THE FUTURE OF TRANSPORT

PUBLISHED PROJECT REPORT PPR2072

Glare from vehicle lighting on UK roads: Literature Review

G Beard, S Helman, S Hammett

Report details

Report prepared for:	Department for Transport
Project/customer reference:	TRL GFA 010
Copyright:	© TRL Limited
Report date:	January 2025
Report status/version:	1.0
Quality approval:	

C Booth (Project Manager)		S Helman (Technical Reviewer)	

Disclaimer

Contents amendment record

This report has been amended and issued as follows:

Version	Date	Description	Editor	Technical Reviewer
1.0	14/02/2025	First draft	GB, SHa	SHe

Table of Contents

1 Introduction

Despite international requirements and national legislation governing vehicle lighting, the Department for Transport (DfT) continues to receive a significant volume of correspondence from the public raising concerns about glare experienced by drivers from vehicle lighting on the roads. The Department has committed to carrying out research in this area with the objective of developing/gathering scientific evidence on the extent to which vehicle lighting-induced glare may occur on the roads of Great Britain and determining the potential root causes of such glare.

Note that while the focus of this report is primarily on headlamps, other vehicle lighting could be relevant to the experience of glare (for example daytime running lights, brake lights) and where relevant in this report these are encompassed by the more general term "vehicle lighting".

The aim of this project is to inform strategies for reducing the likelihood of drivers experiencing glare. The project will measure luminance and illuminance levels in real-world driving conditions, how these relate to various features in the driving environment (e.g. vehicle headlamps present around the test vehicle, road types and locations) and how these, and other factors might impact on the potential for drivers to experience glare. The data will also facilitate in-depth analysis to understand the features associated with conditions in which glare may occur.

The project seeks to provide an evidence base upon which to make recommendations for future guidance and proposals for regulation amendments, and to support future engagement with both the public and vehicle manufacturers concerning headlamp technologies and their potential to cause glare.

1.1 Project approach

The project consists of six work packages:

WP1: Project management

- Management of the project as a whole, ensuring high-quality outputs and delivery of the objectives against agreed timescales.

WP2: Stakeholder engagement

- Engagement with stakeholders to ensure the evidence review (WP3) and on-road data collection (WP4) are based on the state-of-the-art in terms of knowledge and understanding of vehicle lighting, human vision and glare.

WP3: Evidence review

- Review of evidence to evaluate the current state of research on glare associated with vehicle headlamps, including the impact of luminance, alongside other factors that may contribute to the experience of glare when driving.

WP4: On-road data collection

- Collection of real-world driving data using an instrumented car with bespoke luminance-measuring apparatus to capture luminance levels at the eye position of a car driver on UK roads.

WP5: Modelling

- Development of a machine learning model to understand which variables, as informed by the findings from the evidence review and on-road data collection, are associated with high luminance levels and glare at driver eye height.

WP6: Reporting and dissemination

- Production of a final report outlining the methodology and findings from all project activities and suggested recommendations for next steps.

This report presents the literature search method and findings from the evidence review – Work Package 3 (WP3).

1.2 Background

In this section we summarise key terminology, vehicle lighting regulations in the UK, and common types of headlamp technologies relevant to the topic of headlamp glare to provide background context.

1.2.1 Terminology

1.2.1.1 Glare

Glare is defined by the International Commission on Illumination (CIE, 2020) as a "…condition of vision in which there is discomfort or a reduction in the ability to see details or objects, caused by an unsuitable distribution or range of luminance, or by extreme luminance contrasts". In short, glare can cause discomfort (discomfort glare) and can cause a reduction in visual performance (disability glare). These are defined in the following ways:

- **Discomfort glare**: "glare that causes discomfort without necessarily impairing the vision of objects" (CIE, 2020). Another definition provided by Rae (2000, cited in Bullough et al., 2011) is "…the annoying of even painful sensation that can be elicited from a bright source of light in the field of view."
- **Disability glare**: "glare that impairs the vision of objects without necessarily causing discomfort" (CIE, 2020). Rae (2000, cited in Bullough et al., 2011) defines this as "…the reduction in visibility that a bright light might cause."

1.2.1.2 Light and brightness

The absolute physical power of light is measured by radiometry as spectral flux or power (measured in watts). However, when we talk about light and brightness, we generally think of how things look. Whilst this is obviously related to the power of the light in a scene it is not directly related to it because, among other reasons, the visual system has different sensitivity to different colours. The *perceived* brightness of light experienced by the human eye is therefore measured using photometric (as opposed to radiometric) units that account for the visual system's differing sensitivity to different colours by "weighting" the relative contribution of each colour proportionally to the eye's sensitivity (the luminosity function). There are several photometric quantities relevant to the assessment of glare, which are defined in the following sections.

1.2.1.3 Luminous flux

Luminous flux is the total amount of light emitted from a light source and is measured in **lumens** (lm). Luminous flux does not give us a good indication of brightness as brightness depends upon the observer's distance from the light source and the spread of the light.

1.2.1.4 Illuminance

Illuminance is the total luminous flux that lands on a surface per unit area. It is measured in **lux** or lumens m^{-2}. As with luminous flux, illuminance does not give us a good indication of brightness since it is a measure of light incident upon a surface and thus is dependent upon the surface's distance from the light source, its perceived brightness depending upon the reflectance of the surface.

1.2.1.5 Luminous intensity

Luminous intensity is a measure of the colour-corrected power emitted by a light in a particular direction, measured in **candelas**. It is from this metric that we can derive a measure akin to perceptual brightness (luminance) by considering its average intensity over a unit of space.

1.2.1.6 Luminance

Luminance is the measure of luminous intensity *per unit area* of light travelling in a particular direction. It is measured in **candelas m^{-2}** and may be thought of as akin to our everyday understanding of brightness, indeed, brightness is the subjective counterpart of luminance.

1.2.1.7 Luminance contrast

Luminance contrast is the difference in luminance or brightness between two points (in space or time).

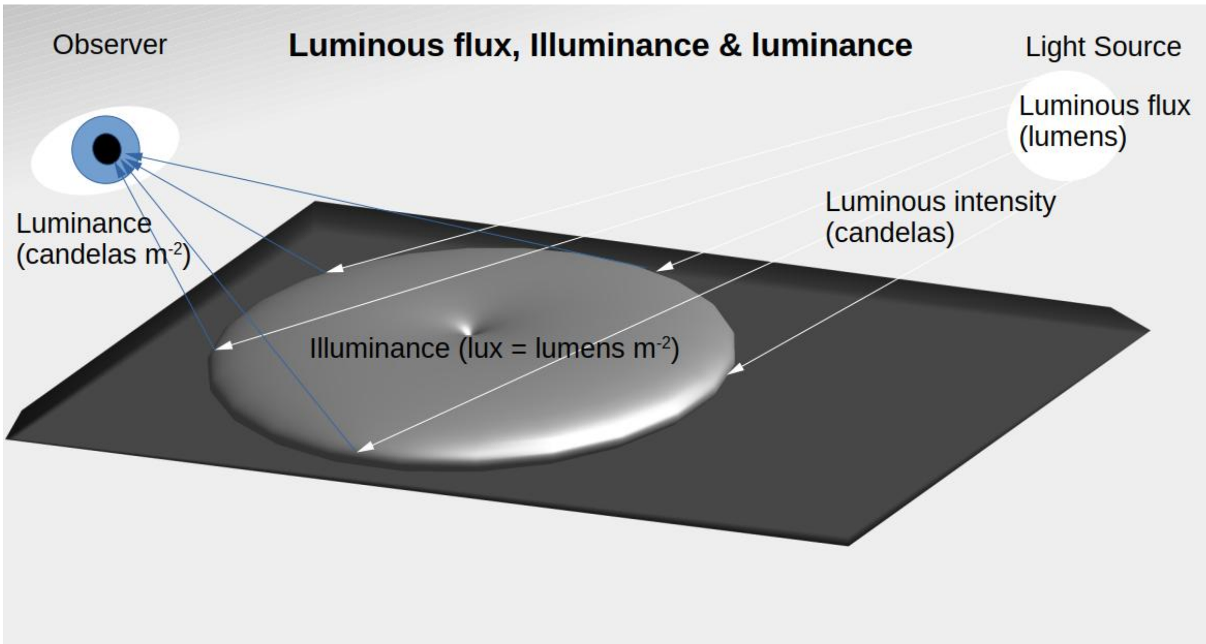

Figure 1: The principal photometric quantities relevant to headlamp glare

1.2.2 Vehicle lighting regulations

In this section, we refer primarily to the regulations governing vehicle lighting in England. It is noted that there are some slight differences to the wording of regulations in Scotland, Wales and Northern Ireland where responsibilities are devolved, however there are no meaningful differences in the content.

The Highway Code for Great Britain[1] sets out several rules which drivers must follow with regards to vehicle lighting:

- Rule 113 states that drivers MUST: ensure all sidelights and rear registration plate lights are lit between sunset and sunrise; use headlights at night, except on a road which has lit street lighting; use headlights when visibility is seriously reduced (further definition of reduced visibility is given in Rule 226 – see below).
- Rule 114 states that drivers MUST NOT: use any lights in a way which would dazzle or cause discomfort to other road users, including pedestrians, cyclists and horse riders, and; use front or rear fog lights unless visibility is seriously reduced (but that they MUST be switched off when visibility improves to avoid dazzling other road users).
- Rule 115 states that drivers SHOULD: use dipped headlights, or dim-dip if fitted, at night in built-up areas and in dull daytime weather, to ensure that they can be seen; keep headlights dipped when overtaking until level with the other vehicle and then change to main beam if necessary, unless this would dazzle oncoming road users, and; slow down, and if necessary stop, if you are dazzled by oncoming headlights.

[1] https://www.gov.uk/guidance/the-highway-code

- Rule 226 states that drivers MUST: use headlights when visibility is seriously reduced, generally when they cannot see for more than 100 metres (328 feet).

These rules are underpinned by The Road Vehicles Lighting Regulations (RVLR) 1989 (Statutory Instrument 1989, No. 1796), as amended, which governs the lighting of all vehicles used on UK roads. Of particular relevance to this project is Part III, Reg 27 which states that "no person shall use, or cause or permit to be used, on a road any vehicle on which any lamp, hazard warning signal device or warning beacon… in a manner… so as to cause undue dazzle or discomfort to other persons using the road"[2]. This applies to all types of lamp on the vehicle including but not limited to headlamps, front and rear fog lamps and work lamps. This regulation also defines the technical requirements which all vehicles must meet whenever used on-road, with Schedule 4 covering dipped-beam headlamps including requirements for their alignment.

