al. 2019). Huisingh et al. (2015) found drivers aged 70 years and over with severe binocular VF impairment (HFA custom 20-point threshold test spanning 60 degrees radius; 7 or more test targets with sensitivity in lowest quartile (≤22.5dB)) had a 40% increased rate of at-fault MVCs compared to controls (RR=1.40, 95%CI 1.07-1.83). Conversely, Okamura et al.

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(2019) found no significant association between VF impairment (defined as either HFA SITA 24-2 mean deviation -5 dB or worse in the worse eye, or -5 dB or worse in the better eye, or Esterman score <90) and the risk for at-fault MVCs. Aside from the different criteria for VF impairment, the latter study included fewer participants with VF impairment. In another study of drivers aged 70 years or over, no significant association was found for VF impairment and involvement in MVCs (Woolnough et al. 2013); however, the period of data review (2 years) was shorter than for other studies and VF impairment was determined using a crude confrontation technique used for screening rather than assessment purposes and lacks sensitivity. Not surprisingly, the sample had relatively few participants with VF impairment (N=89; 7% of sample). Two case-control studies using the same sample investigated the association between central and peripheral VF impairment and MVC risk (McGwin et al. 1998; Owsley et al. 1998). There was no significant association between either the central 30 degree radius or peripheral 30-60 degree radius VF impairment (HFA 120-point screening test; average defect depth > 10 dB loss) and the risk for any MVC involvement over the previous five years (McGwin et al. 1998). However, in univariate analyses of injurious and non-injurious MVC risk, VF impairment within the central 30 degree radius and the peripheral 30-60 degree radius region were associated with significantly increased risk for injurious MVCs compared with controls (OR=2.6, 95%CI 1.1-6.3 and OR=2.4, 95%CI 1.3-4.5, respectively) and VF impairment within the peripheral 30-60 degree radius was associated with increased risk of non-injurious MVCs (OR=1.8, 95%CI 1.0-3.1) over the previous five years (Owsley et al. 1998). In multivariate analyses, these associations did not remain significant. The same drivers were followed prospectively for three years (Owsley et al. 1998), with no significant association reported between central or peripheral VF impairment and state-recorded crash rate.

In a naturalistic prospective study of older drivers which recorded prospective crash events, Huisingh et al. (2017) reported that binocular peripheral VF impairment (inability to detect a small target flashed temporally at 70 or 85 degrees along the horizontal meridian using a confrontation technique) in both eyes was associated with significantly increased rate of any MVCs (RR=1.74, 95% CI 1.18-2.56), and similarly, major MVCs and at-fault MVCs. However, peripheral VF impairment in either eye was only associated with a significantly increased rate of major MVCs (RR=1.53, 95%CI 1.02-2.29).

Four studies have investigated self-reported MVC risk in drivers with VF impairment compared to controls (McGwin et al. 1998; Oladehinde et al. 2007; Adekoya et al. 2009;

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Okamura et al. 2019). In two of these studies (McGwin et al. 1998; Okamura et al. 2019), that also reported state-recorded MVC risk as described above, there was no significant association between VF impairment and self-reported MVC risk. Both Oladehinde et al. (2007) and Adekoya et al. (2009) studied male commercial drivers in Nigeria and also found no significant association between VF impairment and MVC risk. However, in both studies the proportion of MVCs in both the impaired and control groups were high. Furthermore, the visual field measures used lack reliability and sensitivity, with Adekoya et al. (2009) using confrontation testing and Oladehinde et al. (2007) using a suprathreshold automated visual field test with unreported criteria for impairment.

In the two studies of VF impairment and on-road driving, inferior performance was reported for those with binocular visual field loss compared to controls. Although, neither study reported formal statistical analyses of the data collected, it was possible to calculate the likelihood of drivers failing an on-road assessment for the purpose of this review. In one of the studies (Silveira et al. 2007), eight of 17 drivers who did not meet visual field licensing guidelines failed a 20-minute driving test compared to three of 77 drivers who met the guidelines (OR=21.93, 95%CI 4.90-97.92). In the other study (Kasneci et al. 2014), 10 of 20 drivers with binocular visual field loss from either hemianopia or advanced glaucoma failed a 20 km road test (based on German Driving Licence standards, where assessors were masked to the visual status of the drivers), compared to three of 20 drivers in the control group (OR=5.67, 95%CI 1.25-25.61).

Visual acuity and/or visual field impairment

In a large population-based retrospective cohort study (Decina & Staplin 1993), those who failed to meet the driver licensing standard in Pennsylvania, USA, for either VA and/or VF criteria (VA worse than 6/12 and/or horizontal binocular VF less than 140 degrees), as determined using an Optec 100 vision screener, had increased risk for state-recorded MVCs compared to those who passed the driver licensing standard (χ^2=63.5, p=0.001). The source of the significant effect was relative over-involvement in MVCs by younger drivers (age 45 years and under) with good vision and by older drivers (age 66 years and over) with poor vision. However, the confidence that can be placed on these findings is limited, given the study was rated as 'poor' quality due to low participation rates, inadequate assessment of visual fields (using a single peripheral target), unclear description of analyses and inconsistent reporting of results.

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DISCUSSION

Summary of results

This systematic review summarised the results of studies that have compared the MVC risk (state-recorded, self-reported or recorded during naturalistic driving) or on-road driving performance of drivers with vision disorders or visual impairment with those without vision disorders. One of the main findings of this review is that the number of high-quality studies is limited. Forty-eight studies met our inclusion criteria and of these, less than half were rated as being of 'good' quality (N=18, 39%). Notwithstanding the sizeable proportion of 'good' quality studies, there were often relatively small numbers of drivers with visual impairment and the evidence regarding the impact on driving outcomes for most vision disorders is mixed.

Most of the included studies reported MVC risk (N=39), with around half including state-recorded data, however, relatively few included at-fault MVC data (N=10), which provides a better understanding of the potential impact of vision disorders or vision impairment on driving safety (Owsley et al. 2015). Other MVC studies included self-reported data which has inherent limitations (McGwin et al. 1998), whilst one study included data from in-vehicle monitoring which records MVCs as well as near-misses.

In terms of the vision disorders in the included studies, VA impairment was the most commonly reported (N=15), followed by VF impairment (N=12), which is likely to be because these measures of visual function are most commonly included in driver licensing standards and are therefore most widely available to researchers when assessing MVC risk. It is important to note, however, that the methods for assessing and defining impairment of both VA and VF varied widely between studies, making it difficult to combine the evidence and draw definitive conclusions.

In terms of the studies reporting different vision disorders or specific eye diseases, glaucoma was most common (N=12), followed by AMD (N=5) and cataract (N=3). Other vision disorders that were included in only a limited number of studies were homonymous hemianopic and quadrantanopic field loss, retinitis pigmentosa, Stargardt's disease and cone-rod dysfunction. In addition, some studies reported data collapsed across a range of different

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eye diseases (see section "Combined eye diseases"), which is problematic when trying to understand the effect of specific eye diseases on driving outcomes and makes comparison across studies impossible. There were no studies that met the inclusion criteria for this review on MVC risk or on-road driving performance in drivers with diabetic retinopathy, which is an issue given that this condition is a significant cause of visual impairment (Flaxman et al. 2017). Most studies involved older drivers, which is likely a consequence of the age-related increase in eye disease, vision disorders and subsequent visual impairment (Wang et al. 2000).

Cataract

Three studies were identified that were of 'good' quality but reported mixed results regarding the MVC risk of drivers with cataracts relative to controls. One cataract-specific study reported increased at-fault MVC risk in drivers with cataracts compared to those without cataracts; conversely, two studies that included a range of different vision disorders, including cataract, failed to find an association between cataract and increased MVC risk. Of note is that all of these studies were published more than 20 years ago, when patients were largely referred for surgery based on reduced VA, whereas, patients are now typically referred based on both their VA as well as symptoms (Quang Do et al. 2014); thus it might be anticipated that the VA of those currently driving with cataracts would be better than in earlier studies. However, the VA levels reported for drivers with cataract in a recent Australian study, indicated that 31 percent failed to meet the VA requirement for an unconditional licence (6/12 in one or both eyes) (Keay et al. 2016), suggesting little difference in the levels of VA of drivers with cataracts in this and earlier studies (VA of 6/18 and 6/9 in the worse and better eyes respectively) (Owsley et al. 1999).

Given the high prevalence of cataract in older adults, its' impact on visual impairment and the limited, mixed evidence for MVC risk, more studies of driving outcomes are indicated (Foreman et al. 2018), given that an estimated 30 percent of the older population have significant cataract in at least one eye (Rochtchina et al. 2003). However, it should be noted that while there were mixed findings regarding the effects of cataracts on driving in this review, it is important to consider a strong body of evidence that demonstrates reduced MVC risk following cataract surgery (Owsley et al. 2002; Keay 2012; Schlenker et al. 2018; Meuleners et al. 2019),

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Age-related macular degeneration

Five studies reported on the MVC risk of drivers with AMD and were rated as 'fair' (N=1) or 'good' (N=4), with MVC risk in drivers with AMD either reduced or equivalent to that of controls, particularly for those with intermediate AMD. Conversely, on-road driving performance was rated as less safe than controls, particularly for those with intermediate AMD. These conflicting findings may reflect the fact that many older drivers with AMD self-regulate their driving habits, including avoiding challenging driving situations (night time, unfamiliar areas, rush hour) compared to their age-matched counterparts (Ball et al. 1998; Weaver Moore & Miller 2005; Sengupta et al. 2014), resulting in them incurring fewer MVCs, despite having poorer driving performance. However, the limited number of studies involving this condition and the small sample sizes (Szlyk et al. 1995), together with the increasing prevalence of this age-related condition (Wong et al. 2014), where the prevalence of early and intermediate AMD in adults aged 50 years and older is around 15 and 10 percent respectively (Keel et al. 2017), suggests the need for further studies to fully understand the impact of AMD on driving ability and safety.

