NIGHT DRIVING AND ASSESSMENT OF MESOPIC VISION FOR OLDER ADULTS

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ABSTRACT

The crash risk associated with night-time driving is twice the daytime risk, when adjusted for distance travelled, while pedestrian fatality rates are up to seven times higher at night than in the day. Importantly, reduced visibility is a major contributor to these increased night-time risks, particularly for pedestrian-related crashes. For many older adults, driving at night is difficult due to age-related ocular changes which degrade mesopic vision, increase sensitivity to glare and cause delayed adaptation to rapidly changing light levels. Up to one-third of older drivers report vision-related night driving difficulties; however, there are no standardised and validated tests of visual function available for clinicians to base their advice to patients about their visual fitness to drive safely at night. This program of PhD research provides a unique and comprehensive assessment of the interrelationships between self-reported vision-related night driving difficulties, clinical tests of visual function, and closed-road night driving performance in the presence and absence of intermittent glare.

Study 1 involved an in-depth review of the vision and driving literature and previous vision-related quality of life questionnaires as a basis for developing a new night driving questionnaire. The questionnaire included items relating to demographic and night driving characteristics (7 items), general vision ratings (8 items), vision-related night driving difficulties (11 items), and a single open question about specific night driving difficulties. It was completed either in an online or paper format by 283 participants (50 to >80 years) who had concerns about their vision for night driving including difficulty with low-lighting conditions, glare from oncoming headlights, or adapting to changes in light levels when driving at night. The vision-related night driving difficulty items were analysed separately using Rasch analysis to form the vision and night driving questionnaire (VND-Q). Rasch analysis showed that the 9-item VND-Q was unidimensional, valid and reliable with excellent discriminant ability (person separation index 3.04; person reliability 0.90). Targeting was better for those with greater self-reported night driving difficulties. Participants with self-reported bilateral eye conditions and worse ratings on general vision items had significantly more night driving difficulties with the VND-Q than individuals without eye conditions (p=0.03) and with better ratings on the general vision items (p<0.001). Females reported more difficulties than males (p<0.001) and drove shorter distances at night per week which was also associated with greater difficulties (p<0.001). A repeatability coefficient (Rc) of 2.07 demonstrated excellent test-retest repeatability.

Study 2 examined the associations between VND-Q scores and a range of clinical visual function tests conducted under photopic, mesopic and glare conditions. Seventy-two older participants (65.1 ± 8.7 years) from the Study 1 sample who had provided their contact details and reported the greatest night driving difficulties (greater VND-Q scores), were recruited. Participants' VND-Q scores were significantly associated with poorer measures of visual function for the 72 older drivers, including photopic high contrast visual acuity (HCVA) (p=0.002), photopic low contrast visual acuity (LCVA) (p=0.011), Mesotest in the absence and presence of glare (p=0.001; p= 0.035, respectively) and halo area (p=0.001). Importantly, for a subgroup of 29 participants (65.0 ± 8.4 years) who had good photopic HCVA yet reported moderate to high night driving difficulties, assessment of mesopic CS and the Mesotest II (in the absence and presence of glare) varied significantly according to the level of self-reported difficulties (p=0.004; p=0.001; p=0.002, respectively). For this subgroup of participants photopic measures of visual function were not significantly associated with their level of self-reported difficulties (p=0.35 to 0.53), highlighting the importance of mesopic tests of visual function.

Study 3 involved a closed-road assessment of night driving performance in the absence and presence of intermittent glare, together with visual function tests, and questionnaires about driving habits and night driving difficulty incuding the VND-Q. Participants were recruited from the Study 2 sample and were a convenience sample of drivers who had previously reported the greatest levels of night driving difficulties. Twenty-six older drivers were tested (71.8 ± 6.3 years) and the cohort had a range of levels of visual function and self-reported vision-related night driving difficulty. Investigation of the effect of glare on driving performance revealed that intermittent glare caused an overall decrease in night driving performance (p=0.002) and had significant effects on the recognition of pedestrians wearing retro-reflective vests (p<0.001). The presence of intermittent glare resulted in a 38% decrease in pedestrian recognition. Drivers slowed down significantly in the presence of the intermittent glare (p=0.001) and this appeared to improve their avoidance of low contrast hazards, although the change in driving speed and improvement in performance was only slight. Night driving performance on recognition and hazard avoidance tasks was more strongly associated with outcomes of mesopic tests of visual function such as motion sensitivity (p=0.002), mesopic HCVA (p=0.002) and mesopic CS (p=0.014), than outcomes of photopic measures of visual function or glare based tests. Night driving performance was also significantly associated with self-reported VND-Q scores (p=0.005) providing support for the validity of the questionnaire developed in Study 1. Study 3 also provided evidence that the Mesotest II pass/fail criteria for night driving discriminates between drivers with better and poorer night driving performance (p = 0.018).

In summary, given that night driving is hazardous, the decision regarding whether to drive at night must be considered carefully by balancing safety implications against impacts on older drivers' independence and quality of life. This research adds to the evidence that the commonly used measurement of photopic HCVA is not optimal for assessing visual fitness to drive at night. Importantly, the outcomes of mesopic tests of visual function such as motion sensitivity and mesopic VA were more strongly associated with measures of night driving performance than photopic HCVA. A 9-item VND-Q was also significantly associated with closed-road night driving performance and shown to be valid for use in an older driver population to help quantify the level of visual difficulties that older drivers report at night. The outcomes of this research will help to guide future investigations regarding the standardised assessment of visual fitness to drive at night and advice that clinicians can provide patients to help ensure their safety and comfort on the road at night.

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LIST OF ABBREVIATIONS

ADVS	Activities of Daily Vision Scale
AMD	Age-related Macular Degeneration
CS	Contrast Sensitivity
DCS	Driving Comfort Scale
DGI	Disability Glare Index
DIF	Differential Item Functioning
GLMM	Generalised Linear Mixed Models
HCVA	High Contrast Visual Acuity
IOL	Intraocular Lens
LASIK	Laser-Assisted in Situ Keratomileusis
LCVA	Low Contrast Visual Acuity
LLQ	Low Luminance Questionnaire
LOA	Limits of Agreement
LogMAR	Logarithm of the Minimum Angle of Resolution
MLE	Maximum Likelihood Estimation
NEI-VFQ	National Eye Institute Visual Function Questionnaire
NHTSA	National Highway and Transport Safety Administration
PCA	Principal Component Analysis
PR	Person Reliability
PROMs	Patient Reported Outcome Measures
PSI	Person Separation Index
QoL	Quality of Life
SKILL	Smith-Kettlewell Institute Low Luminance
VA	Visual Acuity
VAQ	Visual Activities Questionnaire
VFI	Visual Function Index
VND-Q	Vision and Night Driving Questionnaire

STATEMENT OF ORIGINAL AUTHORSHIP

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

QUT Verified Signature

Signature:

Date: 24/10/2016

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Chapter 1. VISION AND NIGHT DRIVING - AN INTRODUCTION

Driving is important for older adults' independence and quality of life.[1,2] Night driving is one of the most demanding of all driving situations and can be particularly difficult for older adults due to age-related changes in vision which are often cited as the main reason for restricting or ceasing night-time driving.[3–6] Vision provides the majority of information relevant to the operation and guidance of a vehicle and is necessary to anticipate hazards and react quickly in response to changes in the road environment.[7] Importantly, poor visibility at night, rather than increased fatigue and alcohol use at night-time, has been shown to be the key factor responsible for the seven times greater pedestrian fatality rate, compared to day-time.[8] Visual factors are also believed to contribute to the overall two to four times greater risk of a fatal crash at night compared to day-time, when adjusted for distance travelled.[9,10]

Currently, the relationship between self-reported vision-related night driving difficulties, visual function, and driving safely at night is unclear, as there are no standardised and validated measures of visual function that can be used to predict fitness to drive at night. This is an important problem as age-related health concerns and preservation of quality of life are critical issues. These issues will become even more relevant over the next two decades as the average age of Australia's population is predicted to rapidly increase, similar to other developed countries.[11]

Approximately one-third of older adults self-report difficulties at night with their vision in dim lighting, glare, and when adapting to changing light levels, particularly in relation to night driving.[3,12] For example, older drivers report difficulties coping with oncoming headlight glare, reading road signs on poorly lit roads, and visually adjusting when travelling into and out of tunnels.[3–5,13,14] For the purpose of this thesis, these collective issues will be referred to as mesopic-related symptoms or vision-related night driving difficulties. Mesopic light levels refer to the luminance levels for night driving which occur in-between the almost complete darkness of scotopic conditions and the brighter daylight levels of photopic conditions.[15] It should also be noted that the studies included in this thesis differentiate between disability glare which specifically degrades vision, and discomfort glare which relates to the experience of discomfort but not necessarily functional impairment.[16]

There is evidence that patients are not always insightful regarding their visual limitations at night[17–19] or their driving abilities[20,21] but importantly, educating patients regarding their visual limitations has shown promise for assisting the regulation of safe driving practices.[22] However, there is a lack of evidence to support the use of techniques for eye-care practitioners to assess vision specifically for night driving and to determine the level of visual impairment that might impact upon night-time driving performance and safety. These factors make it difficult for health practitioners to provide advice on visual fitness to drive at night. Therefore the stimulus for this program of PhD research was the need to gather information regarding the interrelationships between self-reported vision-related night driving difficulties, clinical measurements of visual function, and actual night driving performance.

This research builds upon previous studies that have demonstrated that there are age-related changes in mesopic vision and disability glare,[23–25] and that these visual impairments impact upon night driving abilities.[14,17,26–29] This research is the first to examine older drivers who self-report vision-related night driving difficulties yet have clinically normal vision for their age, based on the results of photopic level vision assessments. The overarching aim was to determine how the outcomes from standard and non-standard clinical tests of visual function are associated with self-reported levels of vision-related night driving symptoms and subsequently how these measures relate to closed-road night-time driving performance.

In order to achieve the proposed objectives, a novel vision and night driving questionnaire was developed in Study 1 (Chapter 3) based on existing night driving literature, previous questionnaires about vision-related difficulties and a qualitative analysis of participants’ concerns about their vision for night driving.

Rasch analysis was used to develop the vision and night driving questionnaire content and assess its validity. Subsequent studies utilised the newly developed questionnaire to quantify vision-related night driving difficulties and to determine how self-reported difficulties corresponded to performance on standard and non-standard tests of visual function (Study 2, Chapter 4), and to actual closed-road night-time driving performance (Study 3, Chapter 5). This research provides an important step towards an improved understanding of the visual requirements necessary for safe night-time driving and how this might be best assessed in clinical and research settings.