In addition, all elements of lighting must conform to UK type approval regulations at the time of first vehicle registration to ensure that vehicle lighting is safe and fit-for-purpose. Type approval involves independent assessment of representative vehicles, rather than every single unit produced, and manufacturers are required to ensure that the specifications of the vehicles mass produced for the market match those of the 'representative vehicles' put forward for testing. In the UK, the Vehicle Certification Agency (VCA) is the designated Approval Authority which oversees vehicle testing, certification and conformity of production checks.

The technical requirements for vehicle lighting, which must be demonstrated through type approval, are specified in Assimilated Regulation (EU) 2018/858, with detailed technical rules laid down in UN Regulation No. 48[3] (installation of lighting) and UN Regulations No. 98[4], 112[5] (lamps)[6]. These regulations specify detailed requirements for all vehicle lighting, including the colour, light intensity, light distribution, height and positioning. A key objective of these requirements is to ensure adequate functionality and to prevent glare or confusion for other drivers. For main-beam and dipped-beam headlamps, key relevant requirements include:

---

[2] The Road Vehicle Lighting Regulations 1989 Part III Reg 27: https://www.legislation.gov.uk/uksi/1989/1796/regulation/27/made

[3] UNECE Regulation No 48 — Uniform provisions concerning the approval of vehicles with regard to the installation of lighting and light-signalling devices: https://op.europa.eu/en/publication-detail/-/publication/192086c4-870f-11e6-b076-01aa75ed71a1/language-en

[4] UNECE Regulation No 98 – Uniform provisions concerning the approval of motor vehicle headlamps equipped with gas-discharge light sources: https://op.europa.eu/en/publication-detail/-/publication/5d1c79ad-f3a4-11e3-831f-01aa75ed71a1

[5] UNECE Regulation No 112 – Uniform provisions concerning the approval of motor vehicle headlamps emitting an asymmetrical passing-beam or a driving-beam or both and equipped with filament lamps and/or light-emitting diode (LED) modules: https://op.europa.eu/en/publication-detail/-/publication/4782bab5-29d5-11e4-8c3c-01aa75ed71a1/language-en

[6] The more recent UN Regulation No 149 consolidates these two regulations into one and can be used in the future for type approval; currently the technical contents are identical

- White colour
- Two or four lamps permitted for main-beam, two for dipped-beam
- Positioned at front of vehicle – with light emitted causing no discomfort to driver either directly or indirectly
- Automatic control of main-beam and dipped-beam allowed, but manual control must also be available
- Maximum intensity of the main-beams shall not exceed 430,000 candela (cd)
- The transitions between main-beam and dipped-beam shall be achieved so as not to cause discomfort, distraction or glare
- Orientation: To the front and vertical orientation defined dependent on mounting height (see UNR48, 6.2.6.)
- Automatic headlamp levelling devices and headlamp cleaning devices (both are effectively required for light sources emitting over 2000 lm – see UNR48, 6.2.9)

Whilst only vehicles with type-approved lighting systems can be sold legally in the UK (and EU) under the regulations described above, after-market lighting conversion kits are available on the market (RoSPA, 2021). It is not, however, legal to sell or use conversion kits for converting Halogen to Xenon high-intensity discharge (HID) headlamps or to light emitting diode (LED) headlamps for on-road use through replacing individual bulbs (see 1.2.3 for an explanation of the different technologies). This is because these bulbs are designed for use only as part of HID and LED headlamp units (encompassing lens and reflector) with type approval only for the whole unit (see DfT statement on aftermarket HID headlamps[7] and the MOT inspection manual[8]. A headlamp unit previously used with a Halogen bulb will not be suitable for use with a HID bulb or LED bulb and may contribute to an incorrect beam pattern with glare in some places and insufficient light in others. Therefore, to convert from Halogen to HID or LED headlamps, the entire headlamp unit must be replaced in the vehicle. Further information on different headlamp technologies is provided in the following section.

1.2.3 Headlamp technologies

This section outlines the different types of headlamp technologies which exist in the market today.

Fundamentally, there are three main types of headlamps; 1) Halogen; 2) Xenon High-Intensity-Discharge (HID); and 3) LED. Halogen bulbs consist of a thin tungsten filament encased in a small capsule which is filled with halogen gas. Compared with a standard light

[7] DfT statement on aftermarket HID headlamps: https://www.gov.uk/government/publications/aftermarket-hid-headlamps/aftermarket-hid-headlamps

[8] MOT inspection manual: https://www.gov.uk/guidance/mot-inspection-manual-for-private-passenger-and-light-commercial-vehicles/4-lamps-reflectors-and-electrical-equipment

bulb, halogen bulbs can emit more light per unit of energy, and they last longer[9]. Halogen headlamps emit a bright white light, producing 1400 lumens and 30mcd/m^2 (RoSPA, 2021).

Xenon HID headlamps use xenon gas in a sealed system and an electric arc generated between two electrodes to generate a white-blue light[10]. Xenon HID bulbs emit a brighter light than halogen bulbs – producing 3000 lumens and 90mcd/m2 (RoSPA, 2021).

LED (Light Emitting Diode) bulbs produce 'directional' light, which enables lighting designs to be used which make use of multiple LEDs in clusters or matrices (RoSPA, 2021). LEDs have a longer lifespan than Halogen and Xenon bulbs, since there is no filament which, in Halogen and Xenon bulbs, tends to burn out over time[11]. LEDs are also more energy efficient.

LED headlamps are the most modern, followed by Xenon HID and halogen as the oldest technology.

In addition to the three types of headlamp 'bulb', there are several additional technologies which can impact the way the headlamps behave. These include:

- (Advanced) Adaptive Front Lighting Systems (AFLS), which enable adjustments to be made to the direction of the headlamp beams to face the direction of travel based on the angle of the steering wheel. This is used to improve visibility round corners, and to enable narrower beams to be used on motorways.
- Matrix LED headlamps, which make use of the directional and focussed light emitted by LEDs to produce a headlamp where sections of the headlamp beam can be masked out by automatically switching off some of the individual LEDs. This has benefits in that the part of the beam facing oncoming cars can be blanked out, in theory reducing the likelihood of causing glare.
- High Beam Assistant, which uses a camera to detect front or rear lamps of other road users and automatically switches between high and low headlamp beams as appropriate.

[9] How does a halogen light bulb work? https://home.howstuffworks.com/question151.htm

[10] Xenon bulbs: A complete guide: https://www.powerbulbs.com/blog/2022/07/xenon-bulbs-a-complete-guide

[11] What are LED headlights and how do they work? https://www.motorpoint.co.uk/guides/what-are-led-headlights

2 Method

It was known prior to conducting this review that driver behaviour and experience vary with age, that the physiological changes associated with aging can impact the perception of glare, and that driving behaviour and experience will affect the perception of glare; for example, if a driver regularly drives at night, then they are more likely to experience glare than those who only drive in daylight hours. Therefore, it is possible that age has two impacts on the perception of glare, one because of physiological changes associated with aging, and another because of driving behavioural changes associated with aging.

To help unpick these factors, the literature review sought to address the following research questions:

1. How does driver behaviour and experience vary with age?
2. What are the key factors influencing driver experience of glare from vehicle headlamps?

To address these questions, the evidence review employed a structured 'narrative review' approach consisting of the following tasks:

1. Review of initial literature known to project team.
2. Development of keywords and inclusion criteria.
3. Conduct searches of global literature databases.
4. Review abstracts of relevant papers and shortlist articles based on inclusion criteria.
5. Review full text of most relevant articles from the initial and searched literature.
6. Document findings.

A summary of this review process can be seen in Figure 2. The numbers of papers found at each stage of searching is noted in the sections for the two research questions.

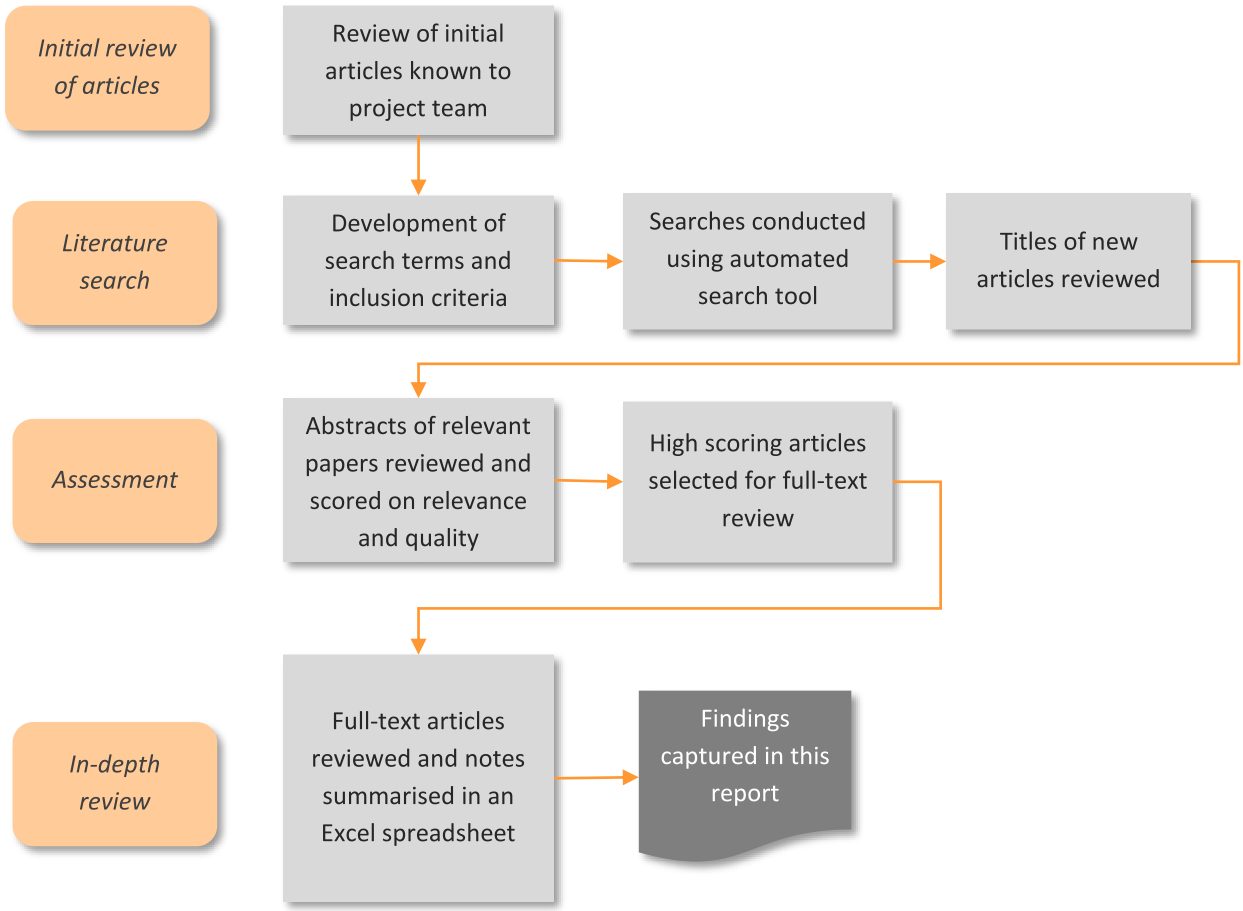

Figure 2: Flow chart depicting the evidence review process

2.1 Search terms

A list of search terms was generated to guide the evidence review (see Table 1). These search terms were applied in several research databases (Google Scholar, ScienceDirect, TRID[12], BASE[13], and PubMed) as Boolean search expressions. Multiple searches were conducted within each database through an iterative process, wherein search terms were tested individually and in combination with each other to identify which terms generated relevant results. The titles of the first 100 results following each search were reviewed and the sources with relevant titles were downloaded for abstract review. This ensured that the search was as effective and thorough as possible at drawing out appropriate literature.