Glaucoma

Based on the nine glaucoma MVC studies, all rated as either 'good' (N=4) or 'fair' (N=5) quality, there is mixed evidence regarding glaucoma and MVC risk, with one study indicating reduced risk, some equivalent risk and others increased risk. Although there is insufficient evidence of inferior on-road performance in glaucoma drivers compared to controls from four studies of 'good' or 'fair' quality, there is some evidence of increased risk of critical errors during on-road driving assessments, even for those with early or mild glaucoma. However, further 'good' quality studies with larger sample sizes of drivers with glaucoma are warranted, given the prevalence of glaucoma in people aged 40-80 years is 3.5% (Tham et al. 2014), it is a leading cause of visual impairment and blindness (Flaxman et al. 2017) and because glaucoma tends to go unnoticed and undiagnosed in over half of all cases (Quigley 2011).

Homonymous hemianopia and quadrantanopia

Three papers were identified, where MVC risk and on-road driving performance in drivers with homonymous hemianopia and quadrantanopia were compared with drivers with normal fields, which reported data from the same study cohort, with study quality rated as 'good'/'fair' (Wood et al. 2009; Elgin et al. 2010; McGwin et al. 2016). The fact that there

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are so few studies that have assessed the driving ability and safety of this population is important given that most jurisdictions deny drivers with this type of field loss the opportunity to drive (Yan et al. 2019), regardless of the lack of evidence suggesting that all drivers with this condition are unsafe to drive. Indeed, McGwin et al. (2016) commented that while the MVC risk of the drivers with hemianopic and quadrantanopic loss is not dissimilar to that reported for other conditions (such as cataract), drivers with these other conditions are not prohibited from driving in most jurisdictions across the world. In addition, while a number of the drivers with this type of field loss were rated as unsafe, there were a number who were rated as safe as that of the controls (Wood et al. 2009). This suggests the need for a case by case assessment of such individuals, including standardised assessment of impairment and on-road evaluation, particularly as there may be associated cognitive impairment. More studies with larger sample sizes exploring the driving safety and ability of drivers with this type of field loss are needed to identify the extent and nature of individual driver differences.

Genetic retinal diseases

With only three 'fair' quality, small, older studies of MVC risk and no studies of on-road driving performance in genetic retinal diseases, there is insufficient evidence from which to draw conclusions. Genetic retinal diseases are low in prevalence compared with other eye diseases **(Flaxman et al. 2017)** and the issue of meeting the visual standards for driver licensing typically arises at a young age, when an individual first considers applying for driving licensure. Nevertheless, having better understanding of the impact of these conditions on driving ability and safety is important as individuals rely on driving to maintain their independence and lack of a driver's licence can also limit workforce opportunities.

Combined eye diseases

Three studies including one reporting MVC risk and two of on-road driving performance presented data for drivers with a range of different eye diseases. Study data and results were pooled, rather than presenting data for individual diseases separately which makes comparison with other studies challenging. The finding that MVC risk was not elevated in those with visual impairment compared to controls, was suggested to reflect the use of compensation strategies (Szlyk et al. 1995), however, any conclusions drawn are limited by the heterogenous nature of the diseases included in this study. On-road driving performance was reduced in drivers with visual impairment in one study (Wood & Mallon 2001), while in

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another, drivers with central visual impairment who used a bioptic telescope had equivalent driving scores to that of controls (Wood et al. 2013). While the latter study provides some evidence that drivers who fail to meet VA licensing standards can drive as safely as controls with the assistance of these devices, the study results were limited by a relatively small sample size.

Visual acuity impairment

Studies exploring the MVC risk of drivers with VA impairment were the most common in this systematic review. Of the studies reporting either state-recorded MVC risk or objectively measured MVC risk during naturalistic driving, all were rated as 'good' (N=7) or 'fair' (N=2) and none found an association between VA impairment and increased MVC risk, regardless of the study design, method of measuring VA, whether it was monocular or binocular and the level of VA used to define impairment or whether or not drivers wore their visual correction for driving

Of the studies that included self-reported MVC risk, none were rated as 'good', with most being rated as 'fair' (N=3) or 'poor' (N=5). Of those rated as 'fair', two reported increased MVC risk for some VA cut-offs, while one study reported no difference in MVC risk. An important limitation in interpreting the outcomes of these studies of VA impairment, is that the cut-points used to define 'reduced VA' vary between studies, typically relating to local driving standards, which makes valid comparisons challenging. However, assuming that state-recorded MVC risk provides the most objective data on safety compared to self-report, and that greater confidence can be placed on studies that are rated of higher quality, the evidence suggests that mild levels of VA impairment are not associated with increased MVC risk.

Visual field impairment

Of the five studies rated 'good' quality and the two rated 'fair' quality on VF impairment and MVC risk, there is some evidence of increased MVC risk in older people with more severe VF impairment in both eyes compared to older people with no VF impairment. Consistent with this, two small 'fair' quality on-road studies suggest poorer overall driving performance in those with binocular visual field loss compared to those with no VF impairment. Given that most jurisdictions include some form of visual field criteria in driver licensing standards, further 'good' quality MVC risk and on-road performance studies to determine evidence-based visual field criteria for licensure should be a priority, particularly as VF impairment

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can be caused by common eye conditions (e.g. glaucoma) and visual field loss is more likely to remain unnoticed and undetected than visual acuity loss. Attention should be given to ensuring that studies include adequate sample size, consistent standardised visual field measures and criteria, as well as well-defined driving outcome measures.

Methodological limitations observed in the studies

While a number of studies were identified that met the inclusion criteria for this systematic review, many had several methodological and reporting limitations that make synthesis and interpretation of the data across studies challenging. Limitations included drivers with varying degrees of visual impairment not consistently measured with standardised tools, relatively small sample sizes (particularly for the studies of on-road driving performance which ranged from sample sizes of 10 to 75 for drivers with visual impairment), inconsistent outcome criterion measures, as well as unclear statistical approaches and presentation of results. A particular limitation in terms of the data analysis is the lack of consistent adjustment for confounding factors, such as age, gender, or driving exposure which have a significant impact on driving ability and safety and vary greatly between different study populations. In addition, driving exposure that is typically derived from self-reported data does not necessarily reflect objective measures of driving exposure (Kaye et al. 2018). There are also additional limitations that are more relevant to studies of MVC risk or on-road driving performance which are described separately in the following sections.

An important limitation of the MVC studies included in this systematic review is that half included self-reported rather than state-recorded MVC risk. While collecting retrospective self-reported MVC data is easier and more convenient than accessing and interpreting MVC records from state or police authorities, it is limited by driver recall bias (less likely to recall minor crashes or whether a crash occurred within the specified timeframe), deliberate concealment of a crash due to fear of loss of licence, in addition to problems regarding the allocation of blame or responsibility (McGwin et al. 1998). As such, these self-reported outcome measures have been shown to poorly predict state-recorded MVC risk (McGwin et al. 1998). Some studies of self-reported MVC risk also do not collect information on exposure rates in terms of distances travelled and thus present data as absolute numbers of MVC rather than as MVC rates; examples from this review include Davison (1985) and Hofstetter (1976). This is a particular issue for older drivers with visual impairment who have insight into their limitations as they often restrict their driving exposure, avoiding more

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challenging driving situations such as night-time or peak hour traffic (Owsley et al. 1999; DeCarlo et al. 2003; Janz et al. 2009), which may explain why they do not have high MVC risk despite the fact that their driving ability may be unsafe. In addition, drivers with more severe loss typically have their licence revoked because they fail to meet the visual requirements for licensing, and therefore are not well represented in MVC records. This is particularly the case for drivers with central vision loss such as AMD, where the number of drivers with advanced AMD who participate in MVC studies is much lower than that of drivers with early or intermediate disease severity (McGwin et al. 2013).

There are also limitations of state-recorded crash data, which can include inaccurate reporting of the characteristics of both the crash and that of the driver, as well as the factors contributing to the crash (Abay 2015; Imprialou & Quddus 2019). State-recorded MVCs also tend to include only more serious crashes that require law enforcement attendance, with minor crashes not captured because they are not reported to police authorities (McGuire 1973), and there is also potential reporting bias in police-reported crash data (Shinar et al. 1983; Abay 2015). Of the studies that included state-recorded MVC data included in this review, only around half included data from at-fault MVCs, which provide a better understanding of the impact of vision on driving safety, rather than those situations where the driver's role in the MVC is limited to being on the roadway in a particular situation (e.g. being hit from behind when stopped). Whilst "at-fault" crashes do convey culpability, they do not necessarily confer direct causality related to the vision disorder or impairment, *unless* referred to specifically in the MVC record by the record author (usually law enforcement). In this regard, naturalistic driving studies are useful because they collect objective data on MVCs and include major, minor, and near miss MVC data, including pre-crash information about driver behaviour and contextual factors in the road environment, as well objective information regarding driving exposure (Owsley et al. 2015; Owsley et al. 2020). In addition, while a number of the MVC studies reported on large populations of drivers, they included relatively few drivers with specific eye disorders or impairment of VA or VF, limiting the confidence that can be placed on the outcomes.

A limitation of both self-reported and state-recorded retrospective MVC studies is that while the vision measures are conducted at the time of the study, the MVCs occurred previously, from one year and up to 10 years prior to the vision measures in some studies (Tanabe et al. 2011). While extended time frames allow more time to collect MVC data, the longer the period between the MVC event and assessment of vision, the less likely it is that the visual

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status of the driver reflects that when the MVC occurred. In addition, it is unclear whether drivers were wearing their refractive correction at the time of the MVC. In addition, many of the prospective studies included only a short duration of follow-up which limits the period of exposure over which MVCs can be monitored, potentially leading to only small numbers of MVCs in the analysis.