Figure 1-1 illustrates the interrelationships that are separately analysed in the following chapters.

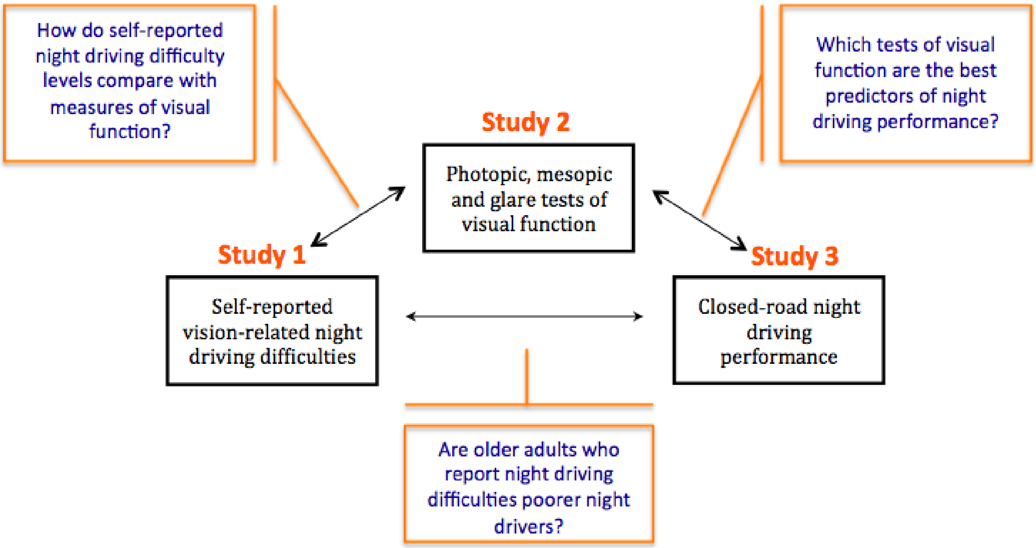


Figure 1-1: Concept map of the three phases showing interrelationships that were separately analysed throughout the PhD program.

Chapter 2 provides a comprehensive review of the literature on mesopic vision, vision-related night driving difficulties, and night driving. **Chapter 3** expands upon the literature review by reviewing the Rasch approach for developing patient reported outcome measures (PROMs) and subsequently applying this analysis technique in Study 1 for developing a vision and night driving difficulty questionnaire. **Chapter 4** extends the review of existing photopic, mesopic and disability glare-based tests of visual function and describes Study 2 which investigated the association between visual function test performance and self-reported vision-related night driving difficulties. **Chapter 5** outlines driving study designs and the known relationships between self-reported vision, night-time crash risks, driving performance, and visual function. The experimental component of Chapter 5 describes Study 3 which assessed the night-time driving ability of a cohort of older adults and examined the interrelationships between their self-reported driving difficulties, outcomes of visual function assessments, and driving performance as measured on a closed-road night time circuit, with and without intermittent glare. Finally, **Chapter 6** summarises the research findings and outlines recommendations and future investigations based upon these outcomes.

Chapter 2. LITERATURE REVIEW

2.1 PHOTOPIC, MESOPIC AND SCOTOPIC VISION

The ability of the human visual system to function across a wide range of light levels is primarily due to the dynamic range of the rod and cone photoreceptor systems and the ability to switch rapidly between the two.[30] The rod and cone photoreceptors have characteristic properties and post-receptoral pathways which function in different visual conditions (Figure 2-1). The cones are most densely packed at the fovea of the retina whereas the rods have maximal density in an elliptical zone 2-5 mm from the fovea and are most common in the peripheral retina.[31]

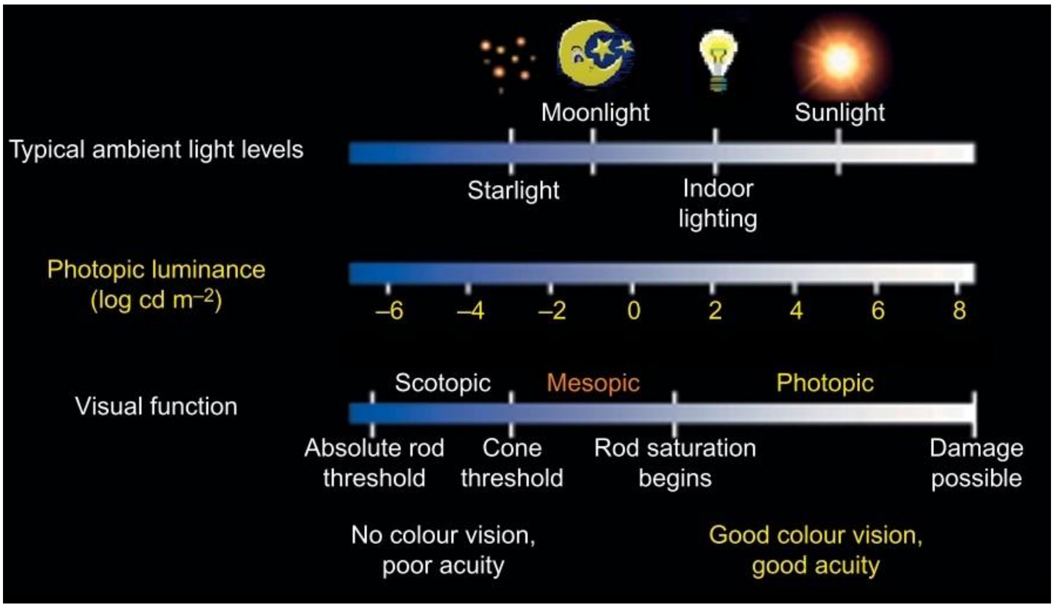


Figure 2-1: Light levels encountered in everyday life and their corresponding luminance and visual function classification. Adapted from Barbur & Stockman[15]

Fine spatial detail and superior colour vision are possible in photopic conditions (luminance greater than 3 cd/m^2) due to stimulation of the cone photoreceptors and their post-receptoral pathways. In scotopic conditions (luminance less than 0.001cd/m^2), when photon levels are low and hence spatial and temporal summation are critical, there is a switch to the rod system which, although more sensitive to the low luminance environment, responds more slowly, has poorer spatial resolution and limited colour perception.[15,32]

The light levels commonly encountered at night, such as when driving, are generally in the mesopic zone extending from 0.001-3cd/m^2 (Figure 2-1).[30,33,34] Mesopic luminance levels span between cone thresholds and the beginning of rod saturation, where both rod and cone photoreceptors contribute to vision and interact through shared neural pathways.[35] The spatial resolution, temporal responses and colour perception of the mesopic system lies in between that of the photopic and scotopic systems through the combination of the rods and cones working together.[36–38]

Mesopic luminous efficiency functions have been modelled using a combination of photopic and scotopic properties. However, rod-cone interactions and the vast differences between the rod and cone systems mean that mesopic visual sensitivity cannot simply be predicted by adding rod and cone responses.[30] The relative contributions of rods and cones and their post-receptoral pathways constantly fluctuates within the mesopic zone varying according to ambient light levels, spectral composition of available light, retinal eccentricity and adaptation state of the retina.[15,39] Furthermore, the impact of optical characteristics such as pupil size, aberrations, and ocular media on visual function also varies within the mesopic zone according to ambient light levels and the spectral composition of available light[15] which determine how much light is transmitted, reflected and scattered within the eye.

2.2 OPTICAL AND NEURAL INFLUENCES ON MESOPIC VISION AND EFFECTS OF AGEING

Mesopic visual function is not only dependent on the interrelations between rods, cones and their post-receptoral neural pathways, but also the optical components of the eye which alter the amount of light transmitted to the retina and the amount of scattered light that can mask the retinal image.[15] The normal ageing process and age-related ocular diseases can affect both the optical and neural components of the eye which can result in visual difficulties, particularly under low luminance and glare conditions.[24,40–42] The following sections describe how the optical and neural components of the eye affect mesopic vision and the impact of the ageing process on visual function.

2.2.1 Pupil size

Pupil size affects retinal illuminance, depth of focus, diffraction and higher order aberrations.[15] Pupil diameter typically varies from approximately 2mm in photopic conditions, increasing in size with decreasing light levels, up to approximately 8mm in scotopic conditions.[15] The dilated pupil in mesopic conditions partially compensates for the reduction in ambient luminance but may also result in reduced vision due to greater effects of refractive defocus and increased higher order aberrations, particularly spherical aberrations.[15] The natural pupil size adopted at a given light level has, however, been shown to optimise the balance between retinal illumination and optical aberrations and this optimisation appears to be evident even for older adults.[37,43]

The diameter of the pupil reduces gradually with increasing age, undergoing what is referred to as senile miosis.[44] Senile miosis reduces retinal illuminance but optical aberrations and concurrent crystalline lens changes (such as cataract), as well as other media opacities in the cornea and vitreous, must also be considered when determining the overall effects of pupil size on mesopic vision. For example when dense nuclear cataracts are present, a larger pupil size in low luminance conditions might be a relative advantage because of the additional area through which light can pass and the subsequent increase in retinal illuminance.[15] However, when cortical cataracts are present, a larger pupil size may result in greater straylight and haziness of vision under low luminance conditions.[15] The relationship between pupil size and mesopic vision is therefore complex and differs between individuals because characteristics of the media may not be homogenous across the pupil area.

When considering glare difficulties which primarily result from scattered light and hence glare within the eye, pupil size is not a determining factor.[45,46] This is because the pupil contracts under the photopic conditions created by glare sources thus contributing less to the amount of scattered light within the eye. Factors which are important for determining the amount of scattered light within the eye include translucency of the iris and sclera, media opacities and pigmentation of the fundus.[45,47,48] These ocular characteristics will be covered in section 2.2.3 which discusses the link between ocular media and glare in detail.