[12] The Transport Research International Documentation Database covers a million records of references to books, technical reports, conference proceedings, and journal articles within the field of transport research.

[13] Bielefeld Academic Search Engine is one of the world's most voluminous search engines especially for academic resources, providing more than 120 million documents from more than 6,000 sources.

Table 1: Search terms

1st Level		2nd Level		3rd Level
RQ1: How does driver behaviour and experience vary with age?				
Age	AND	Driver		Behaviour
Older		Driving		Experience
Elderly		Transport		Self-regulation
		Travel		Nighttime
RQ2: What are the key factors influencing driver experience of glare from vehicle headlamps?				
Headlamp	AND	Vehicle	AND	Glare
Headlight		Driving		Disability glare
Light*		Car		Discomfort glare
Lamp		Road		Vision
Luminance		Driver		Visual performance
Illuminance		Age		Fatigue
Contrast				Motion
Nighttime				Acuity
				Colour vision
				Color vision
				Detection
				Medical
				Veiling glare

2.2 Inclusion criteria

Once the papers with relevant titles had been obtained, the abstracts were reviewed, and an assessment of quality and relevance was carried out. Specific inclusion criteria (see Table 2) were applied on each identified article to ensure that only the highest quality and most relevant literature was taken forward for full-text review. Papers were excluded if they scored less than 5 overall.

Table 2: Inclusion scoring criteria

	Score = 1	Score = 2	Score = 3
Relevance	Not relevant to the objectives of the project.	Some indirect relevance to the objectives of the review. For instance, an article which evidences individual differences in glare experience in a non-driving context.	Directly relevant to the objectives of the review. For instance, an article which shows a clear link between individual traits and the experience of glare while driving.
Quality	Non-scientific article (e.g. online source, newspaper, or magazine article).	Non-peer reviewed scientific article or grey literature / consultancy work which reports non-peer-reviewed research findings.	Peer-reviewed scientific article (e.g. journal paper or conference procedure).

2.3 In-depth review of literature

Following scoring on the inclusion criteria, the shortlisted papers were reviewed in full, with details of each text (including high-level summaries of study purposes, methods, and findings) recorded systematically in an accompanying Excel spreadsheet. If necessary, scores on the inclusion criteria were adjusted following full-text review. The key findings from this review in relation to each of the two research questions are discussed in the following sections.

It should be noted that this review is not designed to provide a comprehensive or systematic coverage of the literature on glare. Rather, it is focused on understanding the essential processes and findings around glare within the context of driving, and particularly related to vehicle headlamps. The purpose of the review is to inform the on-road data collection work, and this is reflected in its structure, and its focus.

3 Findings

3.1 RQ1: Age and driving behaviour

The first research question asked: "How does driver behaviour and experience vary with age?". The objective was to gather evidence on the changes in driving behaviour and experience that occur with age, so as to support understanding of the double impact of age on drivers' experience of glare; one associated with physiological changes to the visual system which are associated with aging, and another associated with driving behavioural changes associated with aging which may affect the exposure of older drivers to glare-inducing situations (in particular, driving at night).

The literature searches identified a total of 66 articles with relevant titles. Following review of the abstracts of these papers and scoring using the inclusion criteria, 25 articles were selected for full-text review. Following full-text review, three papers were excluded due to lack of relevance. The key findings from the remaining 22 articles are summarised in the following sections.

Broadly, the studies identified in this review provided an analysis of older driver behaviour and experience through one of two methods: self-report data gathered through surveys in various forms and directly observed data on driving gathered via in-vehicle telematics (or a combination of both). Clearly, there are some advantages to using observational data, particularly when gathered as part of a naturalistic driving study, in that both the accuracy and ecological validity of the data are likely to be higher than with self-report data (e.g. Zhu, Jiang & Yamamoto, 2022). Several of the studies identified had a specific aim to compare the findings from self-report questionnaires with those of telematics data to establish the differences when applied to research with older drivers. In a study with 61 older driver participants, Blanchard, Myers and Porter (2010) found that participants' estimates of how far they had driven in a week were generally inaccurate, as were estimates of the number of trips made, and the number of stops within a trip. The telematics data also showed that the drivers drove in challenging situations more frequently than they reported they usually do, though there was broad agreement between self-report and telematics data in terms of frequency of nighttime driving, frequency of driving at night and in bad weather, and frequency of driving on highways.

Similar findings were reported by Molnar et al. (2013a) in a study with 156 older adults in Australia. Here, statistically significant correlations were found between self-reported avoidance and actual behaviour in terms of driving at night, driving in unfamiliar areas and driving on high-speed roads, but overall self-reported measures were an underestimate of actual driving behaviour. These studies suggest that some caution is needed in interpretation of self-report data, as while older drivers may report certain driving behaviours, such as avoidance of certain driving situations, their real-world behaviour may differ. This should be borne in mind when considering the findings discussed below.

3.1.1 Changes in driving performance and risk with age

Data from the DfT's Reported Road Casualties in Great Britain[14] shows around a quarter of road fatalities and 16% of serious injuries in 2023 were older drivers. There is an increased casualty rate for drivers over 70 years old (particularly female drivers) compared with other age groups, and the highest casualty rate is for those aged over 80 years old (both male and female drivers). Many reports, spanning several decades, indicate both increased collision and casualty rates for older drivers (e.g. Daigneault, Joly & Frigon, 2002; Hakamies-Blomqvist, 1994, 1995; Keltner & Johnson, 1987; Preusser et al., 1998). However, despite a wealth of evidence indicating that older drivers tend to suffer more collisions, injuries and fatalities, there are difficulties in drawing any firm conclusions regarding driver behaviour as a function of age for several reasons including:

- older drivers drive less frequently
- older drivers drive fewer miles
- older drivers drive more slowly
- older drivers avoid night driving

These differences render interpretation of casualty and collision rates far from straightforward. A lack of consensus within the literature as to what may constitute an "older" driver (e.g. Shanmugaratnam et al. (2010) estimate the range spans four decades) further hampers interpretation.

At least two potential biases have been identified that are relevant to our understanding of the increased collision and casualty rates of older drivers.

Low mileage bias: the increased accident rate for elderly drivers may be an artefact of calculating accident rate as a function of distance. High-mileage drivers predominantly use motorways/dual-carriageways which are inherently safer. At least one study has reported that when older drivers are compared with younger drivers who drive similar distances, there is no age-related elevation in accidents (Hakamies-Blomqvist et al., 2002).

Frailty bias: older drivers are more likely to be severely injured or killed in collisions and several studies has shown that this increased risk may explain the apparent over-involvement of older drivers in collisions. Indeed, Li et al. (2003) showed that whilst collision involvement accounted for 95% of young drivers' (< 20 years) increased death rates per mile travelled, significant increases in deaths per mile travelled did not occur until age 75 in older drivers and accounted for no more that 45% of their increased risk. Similarly Box, Gandolfi and Mitchell (2010) argued that older drivers tend not to have more collisions than other drivers, and the overrepresentation in collision statistics is because older drivers are more likely to be injured than drivers from other age groups due to their increased frailty.

A comprehensive analysis of over 5,000 road traffic collisions involving older drivers in Iran showed that both increasing age (particularly over 75 years old) and nighttime driving

[14] Reported road casualties in Great Britain: older driver factsheet, 2023.

significantly increased the odds of injury for older adults, suggesting age is not the only predictor of risk (Jahanjoo et al., 2023) for this group.

Driving style may also be a factor contributing to the injury risk of older drivers, though the literature identified in this review reports mixed results. In a naturalistic driving study of 84 drivers in Japan aged 50-85 years old, telematics data showed that risky driving behaviours (such as harsh braking and accelerations) were most common in the oldest age group (75-85 years) compared with the younger groups (Zhu, Jiang & Yamamoto, 2022). However, another study by the same authors using 59 older drivers (aged 65-85) and 12 middle-aged drivers (aged 51-64), found that older drivers were more likely to be classified as cautious than the middle-aged drivers, with cautious driving characterised by lower speeds and smoother braking and acceleration (Zhu, Jiang & Yamamoto, 2024a). A third study by Zhu, Jiang and Yamamoto (2024b) reported that older drivers' (65+) levels of risky driving behaviour, and changes in risk-taking over time, varied between individuals, arguing that this may be reflective of "distinctive individual processes of aging" (p.328). A survey with drivers in Egypt showed that older drivers tended to demonstrate more careful driving behaviours and habits than middle-aged drivers, specifically fewer violations, errors and lapses, and were less likelihood to drive while feeling drowsy (Arafa, Saleh & Senosy, 2020). However, other studies have found that older drivers had lower frequencies of high deceleration and speeding events than younger drivers (Molnar et al., 2018), which the authors argued is suggestive of older drivers self-regulating their driving to mitigate perceived increased risk (see section 3.1.3).

The broader effects of age on health and mobility are also likely to contribute to changes in driving performance. Driving is a complex task that requires visual, motor, and cognitive skills, and all of these can be affected by age (Karthaus & Falkenstein, 2016). These are discussed further in the next section.