A methodological limitation of the studies of on-road driving performance is that the majority included in this review reported on the driving ability and safety of only small numbers of participants with vision disorders (ranging from n=10 to 75). To some extent this reflects the challenges of undertaking this type of research, as drivers with visual impairment may be less willing to volunteer in research because of fear of loss of their driving licence, as a consequence of participation. Having only small numbers of drivers with vision disorders in the various studies makes interpretation of the data challenging, which is exacerbated by the fact that the way in which visual impairment is reported, measured and defined varies greatly between studies. While all of the on-road measures were conducted using standardised evaluation criteria to assess fitness to drive, and almost all were administered by a driving instructor or driver-trained occupational therapist, not all evaluators were masked to participant characteristics and the driving courses were conducted in different traffic situations of different lengths, complexity and situations (non-interstate/interstate) making comparison between studies challenging.

A limitation relevant to both types of outcome measure is that many studies are more than a decade old (72% of MVC risk and 42% of on-road driving performance studies were published prior to 2010). This is relevant in that visual standards for licensing have changed in many jurisdictions over this period. In addition, the demands of driving have changed dramatically over recent years, with the road environment in urban contexts becoming more challenging with increased traffic density and road layout complexity.

Strengths and limitations of this systematic review

A major strength of this systematic review is that it is the first to synthesise the literature on MVC risk and on-road driving performance in those with vision disorders and visual impairment compared to drivers without these vision disorders. We adopted a broad search strategy to provide an overall view of all available peer reviewed published evidence, employing multiple databases to identify relevant studies. The broad search strategy resulted in finding more than 6,000 studies, of which 48 met the inclusion criteria.

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In addition, this review only included studies where vision disorders or visual impairments were defined by objective clinical measures or medical records rather than self-reported measures, which can be inaccurate and unreliable. The outcome measures of driving ability and safety for some studies included protocols that were standardised, however, quality did vary between studies and a number were rated as 'poor'. MVCs were identified by official records, or naturalistic study design protocols involving recordings, although many did include self-reported crashes which are less reliable as discussed in a previous section. On-road driving performance was evaluated using standard criteria to assess fitness to drive and were primarily administered by staff experienced in driver evaluation, either a driving instructor or driver-trained occupational therapist, and in all but one study were rated by masked assessors.

This systematic review also has some limitations that need to be acknowledged. The scope of the review did not extend to studies involving driving simulators or the effect of interventions, such as cataract surgery, on driving outcomes and reports from the grey literature were not included. In addition, because less than half of the included studies were rated as 'good' quality, with variable study designs, mixed outcomes, and because sample size was not considered within the quality criteria, it is not possible to pool study results from this heterogenous group of studies to draw firm conclusions. It is also important to recognise that when interpreting the data from this systematic review that the evidence does not address the question of which measures of visual function should be included in licensing standards, or the cut-off levels of visual function that will ensure safe driving.

Conclusions

This systematic review included 48 studies reporting the impact of common vision disorders and visual impairment on MVC risk and on-road driving performance. However, our finding that less than half of the included studies were rated as 'good' quality, with mixed study results, and that for many vision disorders included only small numbers of studies, means that it is not possible to draw firm conclusions about the impact of all major vision disorders on MVC risk or driving performance outcomes. Our findings suggest that there is evidence from some studies rated as 'good' and 'fair' quality that binocular VF impairment is associated with increased MVC risk, however, the evidence is insufficient to specify cut-offs for the level of field loss required for licensure. The evidence regarding cataract, glaucoma, AMD and homonymous field loss and genetic retinal diseases and MVC risk and/or on-road driving

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performance is mixed and there is no evidence linking mild levels of VA impairment that are typically allowed for driving and increased MVC risk. There were also no studies on the impact of diabetic retinopathy on driving outcomes that met the inclusion criteria for this review.

Recommendations for practice and future research

The findings of this review highlight a clear need for further well-designed studies with large sample sizes that explore the impact of vision disorders and visual impairment on MVC risk and on-road driving performance. Our review also identified many of the limitations of self-reported and state-recorded MVC data, thus naturalistic driving studies, which provide the opportunity to obtain both objective crash and driving exposure data, are recommended in order to better understand the link between visual impairment and driving. Future studies should also focus on prevalent eye conditions such as cataract, AMD and diabetic retinopathy. The extent of the binocular VF required to support safe driving should also be explored in future studies, given the association between binocular field loss and increased crash risk. Collectively, these studies would assist with identifying how visual disorders and visual impairment impact on driving ability and safety, to ensure that drivers with such impairments are not being unnecessarily restricted from driving, with the associated impacts on independence and functional mobility (Chihuri et al. 2016; Shimada et al. 2016). However, as discussed, such studies require considerable commitment of time and funding, but are necessary to contribute to evidence-based recommendations that can be used by policy makers and clinicians.

This review suggests that different vision disorders impact on driving ability and MVC risk in different ways and it is important that clinicians are aware of this issue when advising their patients with visual impairment. Importantly, people are often unaware that their vision and driving performance is changing. Regular eye examinations serve not only to detect eye diseases and vision impairment early, but also provide the opportunity for clinicians to inform patients of relevant changes in their vision and how this may affect their driving. This is important to foster insight, encourage self-regulation, compliance with vision health

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management protocols to reduce disease progression where possible and to support transitioning to alternative mobility options when driving independently is no longer possible.

DISCLOSURES

The authors report no proprietary or commercial interest in any product mentioned in this article.

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Table 1: Characteristics and quality assessments of reviewed studies that included motor vehicle crash (MVC) outcomes. Abbreviations are explained in the footnote.

Study, country, study design	Study population – sample size, mean age (SD), % male, disease severity	MVC risk variable	MVC outcomes	Summary of key findings	NIH Quality Assessment*
***Cataract (Note:** 2 additional studies including drivers with cataract are presented in the combined eye diseases section)*					
Owsley et al. (1999, USA)(Owsley et al. 1999) Retrospective cohort study	VI: N=279 older drivers with cataract; 71 (6) years; 53% male; mean VA in better-eye 0.23 logMAR, worse-eye 0.49 logMAR. Control: N=105 older drivers without cataract; 67 (6) years; 48% male	Number of state-recorded at-fault MVCs in previous 5-year period	Any state-recorded at-fault MVCs, N (%): VI: 35 (12.5%) Control: 6 (5.7%) Any self-reported MVCs, N (%): VI: 31 (11%) Control: 6 (6%)	Older drivers with cataract had a higher rate of state-recorded crash involvement compared to controls (adjusted RR 2.48, 95%CI 1.00-6.14). Older drivers with cataract had a similar rate of self-reported crash involvement compared to controls (p=0.19).	Good
***Age-related macular degeneration (AMD) (Note:** 2 additional studies including drivers with AMD are presented in the combined eye diseases section)*					
McGwin et al. (2013, USA)(McGwin et al. 2013) Retrospective cohort study	VI: N=142 older drivers with AMD with range of disease severity (AREDS grade): Early N=56, 72.7 (6.7) years, 52% male; Intermediate N=61, 75 (6.2) years, 53% male; Advanced N=25, 75.9 (6.9) years, 52% male. Controls: N=63 older drivers with no eye disease, 69.2 (5.7) years, 43% male.	Number of state-recorded at-fault MVCs, variable retrospective timeframe (rate defined by person-years and person-miles)	MVC rate per 100 person-years AMD Early: 4.00 AMD Intermediate: 2.04 AMD Advanced: 5.46 Control: 5.84 MVC rate per 1,000,000 person-miles AMD Early: 4.67 AMD Intermediate: 2.21 AMD Advanced: 7.07 Control: 6.38	Older drivers with early AMD had a similar MVC risk compared to controls (person-miles RR 0.73, 95%CI 0.36-1.50). Older drivers with intermediate AMD had a reduced MVC risk compared to controls (person-miles RR 0.35, 95%CI 0.13 to 0.91). Older drivers with advanced AMD had a similar MVC risk compared to controls (person-miles RR 1.11, 95%CI 0.38-3.19).	Good

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Wood et al. (2018, Australia)(Wood et al. 2018) Retrospective cohort study	VI: N=33 older drivers with AMD; 76.6 (6.1) years; 36% male; Severity AREDS grades: early N = 20, intermediate N = 13. Control: N=50 older drivers with no eye disease (age-matched); 74.6 (5.0) years; 36% male.	Number of self-reported MVCs in previous 1-year and 5-year period	Any MVC in previous 1 year, N (%): VI: 3 (9%); Control: 1 (2%) Any MVC in previous 5 years, N (%): VI: 10 (30%); Control: 8 (16%)	No between group difference in the number of self-reported MVCs in the previous 1 or 5-year period (p>0.23).	Good
Szlyk et al. (1995, USA)(Szlyk et al. 1995) Retrospective cohort study	VI: N=10 older drivers with AMD; 75.7 (4.5) years; 100% male; Binocular VA 20/70 (range 20/30 to 20/100). Control: N=11 older drivers with no eye disease (age-matched); 71.0 (8.3) years; 64% male	Number of state-recorded MVCs in previous 5-year period Number of self-reported MVCs in previous 5-year period	Any state-recorded crash, N (%): VI: 0 (0%); Control: 0 (0%) Any self-reported crash, N (%): VI: 1 (10%); Control: 6 (55%) Self-reported crash rate per mile, mean (SD): VI: 0.01 (0.04); Control: 0.26 (0.59)	There was no difference in state-recorded MVC recorded for either group (none recorded). AMD had significantly less self-reported crashes than controls (p<0.03). There was no difference in self-reported MVC rate per mile driven (p=0.10).	Fair
Glaucoma (Note: *2 additional studies including drivers with glaucoma are presented in the combined eye diseases section)*					
McGwin et al. (2004, USA)(McGwin et al. 2004) Retrospective cohort study	VI: N=576 older drivers with glaucoma; 69.5 years; 44% male; severity not reported. Control: N=115 older drivers with no eye conditions; 67.7 years; 50% male	Number of state-recorded at-fault MVCs in previous 5-year period (rate defined by person-time and person-miles)	Overall MVC rate, per person-years / person-miles: VI: 4.83 / 5.73 Control: 7.92 / 8.95 At-fault MVC rate, per person-years / person-miles: VI: 2.75 / 3.26 Control: 2.64 / 2.98	Older drivers with glaucoma had a lower overall MVC rate than controls (person-miles, RR 0.51, 95%CI 0.33–0.80). No difference for at-fault MVCs (person-miles RR 0.99, 95%CI 0.54–1.80).	Good
Haymes et al. (2007, Canada)(Haymes et al. 2007)	VI: N=48 older drivers with glaucoma, 69 (9) years; 50% male; Early to moderate glaucoma, better eye HFA mean MD -3.9 dB [SD 5.1].	Number of state-recorded at-fault MVCs in previous 5-year period	Any State-recorded MVCs, N (%): VI: All 8 (21%), At-fault 5 (14%); Control: All 4 (9%), At-fault 1 (2%)	Older drivers with glaucoma had non-significant higher rate of state-recorded MVC (all, adjusted OR 3.21, 95%CI 0.72-14.27); at-fault, adjusted OR 7.21, 95%CI 0.46-113.40) than controls.	Good