Populations that can have mesopic-related difficulties associated with pupil size, include those who have photorefractive surgery or intraocular lens implantation.[49–51] Larger pupil size has been shown to predict greater visual problems under mesopic conditions for LASIK (Laser-Assisted in Situ Keratomileusis) patients, although investigations show that pupil size is relevant in the early post-operative period but has no significant association with night vision symptoms six to twelve months following surgery.[49,50] For intraocular lens surgery, pre-operative pupil size predicts the likelihood of self-reported haloes and glare difficulties post-surgery, as these vary according to the difference between scotopic pupil size and the phakic intraocular lens optical zone.[51]

2.2.2 Optical defocus and higher order aberrations

Optical defocus and higher order aberrations play an important role in mesopic-related symptoms and reduced mesopic visual function. Retinal image quality decreases for larger pupil diameters and there is a greater range of wavefront aberration (Rms µm) levels for larger pupil diameters. This suggests that some individuals are likely to be more susceptible to visual difficulties from aberrations in low-light conditions than others, irrespective of pupil size.[15]

Increasing age also tends to increase higher order ocular aberrations and reduce visual quality.[15,52] Furthermore, the use of multifocal lenses including bifocal, trifocal and progressive addition lenses increases with age.[53] These corrections also increase blur and aberrations dependent on how a person coordinates their eye and head movements to look through the most appropriate portion of the lens.[54] In addition, the multifocal design itself can be problematic, where multifocal contact lens and intraocular lenses (IOL) have also been shown to cause glare and halo difficulties for older adults.[55–57]

Mesopic vision difficulties due to defocus and aberrations are particularly common for patients who have had LASIK surgery.[58–60] LASIK can almost double higher order aberrations for a 6.5mm pupil diameter,[61] although the incidence of mesopic vision difficulties decreases considerably in the first year following surgery. Approximately 25% of patients report mesopic vision difficulties at 1 month compared to only 5% of patients twelve months after surgery.[62] Post-surgical residual optical blur has been identified as a factor that relates to lower subjective ratings of vision in mesopic conditions[63] and the amount of correction and treated optical zone diameter also predict mesopic vision outcomes following LASIK surgery.[62]

2.2.3 Media opacities and intraocular straylight

Light scattered within the eye, referred to as intraocular straylight, is one of the most important reasons for glare difficulties, such as those experienced from oncoming vehicle headlights when driving at night.[16] The straylight within the eye can be considered as an equivalent veiling luminance or an additional background light against which the retinal image must be distinguished.[47] The veiling luminance from straylight varies depending on the intensity of the glare source and its angle of incidence at the eye, being greater for brighter light sources and wide oblique angles of incidence.[16]

Straylight and glare difficulties vary between individuals according to the optical integrity of the ocular media including effects from the cornea, vitreous and crystalline lens.[45,47,48] Corneal oedema, corneal dystrophies, refractive surgery or turbidity within the vitreous humour all increase overall intraocular straylight.[47,48] Furthermore, the total amount of straylight within the eye is pigmentation dependent, whereby the pigmentation of the iris and sclera determine the translucency of the front surface of the eye and subsequently the amount of straylight entering the eye from outside the pupil zone.[45] It is for this reason that people with lightly pigmented eyes are suggested to experience greater glare difficulties, although no studies have confirmed this hypothesis.[64] In addition, not all of the light reaching the retina is absorbed and there is greater reflectance of straylight into the eye from the fundus of individuals who have less pigmentation.[46] Non-ocular factors such as contact lens surface impurities and dirty windscreens or spectacle lenses also create external sources of straylight which can contribute to overall glare difficulties.[65]

Age-related changes to the crystalline lens, including cataracts, are the most common cause of straylight within the eye.[16] However, the extent that a cataract will degrade vision in the presence of glare, cannot always be easily predicted from slit-lamp grading of the type and extent of cataract, given that light scattered back to the examiner is not necessarily an accurate reflection of scattered light reaching the retina.[66,67]

Straylight has been found to double by age 65 and triple by age 77 compared to that found in young healthy eyes of those aged 20-30 years.[68] One study reported that 75% of drivers older than 70 years of age could not discriminate any level of contrast against a mesopic 0.1cd/m^2 background in the presence of a glare source (Figure 2-2), presumably due to the age-related effects of straylight.[24] Importantly, straylight and photopic high contrast visual acuity (HCVA) are relatively independent of each other,[48] providing evidence that standard HCVA assessments fail to reveal the full extent of glare difficulties experienced such as those occurring with oncoming headlights at night.

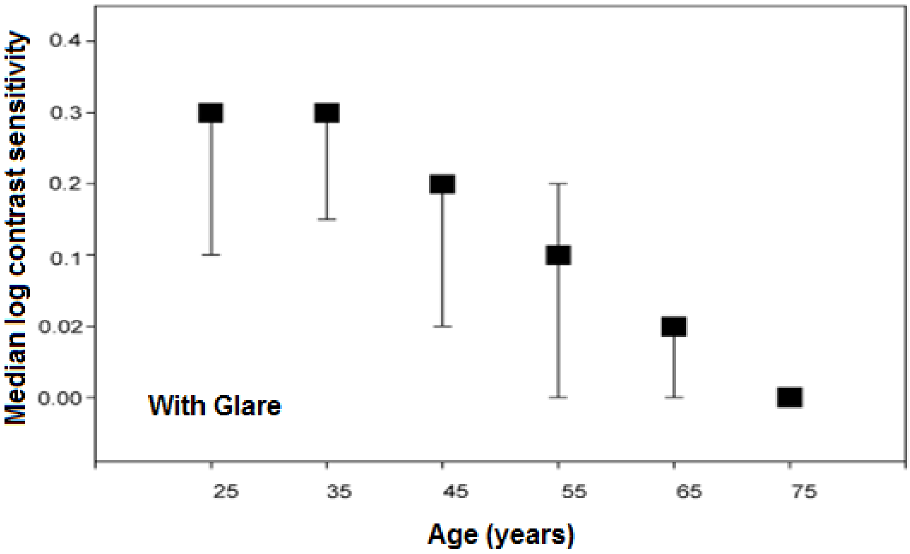


Figure 2-2: Median (inter-quartile range) mesopic contrast sensitivity values as a function of age group in the presence of glare. Vertical bars represent upper and lower quartiles. Source: Puell et al.[24]

2.2.4 Neural degeneration

The operation of both rods and cones under mesopic conditions means that there is greater retinal demand for blood flow and oxygen due to increases in cellular functioning (both rods and cones must function and interact) and the high metabolic requirements of rods compared to the cones.[69–71] These greater retinal requirements are likely to exacerbate neural and other cellular based visual deficits at mesopic light levels. For example, individuals with glaucoma,[42,72] diabetes,[73,74] and age-related macular degeneration (AMD),[13,69,75] all demonstrate specific reductions in mesopic visual function.

In diabetes, patients with retinopathy commonly report vision-related night driving difficulties[76,77] and up to 20% of patients with diabetes have significantly lowered absolute scotopic visual thresholds, taking up to three times longer than normal to recover from a bleaching light.[73] In glaucoma, contrast adaptation deficits have been shown to affect visual discrimination, particularly at low contrast levels.[72] Mesopic-related symptoms have been shown to be potential early signs of AMD[13,78] and mesopic vision has been shown to be reduced in individuals that have a genetic risk of developing AMD but have not yet manifested the condition.[69] In addition, recent evidence demonstrates that individuals with poor mesopic VA are significantly more likely to develop early AMD within three years of diagnosis of impaired mesopic vison.[79]

Even in the absence of retinal disease, there are a number of well documented neural changes that result in poorer mesopic vision and are considered part of the normal ageing process of the eye. Loss of rod photoreceptors, ganglion cells, and changes to photopigment regenerative capacity play a significant role in the age-related reduction of increment light sensitivity and contrast sensitivity, as well as slowed photostress recovery.[40] These neural changes often occur concurrently with age-related lens and other ocular media changes making it difficult to differentiate between optical and neural causes of visual symptoms.[80] However, contrast sensitivity measurements, using methods that bypass the optics of the eye, have indicated that the basis of age-related visual function losses are, in part, driven by age-related neural changes.[81]

In summary, the shift from photopic to mesopic viewing conditions is accompanied by changes in the visual system at multiple levels, from optics to receptor to cortex, and age-related degenerations can impact at each of these levels. Accordingly, complaints of mesopic-related visual difficulties are commonly reported,[13,82] particularly by older patients,[40] and it is therefore important to have evidence-based methods for assessing mesopic visual function and self-reported visual difficulties in mesopic conditions, such as in the night driving environment.

2.3 VISUAL DIFFICULTIES IN MESOPIC ENVIRONMENTS

Commonly reported visual difficulties in mesopic conditions include problems reading in dim light, walking down steps in poorly lit environments, and adjusting to lighting levels when moving between environments with differing ambient luminance levels.[13,83] The most prevalent concerns about mesopic vision, however, are related to driving at night.[3,12,84] These include difficulty driving on poorly lit roads at night,[13] recovering after exposure to bright headlights,[85] and problems with oncoming or tailing headlights at night, which is probably the most common night driving concern.[40,65]

About one third of older adults (>50 years) report having difficulties with night driving,[3,12,84] and 20-56% of older drivers either avoid or cease night driving, many citing visual difficulties as the reason.[3,21] A National Highway Traffic Safety Administration (NHTSA) survey regarding headlight glare received over 5000 complaints related to discomfort and disability from headlight glare, with 37% of respondents in the 55 to 64 year old group rating glare as disturbing.[86] The high prevalence of vision-related night driving difficulties is concerning given that night driving is hazardous even for those drivers who do not have visual deficits.[87,88]

Importantly, the level of patients' self-reported difficulties is associated with their decisions to self-restrict or avoid driving at night[3–6] therefore, measures of visual function that best reflect patients' own perceptions of their difficulties may be useful for predicting or advising driving behaviours. There is evidence that older drivers who avoid night–time driving also have reduced visual function on tests such as photopic LCVA, photopic CS and the Mesotest II (in the presence and absence of glare).[6,24] However, further investigation of a wide range of mesopic and glare-based tests of visual function is necessary in order to determine which clinically viable tests would be the most useful for assessing patients who report night driving difficulties.

Drivers are known to under-estimate visibility at night-time in the presence and absence of glare,[17,89,90] and do not necessarily have insight into their own driving abilities.[20,21] There are also practical barriers to driving self-restriction incuding lifestyle needs, the need to drive for others, and lack of access to public transport.[21] Older male drivers, in particular, have shown reluctance to restrict their driving as it has been suggested that their driving capability is an important part of their self-identity and they are more likely to undertake risky behaviour than females.[91] Thus, despite the encouraging associations between drivers' self-reported vision and measures of visual function, further examination of exactly how closely drivers' self-reported levels of difficulties are related to their night driving performance is also necessary using a well validated questionnaire designed specifically for night-time driving.