3.1.2 Physiological and cognitive changes associated with aging

There are several common changes to human physiology and cognition which occur with aging which can impair driving (Box, Gandolfi & Mitchell, 2010). These include:

- **Physical impairments** – such as restricted joint movements, reduced muscle strength, reduced speed of movement, and reduced flexibility, which can cause difficulties such as scanning the road environment, turning the steering wheel or operating the controls, or reducing reaction times (Box et al., 2010; Karthaus & Falkenstein, 2016).
- **Cognitive impairments** – such as declines in executive functions that control attention and multitasking, reduced reaction times, and greater difficulties in processing information, including inhibition of irrelevant information which can lead to greater likelihood of cognitive overload (Box et al., 2010; Karthaus & Falkenstein, 2016). Tests of cognitive function such as the Trail Making Test (TMT) have shown that poorer scores are associated with reduced driving performance (Zhu, Jiang & Yamamoto, 2024a; 2024b).
- **Sensory impairments** – including eye conditions such as cataracts, glaucoma and tunnel vision which are more common in older age, as well as general reductions in visual acuity and contrast sensitivity, and increases in glare sensitivity which are considered normal with aging (Box et al., 2010; Karthaus & Falkenstein, 2016). Whilst

less safety-critical than vision, hearing loss in older drivers can also reduce performance in terms of a reduced ability to detect traffic noises/cues and warning signals (Karthaus & Falkenstein, 2016).

However, despite these age-related declines in physical and cognitive health, it should be noted that age alone is a poor predictor of driving performance, since both individual driving ability and the effects of aging on health differ considerably person-to-person (Box et al., 2010). Nevertheless, several age-related perceptual changes have been identified that are potentially relevant to driving including acuity, field of view and retinal illuminance.

- **Acuity** – The ability to resolve two points in a scene declines with age. The (mean) average acuity of drivers at 20 years has been estimated as 6/4.2 whereas it deteriorates to 6/7.3 at 70, the UK legal requirement being 6/9 (Davison & Irving, 1980 – see appendix in this paper for description of the Snellen Notation and test chart used). Despite this and the overwhelming evidence that acuity modulates visual performance, there is little evidence that reductions in acuity have anything other than a very weak association with driving safety (e.g. Owsley & McGwin, 2010).
- **Retinal illuminance** – As we age, the light reaching the back of the eye (the retina) reduces due to a reduction in pupil diameter and changes to the structure of the lens (the latter of which has great consequences for glare). Retinal illumination at the age of 60 is on average only around one-third of that found in the 20-year-old eye (Weale, 1961). Given that reducing luminance is known to increase perceived speed (Hammett et al., 2007), a question that therefore naturally arises is whether this luminance change may influence driving behaviour. At least in simulated environments, reducing luminance does indeed reduce average driving speed in a manner that is in quantitative agreement with the known increase in perceived speed yielded by reducing luminance (Pritchard & Hammett, 2012). It is not currently known whether this reduction is also seen in real-world driving scenarios, nor whether the effect mediates the reduction in average speed reported in older drivers.
- **Useful Field of View** – the UFOV test is a computer based visual test that assesses the visual area that a person can extract information from in the absence of eye or head movements (Ball et al, 2002). It comprises three sub-tests that evaluate processing speed in the absence or presence of divided and selective attentional tasks. The size of the UFOV is known to decrease with age (Sekuler et al., 2000) and has predictive value with respect to driving performance in older cohorts (Ball et al., 2005). Poor UFOV performers are around twice as likely to have a collision than good UFOV performers (Ball & Owsley, 1991) and drivers with poor UFOV performance take longer to cross intersections and initiate crossing later (Pietras et al., 2006).

3.1.3 Self-regulation as a mechanism to reduce risk in older drivers

To compensate for reduced driving performance, older drivers tend to ‘self-regulate’. Self-regulation is defined as a “*compensatory coping strategy for older drivers who, recognising some physical, cognitive or functional impairment, purposely limit or restrict their driving, in order to maintain independence but reduce accident risk*” (Gwyther & Holland, 2012, p. 19).

Evidence from the literature shows that behavioural changes typically associated with self-regulation can manifest as:

- Driving less during nighttime (Molnar et al., 2018; Charlton et al., 2019; Zhu, Jiang & Yamamoto, 2022; Louis et al., 2022; Vivoda et al., 2022)
- Undertaking shorter trips (Charlton et al., 2019; Zhu, Jiang & Yamamoto, 2022; Louis et al., 2022)
- Driving less frequently (Louis et al., 2022; Charlton et al., 2019)
- Reducing overall annual mileage (Charlton et al., 2019)
- Avoiding challenging driving conditions such as rush hour periods, bad weather and high-speed roads (Moták et al., 2014; Molnar et al., 2018; Vivoda et al., 2022; Perez et al., 2024)

These self-regulatory behaviour changes may be considered as examples of 'tactical' or 'strategic' self-regulation, defined in Michon's (1985) hierarchical control model (as reported by Zhu, Jiang & Yamamoto, 2024a). Tactical self-regulation involves adjusting driving behaviours such as speed and headway, while strategic self-regulation is where drivers make a conscious decision *before* driving, such as choosing to avoid challenging situations like nighttime driving or driving during peak times (Zhu, Jiang & Yamamoto, 2024a). Strategic self-regulation may also include active route planning, undertaking 'trial runs' of particular routes, pre-arranging rest stops, and making vehicle adaptations (Molnar et al., 2013a).

Vivoda et al. (2022) reported a longitudinal study of 1,554 older adults aged 65-79 years old to investigate those behavioural changes that are most common when drivers first start to self-regulate. The most common *initial* self-regulatory behaviour reported by participants was avoidance of night-time driving (58% of the sample), followed by avoidance of rush hour (27%), avoidance of driving in unfamiliar areas (11%) and avoidance of driving on freeways (5%). This study suggests that reductions in nighttime driving may be one of the first behavioural adaptations made by drivers as they age.

Self-awareness in drivers is an important predictor of self-regulatory behaviour change. As reported by Conlon et al. (2017), "*critical to the Model of Driving Self-Regulation… is awareness of the age- and disease-related difficulties in visual capacity, physical strength and flexibility and cognition that can occur during the aging process*" (p.19). Increased prevalence of self-regulatory behaviours is associated with drivers' perceptions of their own health-related difficulties, lower driving confidence and higher perceived driving difficulty (Conlon et al., 2017; Allen et al., 2019). Lower self-reported comfort and poorer perceived driving ability have been linked to reduced driving exposure, a key driving behavioural change associated with self-regulation (Blanchard & Myers, 2010, Jouk et al., 2014). As well as concerns about their own driving and health, older adults are frequently concerned about the driving of others, which may also contribute to self-regulation (Allen et al., 2019). Taylor et al. (2018) describes these concerns as a form of 'driving anxiety', particularly common in older people over 70, and associated with changes in driving habits and increased use of alternative forms of transport.

There appears to be a reasonable consensus in the literature on the definition of self-regulation and evidence of the ways in which it can manifest as changes in behaviour.

However, evidence also highlighted that such behavioural changes may not be *solely* due to a compensatory strategy for reducing one's exposure to risk; they may also reflect broader lifestyle changes associated with older age (Gwyther & Holland, 2012). Changes in trip times, for example, may be influenced by driver preference and circumstance – for example older drivers over 65 years old are more likely to be retired, and therefore less likely to commute during morning and evening peaks (Zhu, Jiang & Yamamoto, 2022). Similarly, reductions in the number of longer distance trips in older drivers may be because they are more likely to feel fatigued, in general, during such trips (Zhu, Jiang & Yamamoto, 2022).

In a survey study with 246 participants aged 75-94 years old, Molnar et al. (2013b) found that the motivations for driving modifications varied greatly and depended on the driving situation. For example, some drivers reported avoiding driving at night because they don't feel comfortable (in line with a self-regulatory process), while others did so because they don't need to drive at night (suggesting lifestyle or personal preference as the reason). Molnar et al. (2013b) defined three distinct groups of older drivers based on the survey results: *Non-modifiers* – those who did not modify their driving, *Self-regulators* – those who modified their driving due to self-regulatory reasons, and *Others* - those who modified their driving but for non-self-regulatory reasons, such as lifestyle or preference.

3.1.4 Interactive effects of age and gender on self-regulation

There was some evidence identified in the literature that gender is also a predictor of self-regulation, with women tending to exhibit greater self-regulatory behaviours than men (Gwyther & Holland, 2012). In a survey of 395 drivers in a mix of age groups (18-25, 26-64 and 65+ years old), age and sex effects were observed (Gwyther & Holland, 2012). Women were found to be more likely to self-regulate than men, especially being more likely to avoid driving situations including motorways, bad weather, lane changing and heavy traffic. When controlling for experience (time since licensure), greater self-regulation was found with increasing age.

A naturalistic driving study with 108 drivers across three age groups (20-30, 40-50 and 60-70 years old) reported similar findings, with older females, as a group, exhibiting more cautious driving habits than other age/sex groups, driving less overall, less at night and less on high-speed roads (Molnar et al., 2018). The changes in driving behaviour associated with self-regulation were more prevalent in females aged 60–70 than other age and gender groups. The authors pointed to a potential 'cohort effect' as the current older generation of women may not have traditionally been the main driver in the household and so may have gained less experience, or had lower confidence, than men of the same generation (Molnar et al., 2018). This appears to be supported in the literature, with evidence that women are more likely to report higher levels of driving anxiety than men (Taylor et al., 2018), that men tend to drive further than women (Charlton et al., 2019) and that women tend to report poorer driving confidence and greater driving difficulty than men (Conlon et al., 2017). Perceptions of driving and driving behaviours in women of future generations may differ from the current cohort of older women (Molnar et al, 2018).

3.2 RQ2: Drivers' experience of glare

The second research question asked: "What are the key factors influencing driver experience of glare from vehicle headlamps?" In answering this question, we seek to understand both discomfort glare, and how performance is affected by disability glare, respectively. We consider general factors that affect glare (especially those related to age), and factors specific to driving.

The literature searches identified a total of 42 articles with relevant titles. Following review of the abstracts of these papers and scoring using the inclusion criteria, 26 articles were selected for full-text review. The key findings from these articles are summarised in the sections below.