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Retrospective cohort study	Control: N=47 older drivers with no eye disease; 67 (7) years; 43% male	Number of self-reported MVCs in previous 5-year period	Any self-reported MVCs, N (%): VI: All 11 (27%), At-fault 8 (20%); Control: All 3 (7%), At-fault 1 (2%)	Older drivers with glaucoma had a higher rate of self-reported MVC (all, adjusted OR 6.62, 95%CI 1.40-31.23; at-fault, adjusted OR 12.44, 95%CI 1.08-143.99).	
Kwon et al. (2016, USA)(Kwon et al. 2016) Retrospective cohort study	Total: N=1,899 older drivers, 70-98 years (mean/SD not reported), 56% male. VI: N=206 drivers with glaucoma, 70-98 years; 58% male; severity not reported. Control: N=1,693 drivers with no eye conditions; 70-98 years; 56% male.	Number of state-recorded at-fault MVCs in previous 5-year period	Number of at-fault MVCs, N (%) No MVC: VI 169 (82%) / Control 1474 (87%) 1 MVC: 32 (16%) / Control 192 (11%) 2+ MVCs: 5 (2%) / Control 27 (2%)	Drivers with glaucoma had higher at-fault MVC rate compared with those without glaucoma (adjusted RR 1.65, 95% CI 1.20-2.28).	Fair
Tanabe et al. (2011, Japan)(Tanabe et al. 2011) Retrospective cohort study	VI: N=121 drivers with glaucoma, 62.1 (8.0) years; 65.3% male; Severity: mild N=50, moderate N=51 and severe N=20. Control: N=144 drivers with no eye disease (not age-matched); 61.2 (7.9) years; 66% male	Number of self-reported MVCs in previous 10-year period	Any MVC in past 10-years, N (%) Glaucoma: 7 (5.8%) Controls: 5 (3.5%) Any MVCs by glaucoma severity, N (%): Mild: 0 (0%) Moderate: 2 (3.9%) Severe: 5 (25%)	Significant association between occurrence of self-reported MVC and severity of glaucoma (p=0.007). Drivers with severe glaucoma had increased MVC risk compared with controls (OR 9.3, 95%CI 2.4-35.7).	Fair
Szlyk et al. (2005, USA)(Szlyk et al. 2005) Retrospective cohort study	VI: N=35 drivers with glaucoma; 63.0 (14.7) years; 55% male; severity not reported. Control: N=17 drivers with no eye conditions; 61.6 (14.7) years; 47% male	Number of self-reported MVCs in previous 5-year period	Any self-reported MVCs, N (%): VI: 13 (37%) Control: 0 (0%)	Older drivers with glaucoma had a higher rate of self-reported MVCs (p=0.005; OR 21.0, 95%CI 1.17 - 378.25)† than controls.	Fair
Szlyk et al. (2002, USA)(Szlyk et al. 2002) Retrospective	VI: N=25 drivers with glaucoma; 57.4 (17.3) years; 56% male; Severity not reported. Control: N=29 drivers with no eye conditions; 58.5 (18.9) years; 41% male	Number of self-reported MVCs in previous 5-year period	Number of MVCs, median (IQR): VI: 0 (0-0.25) Control: 0 (0-1.00)	No differences in the numbers of self-reported MVCs for the glaucoma group compared to controls (p=0.77)	Fair

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cohort study					
Devos et al. (2018, USA)(Devos et al. 2018) Retrospective cohort study	VI: N=17 drivers with glaucoma; 65.2 (9.7) years; 52.9% male; Better-eye median MD -1.3 dB [IQR -0.4 to -4.6], worse eye median MD -5.7 dB [IQR -2.0 to -10.6]. Control: N=11 drivers with no eye disease; 61.3 (11.5) years; 18.2% male	Self-reported MVCs in previous 5-year period	Number of MVCs, median (IQR): VI: 0 (0-0) Control: 0 (0-0)	No group differences in the number of self-reported MVC in previous 5-year period (p=0.33).	Fair
Homonymous hemianopia and quadrantanopia					
McGwin et al. (2016, USA)(McGwin et al. 2016) Retrospective cohort study	VI: N=27 drivers with homonymous hemianopia or quadrantanopia, including N = 20 hemianopia; 50.5 (19.6); 60% male; N = 7 quadrantanopia, 50.7 (18.5), 71% male. Control: N=27 drivers with no eye disease and normal visual field (age-matched); 50.4 (18.3) years; 29% male	Number of state-recorded at-fault MVCs in previous 9-year period (2002-2010, or since diagnosis after 2002 for VI group).	No MVC rates per person-years or person-mile reported by VI status.	Drivers with hemianopia or quadrantanopia have higher MVC rates per person-miles (adjusted RR 2.45, 95%CI 0.89–3.95), and elevated at-fault MVC rate (adjusted RR 2.64 95%CI 1.03–6.80), compared to controls. In subgroup analysis, only the hemianopia group significantly differed from controls.	Good
Genetic retinal diseases					
Fishman et al. (1981, USA)(Fishman et al. 1981) Retrospective cohort study	VI: N=42 drivers with RP; 38 years (SD not reported); 52% male; severity not reported. Control: N=87 drivers with no eye disease; 37 years (SD not reported); 44% male	Number of self-reported MVCs in previous 5-year period	Any MVCs in past 5-year, N (%) VI: 21 (50%) Control: 25 (28.7%)	Drivers with RP more likely to self-report any MVC in previous 5-year period compared to those with normal vision (p=0.02; OR 2.48, 95%CI 1.16-5.32) †	Fair
Szlyk et al. (1992, USA)(Szlyk et al. 1992)	VI: N=21 drivers with RP; 42 (12) years; 57% male; severity not reported. Controls: N=31 drivers with no eye disease, 39	Number of self-reported MVCs in previous 5-year period	Any MVCs in past 5 years, N (%) VI: 16 (76%) Control: 12 (39%)	Drivers with RP have higher self-reported MVC risk than controls (OR 5.07, 95%CI 1.47-17.46).†	Fair

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Retrospective cohort study	(12) years; 48% male				
Szlyk et al. (1993, USA)(Szlyk et al. 1993) Retrospective cohort study	VI: N=20 with central vision loss (7 Stargardt's disease and 13 cone-rod dystrophy); 36 (11) years; 40% male Controls: N=29 drivers with no eye disease, 39 (12) years; 52% male	Number of self-reported MVCs in previous 5-year period	Any MVCs in past 5 years, N (%) VI: 7 (35%) Control: 11 (38%)	No significant difference in self-reported MVCs between groups.	Fair
Combined eye diseases					
McGwin et al. (1998, USA)(McGwin et al. 1998) Case-control study	Total: N=278 older drivers, 71 (9.0) years; 54% male Cases: N=175 with state-recorded MVC history and N=125 with self-reported MVC history Control: N= 103 drivers with no state-recorded or N=153 with no self-reported MVC history VI: Glaucoma (N=19), Cataract (N=93) and AMD (N=15); reduced VA (worse than 20/40, N=25), reduced 30 deg central VF (n=24), reduced 30-60 deg peripheral VF (n=72); age/gender not reported Control: No eye disease, VA 20/40 or better; age/gender not reported.	Number of state-recorded MVC in the previous 5-year period. Number of self-reported MVC in the previous 5-year period.	No MVC data reported by eye disease, VA or VF status.	No difference in state or self-reported MVC risk for drivers with cataract or AMD compared to controls (statistics not reported). Glaucoma was a significant risk factor for state-recorded crashes, but not self-reported crashes (OR 2.9, 95%CI not reported). No significant difference in state or self-reported MVC risk for drivers with reduced VA, central VF or peripheral VF, compared to controls (statistics not reported).	Good
McCloskey et al. (1994, USA)(McCloskey et al. 1994) Case-control study	Cases: N=235 older drivers who had an injurious MVC requiring medical care; 65 years and older; 49.8% male Control: N=448 drivers without injurious MVC during previous 1-year period; 50% male	Involvement in a state-recorded injurious MVC (requiring medical care).	No MVC data reported by VI status.	No difference in injurious MVC risk in those with any eye disease (glaucoma, cataract, AMD) compared to those without eye disease. Glaucoma: RR 1.5, 95%CI 0.8-2.9 Cataract: RR 1.0, 95%CI 0.7-1.6 AMD RR 0.9, 95%CI 0.4-2.0	Good