The use of validated questionnaires, referred to as patient-reported outcome measures (PROMs), is becoming increasingly important to support clinical decision making, as these measures capture perceptions from the patients regarding functional ability and quality of life information, such as effects of difficulties or disease on physical, social and emotional wellbeing.[92] For example, PROMs relating to self-reported visual difficulties are used to guide referrals for cataract surgery[93] and to quantify changes in vision-related quality of life following interventions such as refractive [50,94] and cataract surgery.[95,96]

In the field of vision research, PROMs have been used successfully as vision-related quality of life instruments in the areas of low vision,[97] cataract surgery,[98] glaucoma,[83,99,100] AMD,[13] and various ophthalmic treatment trials.[101–106] The first vision-related quality of life PROMs were developed in the early 1980s and since then many PROMs have been developed, adapted and re-analysed using modern statistical techniques.[92] A total of one hundred and twenty-one vision-related quality of life PROMs have been identified, of which forty-eight are considered to have suitable measurement properties according to current criterion for vision-related PROMs analysis.[107] Therefore, it is evident that there are a large number of validated visual function questionnaires available to help quantify self-reported visual difficulties and impacts of visual difficulties on quality of life. However those available, such as the National Eye Institute Visual Function Questionnaire (NEI-VFQ-25),[108] Activities of Daily Vision Scale (ADVS),[98] Visual Function Index (VFI),[109] Visual Activities Questionnaire (VAQ),[110] and CatQuest questionnaire (CatQuest-9SF)[111] contain few items pertaining to mesopic-related symptoms or specific night driving difficulties.

The only available low luminance questionnaire, the LLQ,[13] contains several items for investigating night driving difficulties but also includes a wide range of more general activity limitations such as difficulty moving around in darkened movie theatres and difficulty attending night-time social events. There were only a small number of older visually normal subjects included in the focus group (n=9) on which the original survey was based, whereas there were a larger number of individuals with ocular pathology such as AMD (n=62), because the LLQ was designed to specifically reflect the night vision concerns of individuals with AMD rather than those of visually normal older adults. A group of 41 older adults without eye disease reported relatively little difficulty with vision under low light levels as assessed by the LLQ[13] which does not support other evidence describing the significant night vision concerns of older individuals, particularly the prevalent concerns associated with night driving.[3,12] It is likely that many individuals with eye disease restrict their driving at night due to their visual difficulties[112] thus express greater concerns about other activities that they engage in more often. Therefore, there is a need for a questionnaire targeted for a general population of older adults specifically including drivers without eye disease. Chapter 3 will provide a more complete review of currently available visual function questionnaires and explores the development of a questionnaire for the reporting of older drivers' vision-related night driving difficulties.

2.4 EVALUATION OF MESOPIC VISION IN RELATION TO SELF-REPORTED NIGHT DRIVING DIFFICULTIES AND NIGHT DRIVING PERFORMANCE

A standard clinical eye examination typically involves assessment of visual function under photopic light levels. However, this does not necessarily reflect visual function under other lighting conditions such as the low luminance and glare conditions typical of the night driving environment.[23,43,113,114] Furthermore, standard clinical testing commonly includes HCVA as the only measure of visual function.

An assessment of HCVA provides information about the resolution capacity of the visual system, yet is a poor indicator of overall quality of vision and does not provide adequate information about complex real-world environments such as those encountered when driving at night.[115,116] In particular, with the shift from photopic to mesopic conditions, there is also a reduction in contrast sensitivity (CS) which is the ability to discern between objects of different contrast levels and their background and is not captured by measurement of HCVA.[117] In the night driving environment, CS is particularly relevant because drivers are required to perform tasks such as detecting low contrast, darkly clad pedestrians against the night sky or dark roadway or, finding a turn-off into a poorly lit street or driveway.

Numerous studies conducted over the last 10 years have demonstrated the advantages of, and advocated the use of, non-standard vision tests, particularly those conducted in mesopic and glare conditions, to represent visual function across a range of light levels.[35,41,113,118–123] It is not currently known which tests of visual function best reflect the self-reported night driving difficulties of older adults or which tests are most predictive of measures of actual night driving performance. However, measurements of VA conducted using low contrast letters (LCVA) have been shown to improve upon the standard assessment of HCVA, where it has been demonstrated that LCVA is more sensitive to age-related media opacities than HCVA,[23] particularly when tested in the presence of glare.[66] The self-restriction of night-time driving is also more strongly associated with reductions in LCVA than HCVA, particularly for female drivers who tend to restrict their night driving at an earlier age than male drivers.[6]

The assessment of VA under mesopic conditions also provides additional information to photopic VA, where mesopic conditions show an age-related decline about a decade earlier than photopic conditions.[23] Importantly, mesopic VA is valuable for predicting closed-road driving recognition performance when assessed in conjunction with photopic HCVA.[26] Similar to mesopic HCVA, CS measured under photopic conditions aids in the prediction of night-time driving performance,[26] and like photopic LCVA, it is also more strongly associated with self-restriction of night time driving than HCVA, especially in male drivers.[6]

Measurement of CS under mesopic conditions is proposed to be particularly sensitive to the optical changes associated with age[118] and intraocular lens surgery,[124] and also demonstrates potential for the evaluation of retinal diseases including glaucoma,[42,113] diabetic eye disease[125] and AMD.[75] Mesopic CS is associated with older drivers' avoidance of night driving[24] and two studies have demonstrated links between poorer mesopic CS in the presence and absence of glare and increased crash risk at night.[29,126] Critically, it has been demonstrated that mesopic CS can be impaired even if photopic CS is normal.[113]

Mesopic visual function can be assessed using VA or CS charts with either neutral density filters or dimmable light sources.[15,118] However, there are limited normative data available for testing with vision charts under mesopic conditions.[23,25,113,121] Furthermore, the lighting levels required for testing have not been standardised,[121] and a 5-10 minute period of visual adaptation is necessary,[114,118,120,121,127] which is a disadvantage for clinical use compared to tests conducted in photopic conditions. For disability glare, chart-based tests can be used, such as the Brightness Acuity Test with the Pelli-Robson CS chart, or the Berkeley glare test which uses a near acuity chart mounted on a light box to generate a diffuse glare source. Another option is to use a Halometer which provides a measurement of halo size in order to determine the detrimental visual effects of glare from a point light source.[128,129] These tests and other mesopic and glare-based tests of visual function will be examined in greater detail as part of Chapter 4 which investigates night driving difficulties and the assessment of visual function.

One mesopic test utilised in both Study 2 and Study 3 (Chapters 4 and 5) is the Mesotest II, which assesses CS under built-in mesopic background luminances, either in the absence ($0.032 cd/m^2$) or presence of a glare source ($0.1 cd/m^2$).[65] This test has been adopted in several European countries for assessing visual fitness to drive at night, including Germany, France, and Spain.[119,130] The testing of mesopic vision for driving at night in these countries is recommended for a private vehicle licence, but is not routinely tested except for those drivers applying for a heavy vehicle, taxi or bus licence.[113,130,131] The German Ophthalmological Society's vision standard for a private vehicle licence is a pass on level 1 both in the presence and absence of glare; level 2 for a heavy vehicle licence; and level 3 for a bus licence.[131] Prior to July 2011, the pass level for a private vehicle licence was level 2 (one level more difficult) in the presence and absence of glare,[24,132,133] however, the standard was revised to accommodate improvements in road lighting that have occurred over time.[113] There have been no on-road studies to validate the new standard and only one study provides evidence that there was a greater crash risk for those drivers failing the previous Mesotest II (level 2) than those who passed the recommended level.[29]

It is likely that visual function tests conducted under conditions that more closely reflect the environmental conditions of night driving, would be more strongly associated with patients' self-reported night driving difficulties and actual driving performance. However, there is an important gap in the literature in terms of the relationship between non-standard mesopic and glare based assessments and fitness to drive at night. Thus, clinicians do not currently have an evidence-based guide for assessing their patients' visual capacity for safe night driving.

In the absence of evidence-based advice from their eye-care professionals, patients are likely to self-select whether or not to drive at night. This self-regulation of night driving can be problematic as drivers are known to poorly estimate their visual difficulties,[17–19] and to regulate their driving habits based more on confidence than actual driving abilities.[134] It is therefore important that measures of visual function are investigated for their capacity to predict night driving performance, with it being likely that the most valuable tests for this purpose will be those that simulate the visual conditions under which drivers have most difficulties at night. Testing at mesopic light levels might be particularly important if patients have symptoms but no obvious pathological causes and no detectable vision losses found using standard photopic vision tests.

2.5 RISKS OF NIGHT DRIVING AND EFFECTS OF GLARE ON DRIVING PERFORMANCE

As discussed in Chapter 1, night driving is one of the most challenging driving situations and can be particularly difficult for older adults due to age-related changes in vision which are often cited as the reason for restricting or ceasing night-time driving.[3–6] The greater risk of overall fatal crashes (including vehicles as well as pedestrians and other vulnerable road users) at night compared to day-time (adjusted for distance travelled)[9,10] is related to visibility, as evidenced by the finding that the installation of brighter street lighting reduced fatal injury crash rates by 65% and injury only crashes by 30%.[135] Poor visibility is also the primary reason for greater pedestrian fatality rates at night compared to day-time.[8] A study examining unlit rural roads at night reported a three to seven times increase in pedestrian fatalities accompanying the darker seasonal roadway conditions.[8] Even slight changes in ambient illumination can affect pedestrian collision rates; it has been shown that pedestrian fatalities are 20% lower on nights with a full moon compared to those without moonlight.[136] While the reasons for motor vehicle crashes and pedestrian collisions at night are multi-factorial, it is clear that adequate visual function is a key factor.[137,138]

The low luminance levels at night have been shown to degrade some aspects of driving performance more than others. Simulator studies have shown that visual guidance, as measured by steering accuracy, is relatively unimpaired by low luminance conditions or blur, whilst focal visual functions, such as VA, are negatively affected by both low luminance and blur.[139,140] Conversely, steering accuracy is affected by a reduction in visual field extent, whereas VA is not affected to any great degree.[139,140] Closed-road studies also concur with these findings showing that lane-keeping is relatively preserved under night-time conditions, whereas recognition of low contrast objects, pedestrians, and signs are greatly impaired.[17,26,141]

The above findings support the selective degradation hypothesis which proposed two visual processing systems for night driving.[142] One system, referred to as the "focal" system, was considered a function of the central retina and dedicated to visual tasks such as identification and form perception.[142] The other system, known as the "ambient" system, was considered a function of the peripheral retina and facilitates visual guidance and spatial orientation.[142] The relative preservation of the "ambient" system at night has been suggested as the reason why many drivers are unaware of the inherent visual limitations associated with driving at night.[142] Visual guidance under low luminance is maintained to a greater extent in younger than older drivers, and has been proposed as a reason why younger drivers may be overconfident when driving at night compared to older drivers who tend to approach night driving with more caution.[17]

Surprisingly little research has been conducted about the effects of headlight glare on driving performance at night. Thus it is unclear whether glare causes significant reductions in real-world driving performance that could compromise a driver's safety and that of other vulnerable road users. For individuals who report having night-time driving difficulty or who have reduced visual function, the effects of glare on night driving performance might be expected to be even more detrimental than for the general population. It is therefore important that investigations regarding the effect of glare on night driving performance are examined in drivers who report night driving difficulties for whom the greatest and most serious effects of glare are likely to occur.