3.2.1 General factors associated with the experience of glare

It is well established that glare is caused by the introduction of straylight, or scatter, within the eye (e.g. IJspeert et al, 1990). As we age, the crystalline structure of the lens of the eye alters, in part due to a reduction in anti-oxidants such as glutathione (Weale, 1995). This in turn causes a variety of optical changes including an increase in the amount of scattered light within the eye. Thus, even in the otherwise healthy eye, glare increases as we age with straylight doubling by the age of 65 and tripling by age 77 (Van Den Berg et al., 2007). However, ageing is also accompanied by a variety of other conditions that affect vision such as presbyopia and cataracts, the latter of which leads to significant opacification of the lens and thus widespread light scatter and glare (e.g. Asbell et al., 2005; Van Den Berg et al., 2007). Thus, both normal healthy ageing and age-related disease conspire to increase both the objective cause of glare and its reported incidence. Moreover, our ability to estimate the effect of this glare upon our visual performance ("disability glare") is extremely poor, observers tending to significantly over-estimate the effect of glare upon their own visual performance (Sewall et al., 2016). Thus, the effect of glare increases significantly with age whilst our estimate of its effect is exaggerated even further, opening the possibility that driving behaviour may be modulated not only by the known objective consequences of glare but also by our parlous estimates of its effects.

3.2.2 Specific studies of glare in driving

The driving-related literature reviewed in the current report broadly focuses on three things. First there are studies that examine the reported experiences of drivers in relation to glare, usually using self-reported data in surveys. Second, there are studies that focus on the impact of disability glare or discomfort glare on some measure of driver performance. Third, there are studies that attempt to understand how features in the driving environment (for example headlamp types, brightness of lamps, road geometry) or aspects of drivers themselves (for example various diseases or age) relate to discomfort or disability glare when driving. Many studies cover more than one of these topics. Below, we summarise findings from the review in these broad categories. In short, we ask what drivers say about glare, how glare affects driving performance, and those factors that contribute to glare from vehicle headlamps. In the latter two sections (3.2.2.2 and 3.2.2.3) we discuss the findings separately for disability glare, and discomfort glare. Finally in section 3.2.2.4 we discuss other studies that do not fit within these sections, for completeness.

3.2.2.1 *What drivers say about glare*

Studies focused on this question tend to be either public surveys asking drivers about things that trouble them on the road, or scientific studies interested largely in the ways in which people can self-rate glare (usually discomfort glare using some standard such as the De Boer scale).

Survey data are available from several membership club surveys in the UK. For example, the Royal Automobile Club (RAC), Automobile Association (AA), and Institute of Advanced Motorists (IAM Roadsmart) have all run recent surveys that highlight glare from vehicle headlamps as an area of concern from members of the driving public (see for example RAC, 2024; AA, 2023, IAM Roadsmart – personal communication).

Some survey-based studies were also found in the peer-reviewed literature through the literature search. Viktorová et al. (2022) for example surveyed 539 car drivers in the Czech Republic. They found that most drivers experienced glare at least once a week or almost daily, and that white- or bluish-coloured headlamps were the main glare sources reported. Interestingly, around 60% of participants also stated that they preferred the view of the road provided by these coloured sources.

Many studies have shown that drivers are able to rate the levels of discomfort glare they experience in laboratory and track or simulated driving studies. Since these studies are almost always interested in the effects of this on performance, or associations with other factors, these studies are discussed in the next two sections.

3.2.2.2 *How driver performance is affected by glare*

Before addressing specific effects of disability glare and discomfort glare on driving performance, it is first worth noting the fundamental visual and cognitive functions and processes that are affected or potentially affected by glare. These functions and processes are effectively the mechanisms by which driving – a largely visual and cognitive task – could be expected to be impaired. The following are all aspects of vision and cognition that might be affected by glare (note some of these references, for example Martinsons et al., 2024, draw on literature outside of driving, such as office settings):

- **Contrast sensitivity/visual acuity:** Disability glare reduces the eyes' sensitivity to contrast, making objects more difficult to distinguish from their backgrounds (Gil et al., 2021; Reddy & Reddy, 2017; Davoudian et al., 2014). Lower ability to detect objects has an obvious relevance for driving safety.
- **Motion perception:** Anderson and Holliday (1995) showed that glare decreased the ability of observers to detect the direction of motion of low contrast targets. However, this study used only two (relatively young) observers. A later study by Sepulveda et al. (2022) showed that while older people (mean 70 years) had elevated thresholds for three of four motion detection tasks used, relative to people with a mean age of 25 years, the presence of glare did not affect these thresholds for either group. These are the only two studies that we are aware of as having examined the issue of motion detection and glare directly and we note that no studies have addressed the question of how glare may affect the perception of speed p*er se,* making this a potential gap in evidence.

- **Mental fatigue:** There is some evidence that discomfort glare can increase mental fatigue (Mace et al., 2001, cited in Mehri et al., 2017). Driving while fatigued or under high mental workload is clearly undesirable.
- **Visual fatigue and eye strain:** Findings in Stone (2009, cited in Lincoln, 2023) suggest that discomfort glare can in some individuals lead to watery or itchy eyes, tense muscles and headaches. Martinsons et al. (2024) also notes that discomfort glare is suspected to trigger headaches in some people suffering with migraines, although this paper examines solid state lighting in contexts other than driving (for example office environments). Driving with any eye-related deficit would be expected to lead to lower performance, given the importance of vision in driving.
- **Eye and head movements:** Glimne et al. (2015, cited in Martinsons et al., 2024) used eye tracking to examine reading speed. The study found that there were increased fixation durations when glare was higher, leading to slower reading speed. While this study is again not directly related to driving, eye movements are known to play an important role in perceiving and anticipating hazards on the road ahead, meaning any change in eye movements could theoretically impact driving safety.
- **Pupil constriction:** The pupil in the human eye constricts when exposed to bright light, and this constriction is slower to reverse when the light is removed for blue light than for red light (Mathôt, 2018, cited in Lincoln, 2023), although note this findings was not directly related to glare – it was tested with an eye looking at a computer monitor with either a red or blue full screen display. Pupil constriction may be another mechanism through which nighttime vision may suffer when driving, after a period of bright light (especially blue light). The net effect may be complex however, since pupil constriction will also reduce the amount of straylight entering the eye when a source of glare is present, potentially improving contrast sensitivity. This is another potential gap in the evidence.
- **Disrupted binocular vision:** Martinsons et al. (2024) cites several references suggesting that discomfort glare and disability glare can both potentially disrupt binocular vision, resulting in disparities in eye fixations.

In short, there are several visual and cognitive functions that are, or potentially are affected by both disability and discomfort glare, and which could have impacts on driving safety. We now consider disability glare and discomfort glare separately for their effects on driving performance directly.

Disability glare

Several papers have examined the degree to which some aspect of driving performance is affected by disability glare. ‘Performance’ in these studies ranges from control of the vehicle to visual detection of targets in the driving environment.

Some studies have taken place in laboratory conditions, seeking to maintain very close control over the variables under investigation. One example is Davoudian et al. (2014) who investigated disability glare from a streetlight source rather than from headlamps. Forty-two participants (21 male) between the ages of 20 and 75 years were tested. Participants were positioned 4m from a white screen on which a street scene was presented. This street scene was controlled by software that could overlay one of two targets (a ‘Landolt C’ – a standard stimulus for testing vision – and a black dog stimulus). LED light sources that were either small or large and were either ‘warm’ or ‘cold’ white were placed at a position in the street scene corresponding to a lamp column, and participants were tested for their ability to detect the Landolt C orientation at a foveal location, and the presence of the dog target peripherally, under different glare conditions. Glare conditions were either ‘none’, ‘low’ (≈1 lx at the observer’s eye) or ‘high’ (≈2 lx at the observer’s eye). Veiling luminance was also measured directly for each participant. The results showed that warmth or light, and size of light, made no difference to target detection (measured through calculating luminance contrast threshold for all observers). Increased glare did adversely affect target detection.

Bullough et al. (2004) provided a detailed investigation (on a track) of the effects of glare source illuminance, glare source spectrum, and glare source size in three blocks of testing with different participants in each block. Participants were tested on their speed and accuracy of target detection of high (40%) or low (20%) reflectance ‘flip dot’ targets placed at different lateral positions relative to the glare source, which was varied on the factors noted above. In all blocks, high reflectance targets were detected more quickly and more accurately (i.e. fewer missed targets) than low reflectance targets, and targets in the periphery of vision, and closest to the glare source, were detected less quickly and less accurately. The study found that higher levels of glare illuminance led to longer reaction times on target detection, as well as more missed targets. Glare source spectrum and glare source size did not have any effect on performance.

Kimlin et al. (2020) presents another example of how glare can lower driving performance. In this study, 26 older drivers (mean age 72 years) were asked to detect targets such as animal and pedestrian depictions, road markings and signs, to avoid low contrast foam hazards in the road, and to keep within their lane while driving on a track. A combined measure of overall driving performance was used, and it was shown that a light source providing 13 ± 2 lux, equivalent to 650 ± 10 cd/m2 at the driver’s eyes, resulted in poorer performance (detailed findings in Kimlin et al., 2017, cited in Kimlin et al., 2020).

Bozendowski et al. (2015) manipulated glare in another track-based trial as either ‘low’, ‘medium’ or ‘high’. These conditions were achieved using parking lights, low beam headlamps and fog lamps with a neutral density filter to reduce illumination levels to 6%, and unfiltered low beam headlamps and fog lamps respectively. The task for participants was to detect a pedestrian wearing either general (dark) clothing, or a high-visibility jacket. The high glare condition was associated with shorter detection distances (i.e. later detection) than the low glare condition, and the pedestrian wearing a high visibility jacket was detected at longer distance (earlier detection) than the one wearing dark clothing; the glare effect was the same however for both clothing types, showing that glare can reduce detection of high or low visibility targets.

Another often-used method to study glare effects is driving simulation. This method offers a little more experimental control over the driving environment than is the case with track trials and permit an even safer testing environment.

Hwang et al. (2018) ran a simulator study in which participants drove nighttime scenarios where they had to detect pedestrians walking along or crossing the road. Five normal vision participants and five participants with mild cataracts took part. The five normal vision participants also took part wearing simulated cataract glasses. The study showed that pedestrian detection was worse under the presence of glare, and with real or simulated cataracts. Pedestrians nearer the source of glare were also harder to detect.

Jones et al. (2022) had 15 healthy adults with normal vision, aged 55-81 years, take part in a night-driving simulation. Participants undertook several tasks, including driving a simulated vehicle while maintaining a constant speed, and identifying hazards of varying contrasts (a wild boar, a man in grey and a man in black) that appeared on the side of the road. They also performed contrast sensitivity measurements both within the simulator and clinically using an Optovist I instrument, with and without the presence of simulated glare from oncoming headlamps. The study found that glare significantly reduced contrast sensitivity (by 41%) in the simulated driving conditions. Moreover, both contrast sensitivity and low contrast visual acuity were significantly associated with night-time hazard detection ability, while high contrast visual acuity was not. The study also found that contrast sensitivity was shown to decrease in dynamic driving conditions, and as a function of age.