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	VI: Presence of eye conditions (glaucoma N=43, cataract N=119, AMD N=27) and reduced VA (worse than 20/20) from medical records; age/gender not reported. Control: Drivers with no eye disease or VA 20/20 or better, age/gender not reported.			No difference in injurious MVC risk for reduced VA categories, compared to 20/20 or better, except for drivers with corrected VA of 20/50-20/60, who showed a reduced MVC risk (RR 0.3, 95%CI 0.1-0.9).	
Szlyk et al. (1995, USA)(Szlyk et al. 1995) Retrospective cohort study	VI: N=60 drivers with various eye conditions and compromised vision; N=37 young, 22-49 years; 51% male; N=23 older 50-80 years; 70% male; Conditions included AMD, RP, cone-rod dystrophy, Stargardt's disease, hemianopia; severity or type of vision loss not specified. Control: N=47 drivers with no eye disease (age-matched); N=27 Younger: 19-49 years; 52% male; N=20 Older: 50-83 years; 65% male	Number of state-recorded MVCs in previous 5-year period Number of self-reported MVCs in previous 5-year period	State-recorded MVCs, mean (SD). (N=66, group breakdown not specified) Young, VI: 0.40 (0.60) Older, VI: 0.18 (0.50) Young, control: 0.39 (0.5) Older, control: 0.27 (0.4) Self-reported MVCs, mean (SD): Young, VI: 0.73 (0.80) Older, VI: 0.48 (0.70) Young, control: 0.63 (0.8) Older, control: 0.42 (0.6)	No difference in rate of state-recorded MVCs (p=0.06), and no interaction with age (p=0.71). No difference in rate of self-reported (p=0.60), and no interaction with age (p=0.89).	Fair
Visual acuity impairment (Note: *5 additional studies on VA impairment are presented in the combined VA and/or VF impairment section and 2 in the combined eye diseases section)*					
Margolis et al. (2002, USA)(Margolis et al. 2002) Prospective cohort study	N=1,416 older drivers, 71 (4.2) years, 0% male VI: N=67 with VA 6/12 or worse, age not reported. Control: N=1,349 with VA better than 6/12, age not reported.	State-recorded MVCs in 10-year period (average 5.7 years).	No MVC data reported by VI status.	Drivers with reduced VA had similar MVC rates compared to a control group (adjusted HR 1.14, 95%CI 0.73–1.80).	Good
Gresset & Meyer (1994, Canada)(Gresset &	Total: Drivers aged 70 years, 100% male Cases: Drivers who with at-fault MVC history (N=1,400)	State-recorded MVC resulting in property damage or mild physical injuries in previous 1-	Proportion with VA 6/12 or 6/15: Cases (MVC): 8.0% Controls (No MVC): 7.7%	No difference in MVC risk between drivers with reduced VA compared to those with normal VA and binocularity:	Good

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Meyer 1994) Case-control study	Controls: Drivers without MVC history (N=2,636) VI: Drivers with VA equal to 6/12 or 6/15 (N=315); VA equal to 6/12 or 6/15 and lack of binocularity (N=162); Control: Drivers with VA better than 6/12, and normal binocularity.	year period	 Proportion with VA 6/12 or 6/15 and lack binocularity: Cases (MVC): 4.4% Controls (No MVC): 3.8%	VA 6/12 or 6/15: adjusted OR 0.97, 95%CI 0.68-1.38 • VA 6/12 or 6/15 and lack of binocularity: adjusted OR 1.23, 95%CI 0.88-1.72.	
Cross et al. (2009, USA)(Cross et al. 2009) Prospective cohort study	Total: N=3,158; 71.9 years (SD not reported); 47.9% male. VI: Reduced binocular VA, worse than 6/6 but better then 6/12 (N=1,197), VA 6/12 or worse (N=126). Control: N=1,835 binocular VA 6/6 or better	Number of state-recorded prospective MVCs (any, injurious, at-fault), 2 to 6-year period	No MVC data reported by VI status.	Drivers with any level of reduced binocular VA had similar MVC risk (any, injurious and at-fault) to those with 6/6 or better.	Fair
Green et al. (2013, USA)(Green et al. 2013) Retrospective cohort study	Total: N=2,000 older drivers, 70-99 years (mean/SD not reported) VI: N=100 drivers with reduced binocular VA (worse than 6/12); age not reported; 44% male Control: N=1,248 drivers with binocular VA 6/12 or better; age not reported; 49.5% male	State-recorded MVCs (all, at-fault) in the previous 5-year period.	All state recorded MVCs, per million person-miles VI: 6.4 Control: 5.6 At-fault state recorded MVCs per million person-miles VI: 3.3 Control: 2.6	No difference in MVC risk for drivers with reduced binocular VA compared to controls: • All MVCs: adjusted RR 1.04, 95%CI 0.74-1.48 • At-fault MVCs adjusted RR 1.08, 95%CI 0.66-1.76	Fair
Davison (1985, UK)(Davison 1985) Retrospective cohort study	Total: N=1,000 drivers, 16-79 years; 84% male; sub-analysis for drivers aged 55 years and over (N=175). VI: Reduced binocular VA (worse than 6/9) (N	Number of self-reported MVCs: • In previous 3-year period; • Any MVC involvement	Any MVC in past 3 years, drivers aged 55 and over, N (%): VI: 2 (50%) Control: 11 (7.0%)	In drivers aged 55 and over, reduced binocular VA significantly increased risk of MVC in previous 3 years compared to those with good VA (p<0.025, one-tailed test).	Fair

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	not reported); Control: VA 6/9 or better (N not reported)	(no timeframe); • Accident type (injury/vehicle damage only)		In all ages, right eye VA (worse than 6/6.5) associated with any accident type (p<0.01, one-tailed test) and left eye VA (worse than 6/6) associated with accident involvement in past 3 years (p<0.05, one-tailed test).	
Keefe et al. (2002, Australia)(Keeffe et al. 2002) Retrospective cohort study	N=1,787 drivers, 62.5 (10.9) years, 45% male VI: Binocular VA worse than 6/12 (N=46) Control: Binocular VA better than 6/12 (N=1,760)	Number of self-reported MVCs in previous 5 years	Any self-reported MVCs, N (%) VI: 8 (17.1%) Control: 331 (18.8%)	People with visual acuity worse than 6/12 were no more likely to have an accident than those with better visual acuity (p>0.9).	Fair
Ivers et al. (1999, Australia)(Ivers et al. 1999) Retrospective cohort study	Total: N=2,326 drivers aged 49 years and older; age and gender not reported. VI: VA in better-eye between 6/12-6/18 (N=100) or worse than 6/18 (N=27), abnormal VF using automated perimeter (screening strategy, impairment not defined, N=not reported). Control: Drivers with VA 6/12 or better (N=2,199), normal VF (N=not reported).	Number of self-reported MVCs in previous 1-year period.	No MVC data reported by VI status.	A 2-line difference in VA was associated with increased risk of MVCs (adjusted PR 1.6, 95%CI 1.0-2.4), as was VA worse than 6/18 in the right eye (adjusted PR 2.0, 95%CI 1.2-3.5). No increased MVC risk based on better-eye VA (adjusted PR 1.2, 95%CI 0.3-5.0) or extent of visual field loss (data not reported).	Fair
Hofstetter (1976), USA Retrospective cohort study	Total: N=13,786 drivers, aged 15 years and over. Analysis presented for 20 years and over. Gender not reported. VI: Reduced VA (in lowest quartile) N=2,071 Control: Adequate VA (highest two quartiles) N=6,325	Number of self-reported MVCs in previous 1-year period.	Reported number of MVCs (probability ratio of poor VA to good VA): No MVC: 0.98 1 MVC: 1.02 2 MVC: 1.68 3+ MVC: 2.42	The proportion of drivers with poor VA who reported 3 or more accidents was approximately double the proportion of drivers with good acuity who reported 3 or more accidents.	Poor
Humphriss (1987, South Africa)(Humphriss	Total: N=366 drivers, age and gender not reported. Cases: N=196 drivers with MVC history	Number of employer-recorded accidents in previous period, unspecified	Proportion who failed VA licence requirements, N (%): MVC: 25 (12.7%)	The proportion of drivers involved in previous MVC who failed to meet VA licence criteria was significantly higher than drivers with no MVC history	Poor

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1987) Case-control study	Control: N=170 without MVC history VI: Drivers who failed licence VA requirements (see below; N=35) Control: Drivers who met licence VA requirements (better than 6/12 in each eye separately, or better-eye 6/6 if worse-eye worse than 6/12 or, at least 6/12 binocularly). N=331	timeframe.	No MVC: 10 (5.9%)	who failed to meet VA licence criteria (OR 2.34, 95%CI 1.09-5.02)†	
Adeoti et al. (2007, Nigeria)(Adeoti et al. 2007) Retrospective cohort study	N=99 commercial drivers, 46 (8) years; 100% male VI: N=6 impaired binocular VA (6/18 or worse); Control: N=93 drivers VA 6/12 or better.	Number of self-reported MVCs, no recall timeframe defined	Any MVC, N (%) VI: 2 (33%) Control: 18 (19.4%)	No significant difference in MVC risk between drivers with impaired binocular VA compared to those with normal VA (OR 2.08, 95%CI 0.35 - 12.28).	Poor
Visual field impairment (Note: *4 additional studies on VF impairment are presented in the combined VA and/or VF impairment section and 1 in the combined eye diseases section)*					
Huisingh et al. (2015, USA)(Huisingh et al. 2015) Retrospective cohort study	Total: N=2,000 older drivers 77 years (SD not reported). VI: N=496; Poorest visual field sensitivity (lowest quartile) based on an automated perimeter (custom field) Control: N=1,504; Average to good sensitivity (three upper quartiles) based on a custom computerised field test	State-recorded at-fault MVCs in previous 5-year period	No MVC data reported by VI status.	Drivers with poorest field impairment had a 40% increased rate of at-fault MVC compared to those with average sensitivity in the three upper quartiles of sensitivity (adjusted RR 1.40, 95%CI 1.07–1.83). Severe binocular visual field impairment (7–21 impaired points) increases risk of at-fault MVCs compared those with no visual field impairment (0 impaired VF points), adjusted RR 1.51, 95%CI 1.08–2.12).	Good
Rubin et al. (2007, USA)(Rubin et al. 2007)	N=1,801 drivers, 65 to 84 years (mean/SD not reported); 49.8% male VI: N=864 with more than 20 points missed on automated perimeter (81-point screening	State-recorded MVCs, time to first crash, variable timeframe (median length of follow-up 3.0 years)	No MVC data reported by VI status.	No differences reported in MVC rates between lowest and highest quintile of visual field impairment. Visual fields were significant predictors of crash involvement, but association varied by the level of	Good