For individuals who do not have specific reductions in visual function or self-reported vision-related night driving difficulties, it has been shown that glare decreases pedestrian recognition distances,[18,137,143] and this effect varies according to pedestrian clothing.[138,144] Disability glare causes reduced CS due to the veiling scattered light that masks the retinal image.[145] Therefore its effects are most disabling for low contrast objects such as darkly clad pedestrians at night.[137] It is estimated that glare can reduce the CS required for the detection of moving objects at night by a factor of six.[146] The effect of glare on driving performance is complex however, because compensatory responses to discomfort glare, even from low illuminance glare sources, can cause impaired vision from squinting, tearing, light aversion and distraction.[143]

In low luminance and glare conditions, reaction times to visual targets have also been shown to be slower,[122,147,148] resulting in delayed responses to hazards and signs and subsequently longer stopping distances and potentially hazardous situations.[122,147] Motion sensitivity of low contrast targets is poorer under low luminance, particularly in the presence of glare or lens opacities,[146] and this may mean that the ability to detect the presence of movement from pedestrians or cyclists is reduced at night, especially for older drivers. A test of motion sensitivity has been shown as the strongest predictor of pedestrian recognition at night[27] and is significantly associated with the detection of hazards using the Hazard Perception Test.[149]

Other tests of visual function that demonstrate associations with closed-road night driving performance include photopic CS and mesopic VA,[26] although the relationship between visual function and night driving performance requires further investigation. This is an important limitation in the literature because it is clear that a single measure of photopic HCVA is not the optimal predictor of night driving performance.[26,27,138] Evidence of significant links between visual function and night driving performance is required as a basis for advice to drivers regarding their capacity for safe night driving and on which to base visual standards for safe night driving.

Older drivers are at greater risk of a fatal motor vehicle crash per distance driven at night compared to drivers of all other ages, except those under 25 years who have very high fatality rates at night due to alcohol consumption and risky driving behaviour.[86,146] One study has also demonstrated that drivers with poorer Mesotest CS, which is more likely to occur with ageing,[24] are less safe drivers and more likely to be involved in a night-time crash.[29,126] The night driving performance of older drivers has also been shown to be poorer than their younger counterparts where they detect fewer road signs,[17] and recognise pedestrians at shorter distances than do younger drivers.[27] Their ability to detect pedestrians in the presence of glare is also poorer than younger drivers.[137,143] Furthermore, evidence from night driving simulator studies suggests that older drivers have less accurate steering ability and lane-keeping compared to younger drivers.[139,152] They also have less effective scanning behaviours, focusing on a smaller area of the visual field and requiring longer fixations, when viewing night-time road scenes in a driving simulator.[152] While it is clear that the declines in vision-related driving abilities that occur at night are exaggerated with increasing age, there are very few studies addressing vision and night-time driving safety in older drivers. Thus further research is necessary to completely understand the contribution of vision to older individuals risks when driving night.

It has been suggested that older drivers may partially compensate for their visual limitations by driving slower at night[17] and a large proportion of older drivers limit their night-time driving, particularly females (Figure 2-3).[3–5] As previously mentioned, visual factors have been shown to be associated with the decision to restrict or avoid driving at night, and those who restrict their night driving are more likely to have reduced levels of visual function, including high and low contrast VA, mesopic VA, and CS.[6,153] However, self-regulation of night driving is not ideal because drivers often overestimate their driving ability and self-regulate their driving based on confidence levels rather than true ability.[6,154]

Some drivers may self-regulate too soon[155,156] which can also be problematic because restricting or avoiding driving at night has a negative effect on quality of life, as well as maintenance of mobility and independence.[1,2]

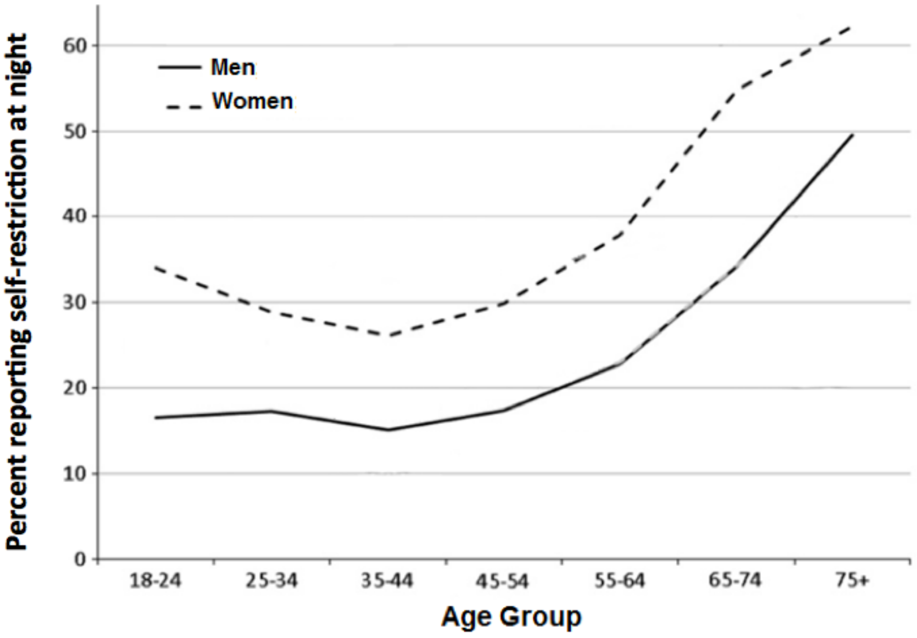


Figure 2-3: Self-reported driving restrictions by age and gender. Source: adapted from Naumann R. Dellinger A. & Kesnow M.[3]

Overall, the evidence demonstrates that self-regulation of night driving is likely to be insufficient to maintain driving safety at night, given that self-ratings of vision under low-luminance and glare are influenced by multiple factors which do not always relate to true disability. The regulation of fitness to drive at night requires objective and evidence-based approaches rather than the current system which relies on drivers' own judgements of their ability to drive safely at night.

2.6 CONCLUSIONS

Ideally, eye-care professionals should be able to investigate any symptoms reported by patients and assess any aspects of visual function that potentially impact on quality of life and safety, although practical constraints such as time and usability of tests needs to be considered. Currently, there is no evidence-based visual function test battery available to assess mesopic-related symptoms, including difficulties seeing in low light, difficulties adapting to changes in light levels, or problems with glare. The literature provides clear evidence that these types of difficulties are common concerns in relation to night driving, yet there is no guide for assessing fitness to drive at night.

Standard photopic vision tests have been shown to be less than optimal for assessing visual difficulties that are apparent under conditions of low luminance and glare at night, such as when driving. Additionally, there is insufficient evidence investigating whether self-reported vision-related night driving difficulties predict poorer night driving performance and increase the risk of motor vehicle crashes at night. Vision-related night driving difficulties are common concerns of older people with potentially serious safety implications, therefore it is important to examine the relationships between self-reported night driving difficulties, clinical vision tests, and night driving performance to address this issue and to guide advice to patients about their visual fitness to drive at night.

Chapter 3. STUDY 1 - QUESTIONNAIRE AND RASCH ANALYSIS: VISUAL DIFFICULTIES OF OLDER DRIVERS AT NIGHT

3.1 INTRODUCTION

Driving at night is perceived to be one of the most challenging driving situations, with visual factors being considered to be largely responsible, especially for older drivers.[6,17,153] Vision-related problems when driving at night, such as disability related to glare from oncoming headlights and difficulty reading road signs at night,[3–5,13] are reported by around one third of drivers aged 50 years or older.[3,12] Furthermore, the proportion of drivers with night driving difficulties rises considerably in the presence of ocular diseases, such as cataracts.[84] The number of drivers who avoid driving at night increases significantly with age, with self-reported and clinically measured reductions in visual function associated with the self-restriction and cessation of night-time driving.[3–6]

Driving is important for maintaining older adults' independence and quality of life.[1,2] Therefore decisions regarding an older driver's capacity to drive at night must consider the balance between restricting night driving due to safety concerns and maintaining mobility and independence where possible. Assessments of visual function reveal the presence of performance deficits and changes but fail to provide insight into the effect that visual impairment or symptoms may have on activities of daily living and quality of life such as mobility, independence and future health. PROMs are necessary to provide clinicians and researchers with information about difficulties with tasks, restriction and avoidance of activities and patient concerns, in a standardised and validated manner.[92]

There are a range of general vision-related quality-of-life (QOL) PROMs, such as the 25-item National Eye Institute Visual Function Questionnaire (NEI-VFQ-25),[108] Activities of Daily Vision Scale (ADVS),[98] Visual Function Index (VFI),[109] Visual Activities Questionnaire (VAQ),[110] and CatQuest questionnaire (CatQuest-9SF).[111]

However, these provide limited or no information about night driving difficulties and are often designed for individuals with particular visual impairments. For example, the Low Luminance Questionnaire (LLQ)[13] is a comprehensive low-light vision questionnaire which includes several night driving items, yet it was designed for patients with AMD and therefore is not targeted for the general older driving population who are likely to have better visual function. The Night Driving Comfort scale (DCS)[157] was designed for a general older driving population, but includes items that relate to a range of physical, cognitive and sensory factors that are not specific to vision.

The validity and reliability of questionnaires has previously been assessed using classical psychometric approaches, where responses are summed according to the underlying assumption that all questions have linearly spaced response categories and are of equal difficulty.[158] For example, in a night driving questionnaire this would mean that ratings of difficulty in driving in poor weather and driving in clear weather would have equal weighting within the overall score. The difference between response categories would also be assumed to be equal across the scale of responses i.e. the magnitude of the difference between the response categories of ‘no difficulty’ and ‘a little difficulty’ would equate to the difference between the categories of ‘a little difficulty’ and ‘moderate difficulty’ and so forth. This approach is limited as the assumptions of equal difficulty items and equal spacing between response categories is not necessarily valid. Many recent PROM tools incorporate the advantages of using Item Response Theory, such as Rasch analysis,[13,111,157,159–161] which eliminates the item and category spacing assumptions of classical test theory, and also allows for missing data through computed Rasch model responses.[111,160,162–164]

Given the lack of PROMs that specifically assess visual difficulties when driving at night for older adults in general, this study aimed to develop and evaluate a PROM using Rasch analysis for a large sample of older drivers who reported concerns about their vision for night driving. Development of the vision and night driving questionnaire (VND-Q) involved item selection and pilot testing, followed by Rasch analysis to optimise the psychometric properties.[162] This chapter describes the use of Rasch analysis for the design of PROMs and provides a comprehensive review of existing questionnaire items that relate to vision and night driving.