Yang et al. (2024) also used a driving simulator to examine driver performance under daytime and nighttime testing conditions, with an additional glare manipulation (a physical light on the bonnet of the car) in the nighttime testing. Twenty drivers aged 60 years and over were asked to drive as they normally would in light simulated traffic, while also attempting to spot targets that would appear above the roadway (boxes with horizontal strips, with equivalent boxes with vertical striped serving as distractors). The glare condition, when compared with nighttime without glare, and daytime conditions, was associated with a higher average driving speed, and a higher standard deviation of lane position. Both would be expected to be detrimental to safety; the former reduces safety margins, while the latter is an indicator of poorer vehicle control. The Yang et al. study is also useful as it demonstrated that a non-driving measure of contrast sensitivity (involving detection of differing contrast letters) was adversely affected by glare, in the same participants as carried out the driving tasks.

One other thing that has been studied in this context is the potential impact of prolonged exposure to glare on performance. Ranney et al. (1999) had truck drivers drive three 8-hour sessions with each session having 30 episodes of glare in rear view mirrors, resulting in 1.4-3.3 lux at driver eye position (values that previously cited work had shown to be consistent with the presence of discomfort glare as measured on the De Boer scale). No effect was found on performance at detecting pedestrians on the simulated road ahead, or on vehicle control variables. Another study (Schiflett et al., 1969) which did find effects of long-term glare exposure was cited in the Ranney et al. paper, although several differences between the studies was noted that could explain the different findings. The effects of long-term exposure to glare should therefore be considered a gap in the literature.

Discomfort glare

There is less evidence for discomfort glare affecting driving performance directly, although there are sound theoretically plausible mechanisms by which someone experiencing discomfort glare could show a deficit in performance (see examples in section 3.2.2.2).

In general, however, the literature reports that discomfort glare does not result in any appreciable reduction in driving performance, despite people tending to think that it will. For example, Balk and Tyrrell (2011) tested drivers on a track for their ability to tell the orientation of a ‘Landolt C’ target (a standard symbol for testing vision). A vehicle parked facing them had its headlamps either on full beam or low beam. Participants were also asked to rate their discomfort glare using the De Boer scale, and although high beam headlamps on the facing car were associated with higher discomfort glare, they were not associated with the distance at which participants could just distinguish the orientation of the stimulus. In addition to collecting actual recognition distance, Balk and Tyrrell also asked people to *estimate* the distance at which they would be able to detect the orientation of the Landolt C stimulus; the high beam headlamps *were* associated with an increase in this estimated distance. Additionally, participants’ estimate error (i.e. how much they underestimated their actual recognition distance) was highly correlated with their De Boer ratings; this is compatible with the conclusion that discomfort glare drove underestimates.

The track study reported by Kimlin et al. (2020), which as reported above showed that a glare source made night-time driving performance significantly worse in a sample of older drivers, also asked participants to rate discomfort glare using the De Boer scale. There was no association between discomfort glare rating and driving performance. However, another self-report measure used in the study, the vision and night driving questionnaire (VND-Q), which measures self-reported difficulty in things like seeing dark coloured cars, seeing other road users, and judging distances when driving at night, was associated with driving performance, with the association being stronger in the presence of glare. This study shows that it is possible to extract self-report data from people in predicting difficulties in driving performance; the failure of discomfort glare to predict driving performance would not appear to be purely related to its subjective nature.

3.2.2.3 What are the factors that contribute to glare effects from vehicle headlamps?

One of the most studied areas in this field is the specific lighting technology used for vehicle headlamps, and how different technologies relate to both discomfort and disability glare. Lincoln (2023) wrote a report for the group chaired by Baroness Dianne Hayter; that report was an important catalyst for the work in the current project, and outlined how LED lights are believed to be particularly problematic. The focus on how developments in lighting technologies may affect driver experience is not new; a decade ago a paper in the British Journal of Ophthalmology discussed the increasing prevalence of high intensity discharge (HID) headlamps, and problems this may cause specifically for older drivers (Mainster & Timberlake, 2014).

The conclusions from the literature on headlamp technologies are mostly that disability and discomfort glare are proportional to brightness, while discomfort glare can also vary with different lighting technologies (for example HID, LED) even when brightness is kept constant. We will now consider the evidence on disability glare and discomfort glare in turn.

Disability glare

Mainster and Timberlake (2014), when discussing light scattering in the eye from bluer or whiter colour temperature lamps cite several studies and established theory to conclude that “The net effect is that stray light reaching the fovea has little wavelength dependence. Thus, blue-white HID headlights should produce no more foveal stray light or disability glare than white headlights of the same luminance."

Findings from empirical studies also show that illuminance is the key driver of falling performance, and spectral content is not as important. Bullough et al. (2004) for example showed that increasing glare illuminance levels lowered performance in a target detection task on a carefully controlled track trial in a stationary vehicle; changing spectral content or size of the glare source (while keeping illuminance levels constant) did not.

Some studies have looked at those individual differences that can affect the experience of glare. Hwang et al. (2018) for example showed that the impact of glare on the detection of pedestrians in a simulated driving task was worse in the presence of real or simulated cataracts. Reddy and Reddy (2017) list more factors that are associated with disability glare, including older age (Pulling et al., 1980; Schwab et al., 1972 – both cited in Reddy and Reddy, 2017).

Discomfort glare

Three important mechanisms through which different lighting technologies might affect discomfort glare are the illuminance resulting from the glare source, the colour temperatures of light emitted (modern lights like LEDs being 'bluer' than older ones) and the other design features of headlamp systems (for example throw of light, and automatic systems that adapt beam shape dependent on context).

Higher levels of illuminance lead to greater levels of self-rated discomfort glare (for example see Bullough et al., 2004).

Studies looking at discomfort glare have also shown that the spectral content of glare sources can lead to changes in ratings, with observers rating light with a bluer appearance as resulting in greater levels of discomfort glare. An example is provided by Sullivan and Flannigan (2001), who showed headlamps of varying wavelengths to participants, while keeping photopic illuminance levels constant between them. Participants (N=16) were asked to provide ratings of discomfort glare using the De Boer scale, and the findings showed that ratings of glare were higher. Findings from Bullough et al. (2004) similarly showed that the spectral content of glare source was associated with changes in De Boer scale ratings, while glare source size was not. The literature review in Caruso et al. (2015) also cited several sources supporting the assertion that shorter wavelengths of light are associated with greater amounts of discomfort glare.

Reagan and Brumbelow (2015) provide evidence that discomfort glare ratings can be affected by automated adaptive headlamp systems, in a track trial. The data also showed that the amount of illuminance at the eye of the observers was well correlated with the De Boer ratings provided for discomfort glare. Zalcmanis et al. (2019) also examined different headlamp technologies, and specifically looked at non-standard lighting technologies, measuring illuminance at various points within a scene, including the 'B50L' test point, a standard test point within lighting regulations corresponding to approximately the point at which an average driver's eye might be expected to be. Using six headlamp designs, standard halogen bulbs resulted in illuminance levels well within the 'satisfactory' range on the De Boer scale (calculated using the Smidt-Clausen and Bindels equation). High intensity discharge bulbs resulted in predicted De Boer ratings in the 'disturbing' and 'just permissible' range.

Reddy and Reddy (2017) provide a review of various other factors that may affect the amount of discomfort glare. These include age – with older people perhaps suffering more (Bennet, 1977, cited in Reddy and Reddy, 2017). However, more recent reports indicate that discomfort glare may be age independent (for example Bargary et al., 2015, cited in Reddy and Reddy, 2017) or even that younger observers may be more sensitive to it (Wolska & Sawicki, 2014, cited in Reddy and Reddy, 2017). One possible reason for these discrepant findings may be the presence of range effects showing that if people are exposed to a wider range of glare intensities, they increase the level of glare they consider tolerable (Lulla & Bennett, 1981, cited in Reddy and Reddy, 2017). Task difficulty has also been implicated in modulating levels of discomfort glare with people exposed to a glare source rating the resulting discomfort glare as greater if they are engaged in a difficult task, rather than an easy one (Sivak et al., 1991; Theeuwes & Alferdinck, 1996).

3.2.2.4 Other studies

Several other studies are relevant to the work in the project in general, although not specifically to the topics in the sections above.

One such study is Nguyen et al. (2023), who demonstrated a polarising filter countermeasure designed to reduce illuminance from LED headlamps. This was shown to be able to reduce illuminance (and therefore the potential for glare) by around 56% (one filter) and 97% (two filters) while maintaining comparable lighting brightness and distance to conventional headlamps. This study demonstrates at least one approach to managing illuminance from headlamps, should widespread adoption be possible.

Thomas et al. (2009) took an approach to measuring disability glare that directly measures the amounts of straylight in the eyes of young and old participants with no eye issues, and old participants with early-stage cataracts. The ‘straylight meter’ works by flashing a ring of light on and off while the participant focuses on the centre. Light scattering in the eye causes the participant to see flickering. Compensation light is added to eliminate the flickering. When the flickering stops, the compensation light value is equal to the straylight value, meaning that a precise quantification of the levels of straylight can be used. This study suggested that the straylight method may have better characteristics (repeatability and discriminative ability between the test groups) than more traditional tests such as the Nyktotest and Mesotest which measure contrast sensitivity. It is likely that future research into headlamp glare will be needed after this project, and one part of this should probably focus on more objective ways of measuring glare (in particular, disability glare) so that driver performance effects can be predicted from such measurements if possible.

Ultimately, it would be beneficial for road safety and road user experience if it were possible to model the likely glare effects from different environmental conditions and contexts. This has been attempted in other fields. Bullough et al. (2011) for example cited the modelling approach from Bullough et al. (2008) in which formulae were developed combining luminance from a source, illuminance from the source and surrounding area, and ambient illuminance before the installation of the source, to predict the De Boer rating for discomfort glare that would likely result. Another study (Gil et al., 2021) used a geometric approach to modelling headlamps and driver eye positions on real road sections that had been scanned with LiDAR, and assumed glare would be present whenever a single ray of light within a headlamp beam connected directly with a driver’s eye position. This study showed that there were certain geometric features of roads (such as bend direction) and of lighting types (swivelling or fixed) that led to more glare, as assumed within the model parameters. One aim of the current research is to begin collecting data from real driving scenarios that will serve as a foundation on which to do similar modelling work.