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Prospective cohort study	strategy). Controls: ≤20 points missed on automated perimeter.			visual field loss. For drivers with less than 20 point missed, very mild field loss had reduced risk of crash involvement compared to no field loss. For drivers with 20 or more points missed, greater VF loss was associated with higher MVC risk.	
Johnson & Keltner (1983, USA)(Johnson & Keltner 1983) Retrospective cohort study	Total: N=10,000 drivers at licence application. 16 to 65+ years (mode 26-35 years); gender not reported. VI: Abnormal VF using automated perimeter (screening strategy) in at least one eye (N= 330, 3.3%). Abnormal VF in both eyes (N=110, 1.1%). Control: Normal VF, age and sex-matched subsample used for analysis.	Number of state-recorded MVCs in previous 3-year period.	MVC rate (per person per 160,000-km, values derived from graph): Abnormal VF, one-eye: 0.8 Abnormal VF, both-eye: 1.3 Control: 0.65	Drivers with monocular field loss had similar MVC rates compared to an age and gender-matched control group (p>0.2). Drivers with binocular field loss had significantly elevated MVC rates compared to an age and gender-matched control group (p<0.005).	Fair
Okamura et al. (2019, Japan)(Okamura et al. 2019) Retrospective cohort study	Total: N=458 drivers, 59.5 (11.3) years, 76.4% male. VI: Drivers with visual field defects defined as -5dB or worse on automated, either better-eye (N=17) or worse eye (N=36), Esterman (<90; N=18) Controls: Drivers with normal visual fields.	Number of police-registered MVCs in previous 5-year period. Number of self-reported at-fault MVCs in previous 5-year period.	Any police-registered MVC, N (%) VI (VFL in better eye): 3 (17.6%) VI (VFL in worse eye): 4 (11.1%) VI (Esterman): 3 (16.7%) Control: 19 (4.5%) Any self-report at fault, n(%) VI (VFL in better eye): 3 (17.6%) VI (VFL in worse eye): 3 (8.3%) VI (Esterman): 1 (5.6%) Control: 29 (6.9%)	Drivers with monocular field loss in either better or worse eye had similar police-registered and self-reported MVC history to a control group. • Police-registered: OR (95%CI) = 2.65 (0.85 - 8.26) (P=0.09)† • Self-reported: OR (95%CI) = 1.23 (0.36 - 4.26) (P=0.74)†	Fair
Woolnough et al. (2013, Multi-national: Canada, Australia, NZ)(Woolnough et al. 2013)	Total: N=1,230 older drivers, 70-94 years; Cases: N=63 with MVC history, 76.0 (5.1) years, 58.7% male; Controls: N=1,167 with no MVC history, 77.1 (4.8) years; 64.5% male. VI: N=89 with visual field defect detected by	Number of state-recorded MVCs in previous 2-year period.	State recorded MVC by VI status, N (%) VF impairment: 6 (6.7%) Control: 57 (5.0%)	No difference in MVC risk for older drivers with visual field defects compared to controls (OR= 1.37, 95%CI 0.58 - 3.28)†	Poor

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Retrospective cohort study	confrontation Control: N=1,141 with no visual field defects				
• ***Visual acuity and/or visual field impairment***					
Owsley, Ball et al. (1998, USA)(Owsley et al. 1998) Prospective cohort study	Total: N=294 older drivers, 71 years (range 55-87 years), 54% male VI: Reduced VA (worse than 6/12), N=37; Visual field impairment in central 30-degree radius (more than 10dB loss) N=37; Visual field impairment in peripheral 30 to 60-degree radius (more than 10dB loss), N=111 Control: Normal VA (6/12 or better), normal VF in central and peripheral regions.	Number of state-recorded crashes in the following 3-year period.	State recorded MVC rate, per million person-miles of travel VA reduced: 10.0 VA control: 6.9 VF impairment central: 7.0 VF central control: 7.1 VF impairment peripheral: 5.8 VF peripheral control: 7.6	No difference in prospective MVC risk based in those with VI compared to controls (p>0.39): • Reduced VA: RR 1.45, 95%CI 0.58-3.64 • Central VF impairment: RR 0.99, 95%CI 0.36-2.75 • Peripheral VF impairment: RR 0.77, 95%CI 0.42-1.40	Good
Owsley, McGwin et al. (1998, USA)(Owsley et al. 1998) Case-control study	Total: N=294 older drivers, 71 years (range 55-87 years), 54% male Cases: N=78 with injurious MVC involvement; N=101 with non-injurious MVC involvement. Controls: N=115 with no MVC involvement. VI: Reduced VA (worse than 6/12), N=36; Visual field impairment in central 30-degree radius (more than 10dB loss) N=37; Visual field impairment in peripheral 30 to 60-degree radius (more than 10dB loss), N=108. Control: Normal VA (6/12 or better), normal VF in central and peripheral regions.	Number of state-recorded injurious and non-injurious crashes in the previous 5-year period.	State recorded MVCs, N (%) VA impairment (injurious): 11 (14%) VA impairment (non-injurious): 14 (14%) VA control: 11 (10%) VF impairment central (injurious): 14 (18%) VF impairment central (non-injurious): 14 (14%) VF central control: 9 (88%) VF impairment peripheral (injurious): 37 (47%) VF impairment peripheral (non-injurious): 40 (40%)	Older drivers involved in injurious MVCs more likely to have visual field impairment (central field OR 2.6, 95%CI 1.1-6.3, peripheral field OR 2.4, 95%CI 1.3-4.5). However, this was not significant when adjusted in a multivariate model adjusting for the presence of eye conditions and useful field of view. No increased injurious MVC risk for drivers with reduced VA (OR 1.6, 95%CI 0.6-3.8) Associations between non-injurious crash involvement and peripheral visual field sensitivity were also observed (OR 1.8, 95%CI 1.0,3.1). However, this was not significant when adjusted in a multivariate model adjusting for the presence of eye conditions and useful field of view. No increased	Good

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			VF peripheral control: 31 (27%)	non-injurious MVC risk for drivers with reduced VA (OR 1.6, 95%CI 0.7-3.6), or central field impairment (OR 1.8, 95%CI 0.8-4.4)	
Huisingh et al (2017, USA)(Huisingh et al. 2017) Prospective cohort study	Total: N=659 older drivers, aged 70 years and older (mean/SD not reported); 54.5% male. VI: VA worse than 6/12 (N=35); VF loss in one eye (N=186); VF loss in both eyes (n=61). Peripheral VF assessed using small target flashed temporally at 70 and 85 deg. Control: VA 6/12 and better; No VF loss in one or both eyes.	Prospective crashes during 3-year follow-up (any, major and at-fault) based on in-vehicle monitoring system.	No prospective MVC data reported by VI status.	Reduced visual acuity was not associated with any type of prospective crash (any crash, adjusted RR 0.98; 95% CI, 0.52-1.84). Peripheral vision impairment in either eye was associated with a higher rate of major crash involvement (adjusted RR 1.53; 95% CI, 1.02–2.29). Peripheral vision impairment in both eyes was associated with an increased rate of crash involvement (adjusted RR 1.74; 95% CI, 1.18–2.56), major crash involvement (adjusted RR 2.32; 95% CI, 1.40–3.83), and at-fault crash involvement (adjusted RR 1.73; 95% CI, 1.14–2.61).	Good
Decina & Staplin (1993, USA)(Decina & Staplin 1993) Retrospective cohort study	Total: N=12,400 drivers presenting for license renewal, 16 to 76+ years (mean/SD not reported), gender not reported. VI: Failed vision screening defined as VA impairment (worse than 6/12) and/or VF impairment (binocular horizontal extent less than 140 degrees). N=not reported. Control: Passed VA and VF vision screening	Number of state-recorded MVCs in previous 3.67-years.	No MVC data reported by VI status.	Drivers who failed vision screening had significantly different MVC risk to controls (p<0.001). Effect due to elevated MVC rates in younger drivers with good vision (compared to those with poor vision), and greater MVC risk in older drivers with poor vision (compared to those with good vision).	Poor
Adekoya et al. (2009, Nigeria)(Adekoya et al. 2009)	Total: N=399 commercial drivers, age 44.7 (10.1) years; 100% male VI: Reduced VA in better-eye (worse than 6/9) N=27, Reduced VA in the worse-eye (worse	Number of self-reported MVCs, no recall timeframe defined	Self-reported MVC, N (%): Impaired VA (better-eye): 6 (22.2%) Adequate VA (better-eye): 77 (20.7%) Impaired VA (worse-eye): 8 (25.0%)	No difference in MVC risk for drivers with impaired VA in better-eye (p=0.85; OR 1.09, 95%CI 0.43 to 2.81)† or impaired VA in worse-eye (OR 1.3, 95%CI 0.56 to 3.00)†, compared to adequate VA.	Poor

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Retrospective cohort study	than 6/24) N=32; abnormal visual field (confrontation technique; N=22). Control: Adequate VA and normal visual fields.		Adequate VA (worse-eye): 75 (20.4%) Abnormal fields: 7 (31.8%) Normal fields: 76 (20.2%)	No difference in MVC risk for drivers with abnormal visual field compared to normal fields (OR 1.85, 95%CI 0.73 to 4.69).	
Oladehinde et al. (2007, Nigeria)(Oladehinde et al. 2007) Retrospective cohort study	N=215 commercial drivers, age 41.5 (6.7) years; 100% male VI: Reduced VA in better-eye (worse than 6/18) N=7, visual field defect in at least one eye (automated perimetry) (N=22) Control: VA in better-eye (6/18 or better), no visual field defects	Number of self-reported MVCs, no recall timeframe defined	Self-reported MVC, N (%): Impaired VA: 6 (85.7%) Adequate VA: 51 (24.5%) Visual field defect: 7 (31.8%) No visual field defect: 50 (25.9%)	Significant increase in MVC risk for drivers with impaired VA in the better eye compared to controls (RR 3.5, 95%CI 2.38-5.14). No difference in MVC risk for drivers with bilateral visual field defect compared to controls (RR 1.07, 95% CI 0.98-6.73).	Poor

VI, visual impairment; SD, Standard Deviation; CI confidence interval; OR, odds ratio; RR, rate or rate ratio; AMD, Age-related macular degeneration; VA, Visual acuity; AREDS, Age-related eye disease severity scale; VF, visual field; dB, decibel; MD, mean deviation; MAR, Minimum angle of resolution; †crude OR calculated using odds ratio calculator.