3.1.1 Rasch Analysis and Patient-Reported Outcome Measures

In developing a PROM, it is important to minimise respondent subjectivity by using rigorously tested questions and providing clear instructions. These questions, or items, may be derived from existing questionnaires, item banks or from focus groups and interviews with patients and clinicians.[13,165] Irrespective of their origin, items must use clear and appropriate terminology, be unambiguous and relevant to the intended population.[166] A PROM can range from a response to a single question, which might include whether a patient is satisfied with a treatment outcome, or can comprise a comprehensive instrument including numerous questions with multiple response categories and several subscales with a sophisticated scoring system.[167]

The response to multiple PROM items enables an overall summary measure to be calculated based on patients' subjective opinions in view of their own circumstances and personal experiences.[165] PROM items may assess patients' level of difficulty with a specific task, for example, one of the items in the ADVS asks "how difficult do oncoming headlights or street lights make driving at night for you?".[98] Items may also ask about the frequency with which a patient experiences a problem as in the NEI-VFQ item "How much of the time do you worry about your eyesight?".[108] The level of agreement with a particular statement can also be asked, such as "I don't go out of my home alone, because of my eyesight"[168]; or, patients may be required to rate differences between symptom severity and frequency in different situations such as difficulty driving at night, in the rain, or in clear conditions as in the ADVS. Furthermore, questions can include patients' assessments of changes in symptoms before and after an intervention, for example, rating glare difficulties pre- and post intraocular lens implantation.[169]

In Rasch analysis, a probability-based model is used to determine an overall score for each respondent with respect to the underlying variable of interest, known as the latent trait.[166] A single underlying trait or unidimensionality is an important requirement for the Rasch model and is confirmed by assessment of Rasch fit parameters. Where multidimensionality is present, the use of sub-dimensions or subscales is necessary to distinguish between multiple latent traits. Another important feature is the inclusion of a range of question difficulties, which is necessary to not only ensure the latent trait is comprehensively examined but to work within the conceptual framework of the Rasch approach where persons (respondents) and items are ranked. Person ability (respondent's level of difficulty) is measured and item difficulty is calibrated along a common, continuous logit scale. The "logit" or log-odd is the logarithm (natural base e) of an odds ratio and separates the data into intervals of equal size and meaning.[166]

The unique pattern of responses for each response category of PROM items enables calculation of positions of person ability and item difficulty along the logit scale. Each item functions differently across the range of respondent abilities; a less difficult item is likely to receive endorsement from only individuals with poor ability, whereas a more difficult item may receive endorsement from individuals even with better ability.[170] The mean item difficulty is centred at zero such that a positively scored item represents an item more difficult than the mean item and correspondingly, a negatively scored item represents an item less difficult than the mean. In terms of person ability, a positive logit score corresponds to a respondent who has more of the latent trait than the overall sample mean, while a negative logit score refers to a respondent who has less of the latent trait than the overall sample mean. It should be noted that the Rasch score directionality is arbitrary and is dependent on whether a higher or lower ability is assigned a more positive score.

For an ideal PROM, the items should be appropriately targeted to the population. The mean item difficulty and person ability of the cohort should be similar, indicating that the mean item difficulty and mean person ability are closely matched. A difference in means of less than one logit is considered acceptable and indicates that the questionnaire items are positioned at the correct difficulty level for the respondents' abilities. Sub-optimal targeting of an instrument may mean it is better suited to other populations, or that additional items of varying difficulty should be included in the PROM. Targeting can therefore be improved by using a population with different abilities (e.g. visually impaired vs visually normal) or altering the item content.

Each response category's unique probability function is referred to as a response curve. When response curves are plotted along the continuous logit scale, each category has a peak endorsement value and also positions where two category curves intersect, indicating equal probability for either response option. This curve intersection position is referred to as a threshold. The presence of disordered thresholds indicates response options that are either underused, have unclear definitions or that are difficult to discriminate from adjacent response options and are therefore undesirable. Response categories can often be collapsed post-testing to improve the model fit, although if this approach is unsuccessful, the questionnaire items may need to be redesigned.

The calculation and assessment of Rasch fit parameters defines how closely the response patterns match the expected Rasch model and can verify validity and reliability of an instrument.[171] Unidimensionality is assessed using item fit statistics (mean square infit and outfit) to ensure items contribute appropriately to the model, where values between 0.7 and 1.3 are generally considered acceptable.[166] Items with fit values outside this range may be removed from the model, usually through an iterative process. For items outside of the acceptable range (particularly those close to the cut-offs), the item content, category response curves, distribution of person fit statistics and DIF analyses all need to be carefully examined to determine if they meet Rasch model requirements before deciding that the item does not contribute appropriately to the questionnaire and should therefore be excluded.

Mean square infit and outfit values differ only by the weighting of person performances used. Infit values are more heavily weighted toward the responses from persons with abilities closer to an item’s difficulty level. Outfit values are more heavily weighted toward and influenced by outliers in the sample with abilities further from the item’s difficulty level. Infit values tend to be the parameter of choice for examining item fit as these are considered in many circumstances to provide a better reflection of true item performance.[160,166]

Individual items should function independently of each other and not be too closely related. Unrelatedness of the item response patterns is implicit when the principal component analysis (PCA) of the residuals shows that the first factor explains at least 60% of the variance and that the proportion of unexplained variance of the second component (first contrast) is less than 5% (eigenvalue <2.4).[166] A group of items that appear to over fit the model or perform too close to the expected pattern (infit<0.7) may be measuring the same information and may indicate that the assumption of local independence has been violated.[166]

For a PROM to be an accurate and reliable measurement tool, it is critical that questionnaire data is repeatable and generalisable to the particular population of interest. It should also be able to discriminate between groups of respondents that vary distinctly in the amount of the latent trait being measured. However, it must function similarly across different subgroups that are within the target population, otherwise it does not provide an unbiased measure for respondents and scores are not directly comparable.[165] This characteristic is assessed using Differential Item Functioning (DIF) parameters, where a DIF contrast greater than one logit indicates differential response patterns across subgroups and means that the item may be interpreted differently by some respondents than others. Items with DIF contrast greater than one logit are usually excluded from the questionnaire. However, it is sometimes possible to rephrase an item so that all respondents interpret it similarly. If there is a consistent systematic bias evident, subgroups can be separately analysed and the item calibrated for each subgroup. The addition of a sub-dimension or subscale for the items may also result in a better functioning instrument and solve DIF issues.

Instrument construct validity is usually determined through comparison with other established PROMs or objective measures for the latent trait. The ability to discriminate between separate groups in the sample with known or hypothesised differences in the latent trait can also provide instrument validity.[172] Correlations between PROMs and other objective measures do not necessarily need to be strong (e.g. $r>0.3$) to support validity, as the new instrument should provide additional information to that derived from existing measures.[173]

3.1.2 Vision and Night Driving Questionnaire Items

As previously discussed, there are a number of vision-related quality of life PROMs which investigate a wide range of vision-related activity limitations.[161] However, those available provide very limited information about vision for night driving and are often designed for groups with particular visual impairments. A vision and night driving questionnaire suited for the general population is needed given that night driving is a particular problem for older drivers who constitute the fastest growing sector of the driving population.

As outlined in the literature review, the only available low luminance questionnaire, the LLQ,[13] contains several items for investigating night driving difficulties but also includes a wide range of general activity limitations and does not support evidence describing the significant night vision concerns of older individuals.[12] The LLQ focus groups, however, generated a wide spectrum of possible concerns with low luminance conditions and therefore the LLQ does provide useful information and items on which to develop a night vision questionnaire designed for visually normal older drivers.

The psychometric properties of the LLQ have been examined and demonstrate good internal reliability (Cronbach $\alpha \geq 0.82$).[13] Construct validity was demonstrated where the 32-item LLQ scores were more strongly associated with rod-mediated dark adaptation parameters (rod-cone break, rod threshold and rod slope) than cone function parameters in those with AMD.[13] A 23-item German version of the questionnaire has subsequently been validated and refined using Rasch analysis.[174] Items of difficulty driving at night and driving at night in the rain were removed from the Rasch version of the LLQ. It is likely that these items misfit due to erratic response patterns given the sample contained both drivers and non-drivers and those with and without visual impairment.

Nineteen other original instruments containing items of vision-related activity limitations, have previously been identified,[167] of which seven contain items relevant to vision and night driving.[98,110,161,168,175–177] Together with the LLQ and two other studies that included questionnaires pertaining to vision and night driving,[157,178] an index of vision-specific night driving items was generated as outlined in Table 3-1. The scope of these items ranges across areas of vision-related clarity, comfort, avoidance, and difficulty with night driving tasks and provides the basis from which to develop a new vision and night driving questionnaire for a general population of older adults, particularly those without eye disease.

Table 3-1: Summary of vision and night driving items from existing questionnaires,grouped according to similar content categories.

Category	**Item**	**Source**
Vision Rating	How would you rate your ability to see clearly at night for safe driving?	(Molnar, Eby, et al. 2013)[178]
Headlights	When driving at night do you have difficulty with headlights from oncoming cars?	(Owsley et al. 2006)[13]
	How much is your driving disturbed by the lights of oncoming cars?	(Carta et al. 1998)[177]
	To what extent is your driving at night impaired by oncoming headlights?	(Prager et al. 2000)[176]
	How much are you hindered, limited or disabled by glare (dazzling light) when driving towards the sun or oncoming headlights?	(Lawrence et al. 1999)[179]
	How difficult do oncoming headlights or street lights make driving at night for you?	(Mangione et al. 1992)[98]
	I have trouble driving when there are headlights from oncoming cars in my field of view.	(Sloane et al. 1992)[110]

Table 3-1: Summary of vision and night driving items from existing questionnaires,grouped according to similar content categories (continued)

Low contrast	Do you have difficulty seeing dark-coloured cars while driving at night?	(Owsley et al. 2006)[13]
Signs	Do you have difficulty reading street signs when driving at night?	(Owsley et al. 2006)[13]
	Would you say that you read street signs at night with no/little/moderate/extreme difficulty?	(Mangione et al. 1992)[98]
	How confident are you driving at night, seeing street or exit signs with little warning?	(Myers et al. 2008)[157]
Moving objects	While driving at night, do you have difficulty judging the distance between you and other moving cars?	(Owsley et al. 2006)[13]
	While driving at night do you have difficulty judging the distance to your turn-off or exit?	(Owsley et al. 2006)[13]
	How difficult does seeing moving objects such as people or other cars make driving at night for you?	(Mangione et al. 1992)[98]
Peripheral vision	When driving at night, objects from the side unexpectedly appear or pop up in my field of view.	(Sloane et al. 1992)[110]
Poor weather	When driving at night in the rain, I have difficulty seeing the road because of headlights from oncoming cars.	(Sloane et al. 1992)[110]
	Do you get upset because you have difficulty seeing while driving in the rain?	(Owsley et al. 2006)[13]
	Have you limited driving in the rain because of difficulty seeing?	(Owsley et al. 2006)[13]
Dawn/dusk	Do you have difficulty seeing while driving at dawn or dusk because of glare?	(Owsley et al. 2006)[13]
Restriction	Do you limit your driving at night because of your vision?	(Owsley et al. 2006)[13]
	How much does your vision hinder, limit, or disable you in night-time driving?	(Lawrence et al. 1999)[179]
	To what extent, if at all, does your vision interfere with your ability to drive a car, by night?	(Pesudovs & Coster 1998)[175]

3.2 AIMS AND HYPOTHESES

The aim of the study described in this chapter was to develop a questionnaire for assessing vision-related difficulties while driving at night, and to evaluate it using a large sample of older drivers who reported concerns about their vision for night driving.