4 Discussion and conclusions

In this literature review, we sought to summarise the evidence around glare associated with vehicle headlamps, to inform the data collection for the on-road component of the work on this project. The review focused on two research questions, namely how driver behaviour, and experience of glare, varies with age, and what the key factors are influencing driver experience of glare from vehicle headlamps.

RQ1: Age and driving behaviour

Overall, the literature identified in this review provides evidence that, whilst age alone should not be considered a sole and reliable predictor of driving behaviour, commonly the driving behaviours and experiences of older drivers differ to those from younger age groups. The reasons for these changes in behaviour are complex, and will vary between individuals, but include reductions in performance such as cognitive slowing, and self-regulation as a mechanism for older drivers to reduce their exposure to risk, as well as more general lifestyle changes and personal preferences associated with older age.

Irrespective of the underlying causal mechanisms, and of most relevance to this project on the glare experienced by drivers from vehicle headlamps, the evidence suggests that, in general, older drivers are likely to drive less at night, drive shorter distance trips, drive less overall and avoid challenging driving situations such as rush hour driving or driving on motorways. The evidence also suggests that these behavioural differences may be more prevalent in older women than older men. From this we can conclude that older drivers (especially women) are likely to be exposed less than younger drivers to circumstances in which vehicle headlamps may lead to experiences of glare (in particular, driving at night).

The significant increase in light scatter associated with age may represent a considerable challenge to both older drivers and society as the population ages, either in terms of precipitating greater self-regulation, or in terms of the effects of glare on those drivers who still drive in circumstances in which glare can be an issue.

RQ2: Drivers' experience of glare

Public surveys show that drivers report glare as a common problem with driving. Several cognitive and visual processes and functions can be affected by glare, including contrast sensitivity and visual acuity, mental fatigue, visual fatigue and eye strain, eye and head movements, and binocular vision. These are all potential mechanisms by which glare might lead to issues with driver behaviour.

The evidence is clear that there are a range of aspects of driving behaviour and performance that can be disrupted by disability glare. These include hazard and target detection (especially low contrast targets and targets near the glare source), driving speed, and driving lane position. In general, increasing glare is associated with worse performance, while spectral characteristics (for example colder versus warmer light) and glare source size does not appear to be. Individual differences such as age and associated complications such as cataracts can affect the levels of disability glare also.

Discomfort glare does not tend to be shown to reduce driving performance, and people tend to overestimate the effects of glare on their levels of performance. Higher levels of glare are associated with increased ratings of discomfort glare, as are 'bluer' spectral characteristics of light (compared with warmer wavelengths).

Other evidence suggests that the effects of glare on drivers can be reduced using some technology approaches, such as polarising filters fitted to lights, and strategically placed road dividers, although these studies tend to be proof-of-concept rather than full trials using deployed technologies. Modelling work shows that certain types of road geometry can be associated with changes in glare from otherwise equivalent light sources.

In short, glare is a problem both in terms of its reported prevalence in the driving population, and its potential impact on driving behaviour choices; it is plausibly a problem in terms of road safety. The extent to which it is a problem in these areas is not well understood, and for this reason this project will collect real-world data on light levels and glare on real UK roads, to further understand the issue.

References

AA (2023). Highlights from 2023 Driver Poll Surveys. AA Yonder Driver Poll Summaries 2023 | AA (https://www.theaa.com/about-us/public-affairs/aa-yonder-driver-poll-summaries-2023#7l) (Accessed 12 February 2025)

Allen, H. K., Beck, K. H. & Zanjani, F. (2019). Driving concerns among older adults: Associations with driving skill, behaviors, and experiences. *Traffic Injury Prevention*, 20(1), 45-51.

Anderson, S. J. & Holliday, I. E. (1995). Night driving: effects of glare from vehicle headlights on motion perception. *Ophthalmic and Physiological Optics*, 15(6), 545-551.

Arafa, A., Saleh, L. H. & Senosy, S. A. (2020). Age-related differences in driving behaviors among non-professional drivers in Egypt. *PLoS one*, 15(9), e0238516.

Asbell P.A., Dualan I., Mindel J., Brocks D., Ahmad M. & Epstein S. (2005). Age-related cataract. *Lancet*, 365(9459):599-609. doi: 10.1016/S0140-6736(05)17911-2. PMID: 15708105.

Ball, K. & Owsley, C. (1991). Identifying correlates of accident involvement for the older driver. *Human Factors*. 33(5): 583-595.

Ball, K., Wadley, V.G. & Edwards, J.D. (2002). Advances in technology used to assess and retrain older drivers. *Gerontechnology*, 1(4): 251-261

Ball, K & Clay, O, Wadley, V, Roth, D, Edwards, J & Roenker, D. (2005). Predicting Driving Performance in Older Adults with the Useful Field of View Test: A Meta-Analysis. *In Driving Assessment Conference* (Vol. 3, No. 2005). University of Iowa. 51-57. 10.17077/drivingassessment.1142.

Balk, S.& Tyrrell, R. (2011). The Accuracy of Drivers' Judgments of the Effects of Headlight Glare: Are We Really Blinded by the Light?. *In Driving Assessment Conference* (Vol. 6, June). University of Iowa.

Blanchard, R. A.& Myers, A. M. (2010). Examination of driving comfort and self-regulatory practices in older adults using in-vehicle devices to assess natural driving patterns. *Accident Analysis and Prevention*, 42(4), 1213-1219.

Blanchard, R. A., Myers, A. M. & Porter, M. M. (2010). Correspondence between self-reported and objective measures of driving exposure and patterns in older drivers. *Accident Analysis and Prevention*, 42(2), 523-529.

Borzendowski, S. A. W., Sewall, A. A. S., Rosopa, P. J. & Tyrrell, R. A. (2015). Drivers' judgments of the effect of headlight glare on their ability to see pedestrians at night. *Journal of Safety Research*, 53, 31-37.

Box, E., Gandolfi, J. & Mitchell, C. (2010). Maintaining safe mobility for the ageing population- the role of the private car. https://www.racfoundation.org/assets/rac_foundation/content/downloadables/maintaining%20safe%20mobility%20-%20rac%20foundation%20-%20140410%20-%20report.pdf. Accessed 12/02/2025.

Bullough, J. D., Van Derlofske, J., Dee, P., Chen, J. & Akashi, Y. (2004). An investigation of headlamp glare: intensity, spectrum and size (No. HS-809 672).

Bullough, J., Hickcox, K., and Narendran, N. (2011). A method for estimating discomfort glare from exterior lighting systems. *ASSIST*, 9(1), 1-7.

Caruso, D., Fabretto, M., Field, S., Evans, D., Murphy, P. & Hall, C. (2015). Market evaluation, performance modelling and materials solution addressing short wavelength discomfort glare in rear view automotive mirrors. *Translational Materials Research*, 2(3), 035002.

Charlton, J. L., Koppel, S., D'Elia, A., Hua, P., Louis, R. S., Darzins, P., ... & Marshall, S. (2019). Changes in driving patterns of older Australians: Findings from the Candrive/Ozcandrive cohort study. *Safety Science*, 119, 219-226.

CIE (2020). ILV: International Lighting Vocabulary, 2nd ed.; CIE S 017/E:2020; CIE Central Bureau: Vienna, Austria. DOI: 10.25039/S017.2020

Conlon, E. G., Rahaley, N. & Davis, J. (2017). The influence of age-related health difficulties and attitudes toward driving on driving self-regulation in the baby boomer and older adult generations. *Accident Analysis and Prevention*, 102, 12-22.

Daigneault, G., Joly, P. & Frigon, J. (2002). Previous convictions or accidents and the risk of subsequent accidents of older drivers. *Accident Analysis and Prevention*, 34, 257-261.

Davison, P. A. & Irving, A. (1980). *Survey of Visual acuity of drivers*. Transport and Road Research Laboratory (TRRL) ISSN: 0266-7045

Davoudian, N., Raynham, P. & Barrett, E. (2014). Disability glare: A study in simulated road lighting conditions. *Lighting Research and Technology*, 46(6), 695-705.

Gil, P. A., De Santos-Berbel, C. & Castro, M. (2021). Driver glare exposure with different vehicle frontlighting systems. *Journal of Safety Research*, 76, 228-237.

Gwyther, H. & Holland, C. (2012). The effect of age, gender and attitudes on self-regulation in driving. *Accident Analysis and Prevention*, 45, 19-28.

Hakamies-Blomqvist L. (1994). Compensation in older drivers as reflected in their fatal accidents. *Accident Analysis and Prevention*, 26(1):107-12. doi: 10.1016/0001-4575(94)90073-6.

Hakamies-Blomqvist L., Johansson K., & Lundberg C. (1995). Driver licenses as a measure of older drivers' exposure: a methodological note. *Accident Analysis and Prevention*, 27(6):853-7. doi: 10.1016/0001-4575(95)00029-1.

Hakamies-Blomqvist, L., Raitanen, T. & O'Neill, D. (2002). Driver ageing does not cause higher accident rates per km. *Transportation Research Part F: Traffic Psychology and Behaviour*, 5(4), 271–274. https://doi.org/10.1016/S1369-8478(03)00005-6

Hammett, S. T., Champion, R. A., Thompson, P. G. & Morland, A. B. (2007). Perceptual distortions of speed at low luminance: Evidence inconsistent with a Bayesian account of speed encoding. *Vision Research*, 47(4), 564-568.

Hwang, A. D., Tuccar-Burak, M., Goldstein, R. & Peli, E. (2018). Impact of oncoming headlight glare with cataracts: a pilot study. *Frontiers in psychology*, 9, 164.

IJspeert J.K., de Waard P.W., van den Berg T.J. & de Jong PT. (1990) The intraocular straylight function in 129 healthy volunteers; dependence on angle, age and pigmentation. *Vision Research*, 30(5):699-707. doi: 10.1016/0042-6989(90)90096-4. PMID: 2378063.

Jahanjoo, F., Sadeghi-Bazargani, H., Hosseini, S. T., Golestani, M., Rezaei, M., Shahsavarinia, K., ... & Asghari-Jafarabadia, M. (2023). Exploring the causal impact of age and nighttime driving on road traffic injuries among elderly drivers: a Bayesian LASSO approach. *Bulletin of Emergency & Trauma*, 11(3), 125.

Jones, P. R., Ungewiss, J., Eichinger, P., Wörner, M., Crabb, D. P. & Schiefer, U. (2022). Contrast sensitivity and night driving in older people: Quantifying the relationship between visual acuity, contrast sensitivity, and hazard detection distance in a night-time driving simulator. *Frontiers in Human Neuroscience*, 16, 914459.