*NHLBI. (2014). "Quality assessment tool for observational cohort and cross-sectional studies.", from www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools.

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Table 2: Characteristics and quality assessments of reviewed studies that included on-road driving outcome measures. Abbreviations are explained in the footnote.

Study, Study Design	Study population – sample size, mean age (SD), % male, disease severity	On-road assessment protocol and outcomes	Driving performance outcomes	Summary of key findings	NIH Quality Assessment*
Age-related macular degeneration (AMD)					
Wood et al. (2018, Australia)(Wood et al. 2018) Cross-sectional study	VI: N=33 drivers with AMD; 76.6 (6.1) years; 36% male; AREDS grades: early N = 20, intermediate N = 13. Binocular VA 0.05 (0.12) logMAR. Control: N=50 drivers with no eye disease (age-matched); 74.6 (5.0) years; 36% male.	Urban 19.4-km route in dual-controlled vehicle with professional driving instructor (DI) and back-seat driver-trained occupational therapist (OT), masked to the visual status of drivers. Outcomes: Overall rating of performance by OT (10-point scale, higher values represent safer performance); Number of critical errors (CE) where DI intervened	Overall safety score, mean (SD): VI: 4.80 (2.05) Control: 6.21 (2.03) Number of CE, mean (SD): VI: 1.42 (1.79) Control: 0.36 (0.80)	Drivers with AMD demonstrated reduced overall driving performance compared with controls (P = 0.012). Drivers with AMD demonstrated higher rate of CE than controls (rate ratio RR 3.05, 95%CI 1.47 to 6.36). Drivers with intermediate AMD had higher rate of CE than controls (RR 4.39, 95%CI 1.80 - 10.71). Drivers with early AMD had similar rates of CE compared with controls (RR 2.11, 95%CI 0.87–5.11).	Good
Szlyk et al. (1995, USA)(Szlyk et al. 1995) Cross-sectional study	VI: N=10 drivers with AMD; 75.7 (4.5) years; 100% male; Binocular VA 20/70 (range 20/30 - 20/100). Control: N=11 drivers with no eye disease (age-matched), 71.0 (8.3) years; 64% male.	Suburban route, 4-block radius, by a state-licensed kinesiotherapist, masked to the visual status of drivers. Outcomes: Overall on-road score (points deducted for errors in a number of areas – more negative scores represent poorer performance)	Overall on-road score, mean (SD): VI: -62.5 (17.3) Control: -40.1 (27.9)	No significance difference in driving performance scores between drivers with AMD and controls (p=0.07).	Fair
Glaucoma					
Wood et al. (2016, Australia)(Wood	VI: N=75 drivers with glaucoma; 73.2 (6.0) years; 69% male; Mild to moderate glaucoma (better-eye mean MD -1.2	Urban 19.4-km route in dual-controlled vehicle with professional driving instructor (DI) and back-seat driver-trained occupational	Driving safety score, mean (SD): VI: 5.17 (1.81) Control: 5.79 (1.96)	Drivers with glaucoma with mild to moderate field loss demonstrated reduced overall driving performance compared with controls (adjusted p=0.028).	Good

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et al. 2016) Cross-sectional study	dB [SD 4.9], worse eye mean MD -7.8 dB [SD 8.5]). Control: N = 70 drivers with no eye disease (age-matched); 72.6 (5.0) years; 67% male.	therapist (OT), masked to the visual status of drivers. Outcomes: Overall rating of driving performance by OT (10-point scale, higher values represent safer performance); Number of critical errors (CE) where DI intervened	Number of CE, mean (SD): VI: 0.83 (1.16) Control: 0.43 (0.73)	Drivers with glaucoma demonstrated higher rate of critical errors than controls (RR 2.06, 95%CI 1.17–3.62).	
Haymes et al. (2008, Canada)(Haymes et al. 2008) Cross-sectional study	VI: N=20 drivers with glaucoma; 68 (7) years; 70% male; Better-eye mean MD -1.7 dB [SD 2.2] and worse eye mean MD -6.5 dB [SD 4.9]. Control: N=20 drivers with no eye disease (age-matched); 67 (7) years; 70% male.	Urban 10-km route with driving instructor (DI) & back-seat occupational therapist (OT) certified in driver rehabilitation, masked to the visual status of drivers. Outcomes: Overall rating of performance by OT (10-point scale, higher values represent safer performance); Number of drivers with critical intervention (CI) by DI	Driving safety score: median (range): VI: 7 (3–9) Control: 7 (2–9) Any CI, N (%): VI: 12 (60%) Control: 4 (20%)	No significant difference in overall driving performance between groups (p=0.60). Drivers with glaucoma more likely to demonstrate CI compared to controls (OR = 6.00, 95% CI 1.46-24.69), and after adjustment for potential confounders (OR = 10.62, 95% CI 1.46-7.35).	Good
Devos et al. (2018, USA)(Devos et al. 2018) Cross-sectional study	VI: N=17 drivers with glaucoma; 65.2 (9.7) years; 52.9% male; Better-eye median MD -1.3 dB [IQR -0.4 to -4.6], worse eye median MD -5.7 dB [IQR -2.0 to -10.6]. Control: N=11 drivers with no eye disease (age-matched); 61.3 (11.5) years; 18.2% male	Urban, rural, and interstate route for 45-min duration in dual-controlled vehicle with trained driving instructor, masked to visual status of drivers. Outcomes: Driving performance scored using Test Ride for Investigating Practical fitness-to-drive (TRIP) checklist (max score 196; higher values represent safer performance).	TRIP test scores, median (IQR): VI: 193 [191–196] Control: 196 [195–196]	No significance difference in driving performance scores between drivers with glaucoma and controls (p=0.16).	Fair
Bhorade et al. (2016, USA)(Bhorade et al. 2016)	VI: N=21 drivers with glaucoma, confirmed diagnosis; 71.5 (8.5) years; 71.4% male; Bilateral moderate to advanced glaucoma.	Urban 13-mile (20.9-km) route in dual-controlled vehicle with driving instructor (DI) and back-seat evaluator (driver rehabilitation specialist), masked to visual status of drivers.	Marginal/fail score, N (%): VI: 11 (52%) Control: 8 (21%) Any wheel intervention, N (%): VI: 6 (29%)	Drivers with glaucoma more likely to demonstrate unsafe driving than controls (marginal or fail score; OR 4.13, 95%CI 1.30–13.14). Drivers with glaucoma more likely to require a wheel	Fair

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Cross-sectional study	Control: N=38 drivers with no eye disease (age-matched); 70.2 (8.4) years; 52.6% male	Outcomes: Overall driving performance scored by back-seat evaluator: pass (no safety concerns), marginal (low to moderate safety concerns), or fail (major safety concerns). Number of wheel and brake interventions by DI.	Control: 3 (8%) Any brake intervention, N (%): VI: 3 (14%) Control: 3 (8%)	intervention compared to controls (OR 4.7, 95%CI 1.03–21.17). No significant difference in brake interventions (OR 1.94, 95%CI 0.36–10.63).	
Homonymous hemianopia and quadrantanopia					
Wood et al. (2009, USA)(Wood et al. 2009) Cross-sectional study	VI: N=30 drivers with hemianopia and quadrantanopia; N = 22 with hemianopia, 52 (20) years, 59% male; N=8 with quadrantanopia, 55 (22) years, 75% male. Control: N=30 drivers with no eye disease and normal visual fields (age-matched); 52 (19); 33% male	Urban non-interstate and interstate 14.1 miles (22.7 km) route in dual-controlled vehicle with certified driving rehabilitation specialist in front seat, and two independent back-seat evaluators masked to visual status of drivers. N=19 (63.3%) of the VI group met criteria to complete the interstate driving. Outcomes: Overall rating of performance by back-seat evaluators for non-interstate and interstate sections (5-point scale, higher values represent safer performance); Categorized into pass (score 3-5)/fail (score 1-2)	Fail for non-interstate section, N (%): Hemianopia: 6 (27.3%) Quadrantanopia: 1 (12.5%) All VI group: 7 (23.3%) Control: 0 (0%)	No significant difference in failure rate between drivers with hemianopia and quadrantanopia and controls (p=0.068). In subgroup analysis, significant different between hemianopia and controls (p=0.027) for performance outcomes on 5-point scale. No differences in the driving performance between controls and VI group who met the criteria for going on the interstate section (p>0.05).	Good
Elgin et al. (2010, USA)(Elgin et al. 2010) Cross-sectional study	VI: N=30 drivers with hemianopia and quadrantanopia; N=22 with hemianopia; 52 (20) years; 59% male; N=8 with quadrantanopia, 55 (22) years; 75% male. Variable severity and side of field loss. Control: N=30 drivers with no eye disease and normal visual fields (age-	Urban non-interstate and interstate 14.1-miles (22.7-km) route in dual-controlled vehicle with certified driving rehabilitation specialist (CDRS) in front seat (unmasked). N=19 (63.3%) of the VI group met criteria to complete the interstate driving. Outcomes: Overall rating of performance by CDRS for non-interstate and interstate	Fail for non-interstate section, N (%): Hemianopia: 6 (27.3%) Quadrantanopia: 1 (12.5%) Control: 0 (0%) Any verbal interventions, N (%): Hemianopia: 10 (45.5%) Quadrantanopia: 4 (50%) Control: 5 (16.7%)	Drivers with hemianopia and quadrantanopia more likely to demonstrate poorer safety ratings on the non-interstate sections (p<0.05). Drivers with hemianopia and quadrantanopia more likely to require verbal interventions (<0.05). Drivers with hemianopia more likely to require physical interventions (p=0.0007). No difference between	Fair