It was hypothesised that (articulated as alternate hypotheses):

- Poorer self-reported general visual function (e.g. distance vision, vision in low-light, vision in glare, difficulty adapting from dark to light and vice versa) would be associated with greater levels of vision-related night driving difficulties and greater (more positive) Rasch scores on the new questionnaire.

- Self-reported binocular eye diseases (e.g. glaucoma, AMD and diabetic retinopathy), prior report of night driving difficulties to an eye care practitioner, and less night driving exposure (km/week) would be associated with greater levels of vision-related night driving difficulties and greater (more positive) Rasch scores on the new questionnaire.

Subsequent studies conducted as part of this thesis determined whether greater vision-related night driving difficulties, as assessed using this newly developed questionnaire, were also associated with poorer visual function (Study 2) and poorer closed-road driving performance (Study 3).

3.3 METHODS

3.3.1 Sample Size Considerations

There is no consensus within the literature as to an appropriate sample size for Rasch analysis of a questionnaire. A sample size of twenty times the number of questionnaire items has been considered appropriate for definitive instruments that have high clinical importance requiring 99% or greater confidence, giving a sample size of about 250.[180] Linacre[180] also states that in general, 25-50 persons per questionnaire response category yields a sufficient sample size to ensure that item parameter estimates are stable, and that as few as 10 responses per category may be necessary to satisfy the Andrich rating scale model. Other evidence demonstrates that sample sizes smaller than 100 may yield inaccurate and incorrectly ordered fit parameters.[181] Based on these considerations the estimated sample size necessary for the current analysis with five response categories was set at 250 participants. Allowing for 10% ineligible data, it was considered necessary to recruit a minimum of 275 participants.

Test-retest repeatability of Rasch analysed questionnaires is infrequently assessed and again there is no consensus regarding sample size requirements, so it is difficult to determine the number of participants necessary for this type of analysis. Between 25-100 respondents has been considered adequate for assessing questionnaire test-retest reliability,[182] therefore this study aimed for a minimum of 25 participants to conduct the questionnaires on two separate occasions. A time interval of two weeks between test and retest was considered long enough to minimise recall yet short enough to minimise the chance of significant changes in vision or circumstances.[183]

3.3.2 Recruitment

Drivers aged 50 years and older who had concerns about their vision for night driving were invited to participate via e-mails to patients of local Optometry and Ophthalmology practices, as well as through advertisements in local newsletters and radio. The advertisements for the study specifically asked for participants who experienced "night driving difficulties due to vision problems in dim light, with glare or with sudden changes in light levels", and information sheets about participation gave examples such as "difficulty with oncoming headlight glare, regaining vision after passing headlights of oncoming cars, or seeing in dim lighting when driving at night" as reasons for participation in the study. Data from respondents who completed the questionnaire but did not report any difficulty with night driving or who had not driven at night within the past year were not included in the analysis.

Participants were asked to complete either an online or paper-based questionnaire which was developed for this study. The questionnaire is described in full in the following sections and included items relating to demographics and night driving characteristics (7 Items), general vision ratings (8 Items), vision-related night driving difficulties (11 items), and a single open question about specific night driving difficulties. Ethical approval of the study was obtained from the QUT Human Research Ethics Committee (QUT HREC #1300000459). The study adhered to the tenets of the Declaration of Helsinki.

3.3.3 Demographics and Night Driving Characteristics

Demographic data collected included age category (in 10 year brackets), gender, and self-reported presence of eye conditions in either eye including: cataracts, cataract surgery, glaucoma, AMD, diabetic eye disease, or any other condition. Participants were also asked if they had previously reported their night-driving difficulties to an eye care professional in order to determine the proportion that had tried to seek help for their difficulties and whether those with greater difficulties were more likely to report to an eye care practitioner. Items regarding night driving characteristics asked about the amount of night driving (average kilometres (km) per week in 25km increments), frequency of night driving avoidance, and whether spectacles were used for night driving.

3.3.4 General Vision Ratings

Participants rated their vision across several general situations, based on well-established questionnaires.[184,185] Ratings of general distance vision, day and night driving vision used a five category scale ranging from ‘very poor’ to ‘excellent’. Ratings of vision under daylight, low-light, glare conditions, and difficulty adjusting from light to dark or from dark to light used a five category scale ranging from ‘no difficulty’ to ‘extreme difficulty’.

3.3.5 Vision and Night Driving Item Generation

Table 3-1 shows the 22 items that this study identified from existing vision-specific quality of life research and questionnaires.[13,98,110,167,175–177,179,186,187]

Evaluation of the vision and driving research[14,138,139,157] also helped to derive an additional three items that were considered relevant but had not been included in existing questionnaires. These items assessed difficulty seeing low contrast objects such as pedestrians and animals, seeing hazards such as potholes and the road-side (curb) and difficulty adjusting after exposure to oncoming headlights. The response scales of existing questionnaires had a range of structures (from 2-7 options) and categories (difficulty, frequency, and level of agreement). Items for the new questionnaire were adjusted to have a common five-option scale of difficulty ranging from 'no difficulty' to 'extreme difficulty' as used in the LLQ.[13]

A small pilot study was conducted involving older drivers who reported night driving difficulties and were recruited through research personnel and their friends in the School of Optometry and Vision Science at QUT (n=35; 15 female, 20 male; median age category: 60-70 yrs). The pilot study included the identified vision-related night driving items, combining items where content was overlapping to result in a total of 12 items covering driving difficulty with low contrast, clarity of vision, glare, visual adaptation, motion and depth perception, and peripheral vision. Open questions were also included in the pilot questionnaire to provide feedback and to identify any specific night driving difficulties that were present.

The pilot data did not identify any issues with understanding of the items except that peripheral vision at night was poorly understood by several participants and thus was not included in the final selection of items. No respondents reported night driving difficulties that were in addition to the original item selection. One respondent reported difficulty distinguishing between the options of 'a little' and 'some difficulty' but the five category scale was retained given that Rasch analysis would assess any potential issues with categories.

Table 3-2 shows the final selection of the eleven vision and night driving difficulty items that were subsequently analysed using Rasch analysis to develop the vision and night driving questionnaire (VND-Q). Instructions to the participants explained that the term "night" referred to driving after dusk or before dawn.

Table 3-2: Item structure, content and response scales for the 11 item questionnaire.

How much difficulty do you have or would you have with the following night driving tasks:*	
Item 1	Seeing dark coloured cars when driving at night
Item 2	Seeing pedestrians or animals on the road side when driving at night
Item 3	Seeing the curb or potholes in the road when driving at night
Item 4	Reading street signs when driving at night
Item 5	Seeing the road because of oncoming headlights when driving at night
Item 6	Seeing because of glare when driving at dusk or dawn
Item 7	Seeing because of glare from headlights of oncoming cars when driving at night
Item 8	Adjusting after passing headlights from oncoming cars when driving at night
Item 9	Judging the distance to your turnoff or exit while driving at night
Item 10	Judging the distance between you and other moving cars while driving at night
Item 11	Seeing the road in rain or poor weather when driving at night

*All items use a five option difficulty scale: no difficulty, a little difficulty, moderate difficulty, a lot of difficulty, extreme difficulty

3.3.6 Rasch Analysis

The VND-Q was developed using Rasch analysis using Winsteps (Version 3.73, www.winsteps.com)[188] and the Andrich rating scale model.[189] The use of Rasch analysis enabled formation of a linear interval scale, in logits, of person abilities and item difficulties. This is in contrast to classical test theory which assumes equal interval steps between response categories and equal emphasis on each item. In the Rasch model for this study, an individual with poor ability had more vision-related night driving difficulty and a more positive or higher logit value. Correspondingly, an item of less difficulty was rated with a higher logit score than a more difficult item.

3.3.7 Open Question about Specific Difficulties

A single optional open question was also included for participants to describe their vision-related night driving difficulties in their own words. The responses were categorised into broad themes by a single reviewer.

3.3.8 Psychometric properties of the VND–Q

Rating scale and reliability

Response category ratings were examined to determine if thresholds were ordered. Disordered thresholds indicate response options that are either underused, have unclear definitions or are difficult to discriminate from adjacent response options.[111,174] Reliability of the scale for discriminating between high and low abilities was assessed using the Person Separation Index (PSI) and Person Reliability (PR) coefficients, where values greater than 2.0 or 0.8, respectively, indicate acceptable reliability and discrimination capability.[111]

Unidimensionality and item fit

Item fit statistics (mean square infit and outfit) were assessed to identify items that contributed appropriately to the Rasch model, where values less than 0.7 suggest item redundancy and over 1.3 indicates excessive measurement noise.[174] Unidimensionality was assessed using principal component analysis (PCA), where the first factor should explain at least 60% of the variance and the proportion of unexplained variance of the first contrast should be less than 5%.[162]

Targeting

The person-item map was inspected to investigate targeting of the questionnaire, where less than a 1.0 logit difference between the mean item difficulty and mean person ability indicates a good match between items and the study population. DIF was assessed to ensure that the underlying trait was measured uniformly across subgroups such as gender, age and ocular pathology status. A DIF contrast greater than 1.0 logit indicates the presence of interpretation bias, with differential response patterns across subgroups.[190]

3.3.9 Questionnaire construct validity

The association between VND-Q Rasch scores and age, gender and amount of night driving was examined using univariable generalised regression models and separate multivariable generalised linear regression models adjusted for each other variable. Construct validity was investigated by analysing the associations between VND-Q Rasch scores and measures of self-reported visual function (presence of eye conditions and general vision ratings), where it was hypothesised that the presence of bilateral eye conditions and poorer general vision ratings would relate to greater vision-related night driving difficulties. Univariable and multivariable generalised linear regression analyses were conducted separately for each of these vision variables, as well as for prior reporting to an eye-care practitioner, adjusting for age, gender and amount of night driving as covariates for multivariable models. Statistical analyses were performed using SPSS version 21.0 (SPSS, http://www-01.ibm.com) and p values <0.05 were used to indicate statistical significance. Residuals of the regression models were assessed to confirm the model assumptions of normality, linearity and homoscedasticity. Data was also screened to identify any outliers, missing data or errors.