Jouk, A., Tuokko, H., Myers, A., Marshall, S., Man-Son-Hing, M., Porter, M. M., ... & Candrive II Research Team. (2014). Psychosocial constructs and self-reported driving restriction in the Candrive II older adult baseline cohort. *Transportation Research Part F: Traffic Psychology and Behaviour*, 27, 1-10.

Karthaus, M. & Falkenstein, M. (2016). Functional changes and driving performance in older drivers: assessment and interventions. *Geriatrics*, 1(2), 12.

Keltner J.L., Johnson C.A. (1987). Visual function, driving safety, and the elderly. *Ophthalmology*, 94(9):1180-8. doi: 10.1016/s0161-6420(87)33309-3.

Kimlin, J. A., Black, A. A. & Wood, J. M. (2020). Older drivers' self-reported vision-related night-driving difficulties and night-driving performance. *Acta Ophthalmologica*, 98(4), e513-e519.

Li G., Braver E.R. & Chen L.H. (2003) Fragility versus excessive crash involvement as determinants of high death rates per vehicle-mile of travel among older drivers. *Accident Analysis and Prevention*. 35(2):227-35.

Lincoln, J. (2023). *Modern vehicle headlights dazzle drivers and may compromise road safety*. Report for Lightaware. https://lightaware.org/wp-content/uploads/2023/12/Vehicle-headlight-glare.pdf. Accessed 12/02/2025.

Louis, R. M. S., Koppel, S., Molnar, L. J., Di Stefano, M., Darzins, P., Porter, M. M., ... & Charlton, J. L. (2022). Examining the contribution of psychological resilience on self-reported and naturalistic driving behavior of older adults. *Journal of Safety Research*, 82, 251-260.

Mainster, M. A. & Timberlake, G. T. (2003). Why HID headlights bother older drivers. British *Journal of Ophthalmology*, 87(1), 113-117.

Martinsons, C., Veitch, J. A., Loughran, S., Nixon, A., Mate, R., Harris, R. & Shen, L. (2024). *Solid-State Lighting: Review of Health Effects.* https://www.iea-4e.org/wp-content/uploads/2024/06/HEALTH-REPORT-IEA-4E-SSLC-Platform.pdf. Accessed 12/02/2025.

Mehri, A., Farhang Dehghan, S., Hajizadeh, R., Zakerian, S. A., Mohammadi, H.& Abbasi, M. (2017). Survey of discomfort glare from the headlamps of cars widely used in Iran. *Traffic Injury Prevention*, 18(7), 711-715.

Molnar, L. J., Charlton, J. L., Eby, D. W., Bogard, S. E., Langford, J., Koppel, S., ... & Man-Son-Hing, M. (2013a). Self-regulation of driving by older adults: Comparison of self-report and objective driving data. *Transportation Research Part F: Traffic Psychology and Behaviour*, 20, 29-38.

Molnar, L. J., Eby, D. W., Bogard, S. E., LeBlanc, D. J. & Zakrajsek, J. S. (2018). Using naturalistic driving data to better understand the driving exposure and patterns of older drivers. *Traffic Injury Prevention*, 19(sup1), S83-S88.

Molnar, L. J., Eby, D. W., Charlton, J. L., Langford, J., Koppel, S., Marshall, S. & Man-Son-Hing, M. (2013b). Reprint of “Driving avoidance by older adults: Is it always self-regulation?”. *Accident Analysis and Prevention*, 61, 272-280.

Moták, L., Gabaude, C., Bougeant, J. C. & Huet, N. (2014). Comparison of driving avoidance and self-regulatory patterns in younger and older drivers. Transportation research part F: traffic psychology and behaviour, 26, 18-27.

Owsley, C. & McGwin, G Jr. (2010). Vision and driving. *Vision Research*. 50(23):2348-61. doi: 10.1016/j.visres.2010.05.021.

Perez, J., Rashidi, M. H., Boni, J. A., Hyun, K., Farrokhi, B. & Park, S. (2024). Older adults’ perceptions and behaviors on driving: A mixed method study. *Transport Policy*, 158, 93-103.

Pietras, T.A., et al. (2006). Traffic-entry behavior and crash risk for older drivers with impairment of selective attention. *Perceptual and Motor Skills*, 102(3), 632-44.

Preusser, D. F., Williams, A. F., Ulmer, R. G., Ferguson, S. A. & Weinsteini, H. B. (1998). Fatal crash risk for older drivers at intersections. *Accident Analysis and Prevention*, 30(2), 151-159.

Pritchard, S. J. & Hammett, S. T. (2012). The effect of luminance on simulated driving speed. *Vision Research*, 52(1), 54–60.

RAC (2024). A glaring problem: RAC calls for action on headlight glare as eight-in-10 drivers affected say problem is getting worse. [Online]. RAC. Last Updated: 10 January 2024. Available at: https://media.rac.co.uk/pressreleases/a-glaring-problem-rac-calls-for-action-on-headlight-glare-as-e [Accessed 12 February 2025].

Ranney, T. A., Simmons, L. A. & Masalonis, A. J. (1999). Prolonged exposure to glare and driving time: effects on performance in a driving simulator. *Accident Analysis and Prevention*, 31(6), 601-610.

Reagan, I. J. & Brumbelow, M. L. (2015). Perceived discomfort glare from an adaptive driving beam headlight system compared with three low beam lighting configurations. *Procedia Manufacturing*, 3, 3214-3221.

Reddy, K. R. P. & Reddy, P. S. (2017). Safety against Head Light Glare. *Safety*, 6(6).

RoSPA (2021). Road Safety Factsheet: Vehicle Lighting. The Royal Society for the Prevention of Accidents, July 2021. Retrieved 12/02/2025 from: https://www.rospa.com/media/documents/road-safety/vehicle-lighting-factsheet.pdf

Sekuler, A.B., Bennett P.J. & Mamelak, M. (2000). Effects of aging on the useful field of view. Exp *Aging Research*, 26(2): p. 103-20.

Sepulveda, J. A., Wood, J. M., Anderson, A. J. & McKendrick, A. M. (2022). The effects of glare on the perception of visual motion as a function of age. *Translational Vision Science & Technology*, 11(9), 1-12.

Sewall A.A., Borzendowski S.A., Tyrrell R.A., Stephens B.R., Rosopa P.J (2016). Observers' Judgments of the Effects of Glare on Their Visual Acuity for High and Low Contrast Stimuli.

Perception, 45(7):755-67. doi: 10.1177/0301006616633591. Epub 2016 Feb 22. PMID: 26908566.

Shanmugaratnam S., Kass S.J. & Arruda J.E. (2010). Age differences in cognitive and psychomotor abilities and simulated driving. *Accident Analysis and Prevention*, 42(3), 802-808.

Sivak, M., Flannagan, M., Ensing, M. & Simmons, C. J. (1991). Discomfort glare is task dependent. *International Journal of Vehicle Design*, 12(2), 152–159.

Sullivan, J., & Flanagan, M. (2001). *Visual effects of blue tinted tungsten-halogen headlamp bulbs*. University of Michigan Transport Research Institute (Report number UMTRI -2001-9).

Taylor, J. E., Connolly, M. J., Brookland, R. & Samaranayaka, A. (2018). Understanding driving anxiety in older adults. Maturitas, 118, 51-55.

Theeuwes, J. & Alferdinck, J. W. (1996). *The Relation between and Driving Behavior Discomfort Glare* (No. DOT HS 8O8 452). United States. Department of Transportation. National Highway Traffic Safety Administration.

Thomas J. T. P., van den Berg, T. J., van Rijn, L. R., Kaper-Bongers, R., Vonhoff, D. J., Völker-Dieben, H. J., Grabner, G., ... & Coppens, J. E. (2009). Disability glare in the aging eye. Assessment and impact on driving. *Journal of Optometry*, 2(3), 112-118.

Van Den Berg T.J., Van Rijn L.J., Michael R., Heine C., Coeckelbergh T., Nischler C., Wilhelm H., Grabner G., Emesz M., Barraquer R.I., Coppens J.E. & Franssen L. (2007). Straylight effects with aging and lens extraction. *American Journal of Ophthalmology*, 144(3):358-363. doi: 10.1016/j.ajo.2007.05.037. Epub 2007 Jul 25. PMID: 17651678.

Viktorová, L., Mičková, K. & Stanke, L. (2022). Czech drivers' glare perception survey. *Sustainability*, 14(14), 8922.

Vivoda, J. M., Molnar, L. J., Eby, D. W., DiGuiseppi, C., Jones, V., Li, G., ... & Zanier, N. (2022). All are not created equal: Assessing initial driving self-regulation behaviors among older adults. *Journal of Transport & Health*, 24, 101310.

Weale RA. (1961) Retinal Illumination and Age. *Transactions of the Illuminating Engineering Society*. 26(2_IEStrans):95-100. doi:10.1177/147715356102600204

Weale, R. (1995). Why does the human visual system age in the way it does? *Experimental Eye Research*, 60(1), 49-55. doi:10.1016/s0014-4835(05)80083-1

Yang, J., Alshaikh, E., Yu, D., Kerwin, T., Rundus, C., Zhang, F., ... & Lu, Z. L. (2024). Visual function and driving performance under different lighting conditions in older drivers: preliminary results from an observational study. *JMIR Formative Research*, 8, e58465.

Zalcmanis, G., Punculis, R. & Vonda, E. (2019). Impact of the use of inappropriate HID lamps on illumination and dazzling. *Procedia Computer Science*, 149, 130-137.

Zhu, Y., Jiang, M. & Yamamoto, T. (2022). Analysis on the driving behavior of old drivers by driving recorder GPS trajectory data. *Asian Transport Studies*, 8, 100063.

Zhu, Y., Jiang, M. & Yamamoto, T. (2024a). Changes in older drivers' risky driving behavior over time: Insights from a naturalistic study. *Transportation Research Part F: Traffic Psychology and Behaviour*, 104, 318-333.

Zhu, Y., Jiang, M. & Yamamoto, T. (2024b). Does a cautious driving style reduce the crash risk of older drivers? An analysis using a novel driving style recognition method. *Transportation Research Part F: Traffic Psychology and Behaviour*, 104, 72-87.

Glare from vehicle lighting on UK roads: Literature Review

TRL
Unit 19, The Business Centre,
Molly Millars Lane
Wokingham, Berkshire, RG41 2QY,
United Kingdom
T: +44 (0) 1344 773131
E: enquiries@trl.co.uk
W: www.trl.co.uk

ISSN: 2514-9652

DOI: 10.58446/ftlv2870

PPR2072