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	matched); 52 (19); 33% male.	sections (5-point scale, higher values represent safer performance), categorized into pass/fail; Number of verbal or physical interventions by CDRS.	Any physical interventions, N (%): Hemianopia: 9 (40.9%) Quadrantanopia: 1 (12.5%) Control: 1 (3.3%) Data for interstate section not reported.	quadrantanopia and controls. No differences in the driving performance between controls and VI group who met the criteria for going on the interstate section (p>0.05).	
Combined eye conditions					
Wood et al. (2013, USA)(Wood et al. 2013) Cross-sectional study	VI: N=23 drivers with vision impairment experienced using bioptic telescopes; 32.8 (12.3) years, 78% male; Conditions: optic atrophy (30%), ocular albinism (26%), Stargardt's disease (13%), cone dystrophy (9%), other disease (22%); Mean VA unassisted 0.68 (0.12) logMAR, VA with bioptic device 0.14 (0.13) logMAR. Control: N=23 drivers with no eye disease and normal vision (age-matched); 33.0 (12.3) years; 43.5% male	Urban non-interstate and highway 14.6-miles (23.5-km) route in dual-controlled vehicle with certified driving rehabilitation specialist in front seat, and an independent back-seat evaluator. Outcomes: Overall safety rating by back-seat evaluators (5-point scale, higher values represent safer performance); Categorized into pass/fail	Fail score, N (%): VI: 1 (4.3%) Control:0 (0.0%)	No significant between group differences in overall driving performance (p=0.89).	Good
Kasneci et al. (2014, Germany)(Kasneci et al. 2014) Cross-sectional study	VI: N=10 drivers with hemianopia; 52.5 (12.8) years; N = 10 drivers with glaucoma; 60.7 (8.7) years; gender not reported. Control: N=20 drivers with no eye disease and normal visual fields (age-	Urban, motorway and highway 20-km route in dual-controlled vehicle with front-seat certified driving instructor (DI) unmasked, and another back-seat DI, masked to visual status of drivers. Outcomes: Back-seat DI graded performance as	Fail, N (%): Hemianopia: 4 (40%) Glaucoma: 6 (60%) All VI group: 10 (50%) Control: 3 (15%)	Study did not report any statistical assessment of the pass/fail rates, as a whole and for the separate groups. Drivers with glaucoma and hemianopia were more likely to fail on-road driving assessment compared to control (OR 5.67, 95%CI 1.25 -25.61; p=0.024).†	Fair

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	matched); N=10 glaucoma controls, 51 (11.7) years, N=10 hemianopia controls, 59.9 (9.1) years; gender not reported.	pass or fail, according to the German driving licence regulations.			
Silveira et al. (2007, Australia)(Silveira et al. 2007) Cross-sectional study	Full sample: mean 70 years (SD not reported), range 60-86 years, 65% male VI: N=17 drivers with visual field defects; age and gender not reported; VF defect defined as any points missed in the 120-degree box criteria on the Esterman field test. Control: N=77 drivers without visual field defects, age and gender not reported.	Urban 20-minute route in a dual-controlled vehicle with driving instructor (DI) and an orthoptist and occupation therapist (OT) in back seat (masked). Outcomes: Overall safety rating (4-point scale). Categorized into pass (score 3 or 4) or fail (score 1 or 2). Number of verbal prompts, wheel and brake interventions by DI.	Fail score, N (%): VI: 8 (47.1%) Control: 3 (3.9%)	Study did not report any statistical assessment of the pass/fail rates. Drivers with visual field defects more likely to fail on-road driving assessment compared to control (OR 21.9, 95%CI 4.9-97.9; p<0.001).†	Fair
Wood et al. (2001, Australia)(Wood & Mallon 2001) Cross-sectional study	VI: N=47 drivers with vison impairment; 70.6 (6.2) years; gender not reported; Disease groups: 23 cataracts, 6 cataracts + glaucoma, 6 cataracts + AMD, 6 cataracts + other, 6 AMD. Control: N=35 drivers with no eye disease and normal vision (age-matched); 68.9 (4.8) years; gender not reported.	Urban 15-km route in dual-controlled vehicle with professional driving instructor (DI) and back-seat driver-trained occupational therapist (OT), masked to the visual status of drivers. Outcomes: Overall safety rating by DI (10-point scale, higher values represent safer performance); Pass/Fail defined as overall rating less than 3.	Overall safety score, mean (SD): VI: 5.6 (0.3) Control: 6.1 (0.3) Fail score, N (%) VI: 9 (19.1%) Control: 3 (8.6%)	No significant difference in overall safety rating between drivers with VI and controls (p>0.05). No significance difference in failure rate between drivers with VI and controls (OR 2.53, 95%CI 0.63-10.13).†	Fair

VI, visual impairment; SD, Standard Deviation; CI confidence interval; OR, odds ratio; RR, rate ratio; AMD, Age-related macular degeneration; VA, Visual acuity; AREDS, Age-related eye disease severity scale; VF, visual field; dB, decibel; MD, mean deviation; MAR, Minimum angle of resolution; †crude OR calculated using odds ratio calculator.

*NHLBI. (2014). "Quality assessment tool for observational cohort and cross-sectional studies.", from www.nhlbi.nih.gov/health-topics/study-quality-assessment-tools.

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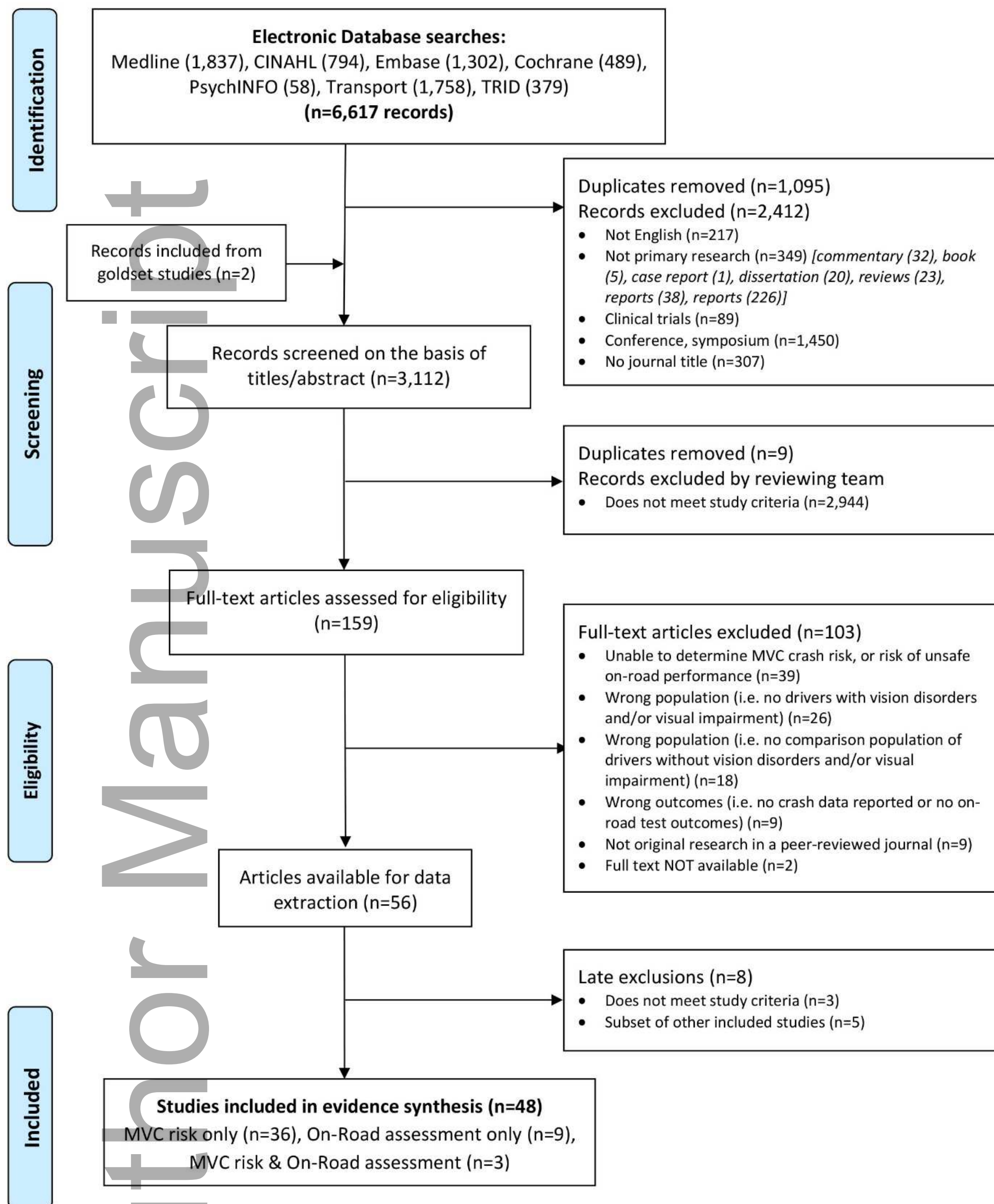

Figure 1: PRISMA diagram

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