3.3.10 Questionnaire repeatability

A subset of participants (n=30) repeated the questionnaire after a 2-3 week interval to evaluate reliability and repeatability of the questionnaire. Intra-class correlation analysis was used to determine the test-retest reliability of the VND-Q using a single-measures, two-way approach. The 95% repeatability coefficient (Rc) was calculated using the standard deviation of the differences between repeated measures and multiplying by 2.[191] A Bland-Altman plot was used to examine the distribution of data, 95% confidence limits and patterns of differences between questionnaire scores at time 1 and 2.[192]

3.4 RESULTS

3.4.1 Respondent Characteristics

A total of 288 completed questionnaires were submitted, of which 283 (98%) reported some vision-related night driving difficulty and were included in the analysis. Most responses were obtained via the online format (88%) and the remaining responses were paper-based (12%). There was no missing data except from eight participants who did not respond to the question about whether they had reported their difficulties to an eye-care practitioner. Participants reported driving an average of 1.9 ± 1.6 nights (after dusk or before dawn) in a typical week. Other demographic and night driving characteristics of the respondents are shown in Table 3-3.

Table 3-3: Self-reported demographic and driving characteristics of respondents.

Demographics	**Response category**	**n (%)**
Age group (yrs)	50-59	104 (37)
	60-69	94 (33)
	70-79	72 (25)
	80 and older	13 (5)
Gender	Male	98 (35)
	Female	185 (65)
Eye condition	None	196 (69)
	Cataract	39 (14)
	AMD	23 (8)
	Glaucoma	16 (6)
	Diabetic eye disease	9 (3)
Previous report to eye-care practitioner	Yes	147 (54)
	No	128 (46)
Amount of night driving (km)[a]	0-24	153 (54)
	25-49	80 (28)
	50-74	19 (7)
	75-100	14 (5)
	>100	17 (6)
Night driving avoidance (because of vision)	None	160 (57)
	A little	44 (15)
	Some	26 (9)
	A lot	34 (12)
	All of the time	19 (7)

[a] in a typical week over the past month

Figure 3-1 shows the distribution of self-ratings of general vision. The majority of respondents (81%) rated their general distance vision as good to excellent, with similar results for ratings of vision for day driving (97%). Fewer participants reported good to excellent vision for night driving (61%). High ratings of difficulty with glare and low-light were more frequent, with 59% of respondents reporting moderate or greater difficulties with glare and 35% reporting similar difficulty under low-light, compared to only 4% who reported moderate or greater difficulty under daylight conditions. Adaptation difficulties were also common, with 45% of respondents reporting moderate or greater difficulty when adapting from dark to light conditions and 33% reporting this level for adapting from light to dark conditions.

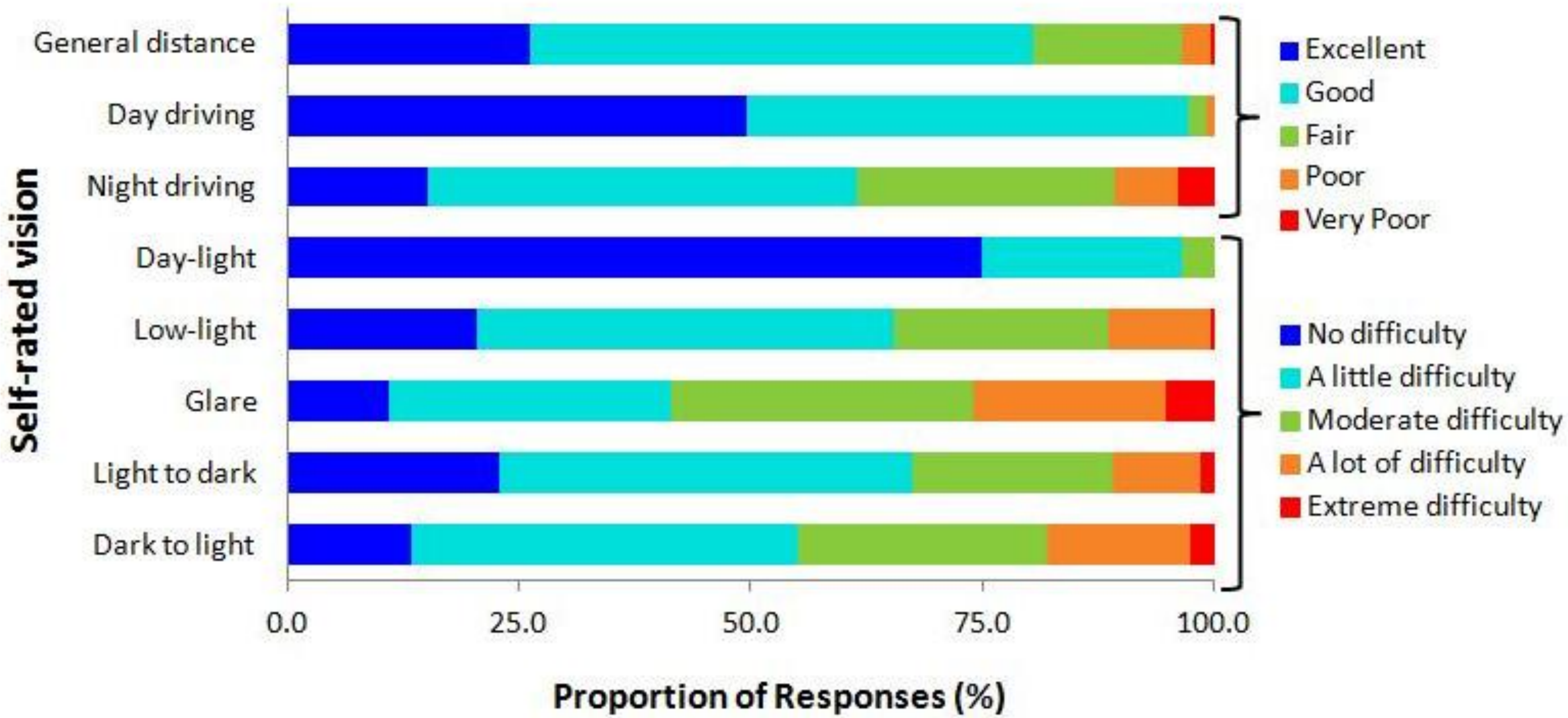


Figure 3-1: Self-rated general vision and difficulty in different lighting conditions.

3.4.2 Psychometric properties of the VND-Q

Rating scale and item fit

No disordered thresholds were evident, so the five category response scale was retained. Inspection of the infit mean square revealed one initial misfitting item, number 3 (infit=0.61), which was removed after inspection of category response curves, individual person fit statistics, and the item DIF statistics. The second Rasch iteration revealed a further misfitting item, number 7 (infit=0.59), which was also removed after similar data inspection. The two misfitting items ('seeing the curb and potholes' and 'glare from oncoming headlights') showed item redundancy (<0.7 mean square infit), given that there was a ceiling effect where most participants reported high levels of difficulty regardless of the extent of underlying night driving difficulties. The remaining nine items showed fit statistics within the acceptable range (between 0.7 and 1.3, Table 3-4). The least difficult item was 'judging the distance between you and other moving cars while driving at night' (item 10), and the most difficult item was 'difficulty seeing the road in rain or poor weather when driving at night' (item 11).

Table 3-4: Item fit statistics and item difficulty of the 9-item VND-Q ordered by most to least difficult.

	Item total correlation	**Mean square**		**Item difficulty (SE)**
		Infit	**Outfit**	
Item 11	0.79	0.97	0.94	-1.56 (0.10)
Item 5	0.82	0.9	0.89	-1.37 (0.10)
Item 4	0.72	1.27	1.27	-0.70 (0.10)
Item 6	0.79	0.98	0.95	-0.67 (0.10)
Item 8	0.81	1.02	1.03	-0.01 (0.10)
Item 2	0.81	0.8	0.79	0.33 (0.11)
Item 1	0.81	0.79	0.83	0.51 (0.11)
Item 9	0.75	1.19	1.03	1.37 (0.12)
Item 10	0.76	1.24	0.9	2.08 (0.12)

Unidimensionality and reliability

Unidimensionality of the 9-item scale was confirmed using PCA, where the first factor explained 69 percent of the variance and the eigenvalue of the second component was 1.7. The 9-item VND-Q demonstrated excellent discriminant ability, with a person separation index of 3.04 and PR coefficient of 0.90. Table 3-5 shows a comparison of parameters for the final 9-item version of the questionnaire and the expected Rasch model requirements. Overall, the fit statistics of the nine item VND-Q and the principal component analysis indicated that the scale was unidimensional, valid and reliable.

Table 3-5: Fit parameters of the VND-Q scale with Rasch model requirements.

Parameter	**9-Item VND-Q**	**Rasch model requirement**
Disordered thresholds	No	No
Number of misfitting items	0	0
Person Separation Index	3.04	>2
Person reliability	0.9	>0.8
Difference between person and item means (logit)	2.07	<1.0
Variance by first factor (%)	69	>60
PCA (eigenvalue for 1st contrast)	1.9	< 2.4
Differential Item Functioning (logit)[a]		
Age group (<60, ≥60yrs)	<1.0	<1.0
Gender	<1.0	<1.0
Amount of night driving (<25, ≥25 km/wk)	<1.0	<1.0
Ocular pathology (nil, pathology)	<1.0	<1.0

[a] DIF across all items for the dichotomized groupings

Targeting

Inspection of the person-item map (Figure 3-2) showed a 2.07 logit difference between person and item difficulty means. While there was an adequate spread of item difficulties, targeting of the 9-item VND-Q appeared to be more appropriate for drivers with moderate to high levels of difficulties than those with only lower levels. There was no notable DIF for age group, gender, amount of night driving, or eye conditions (Table 3-5), with there being less than 1.0 logit difference between category means.

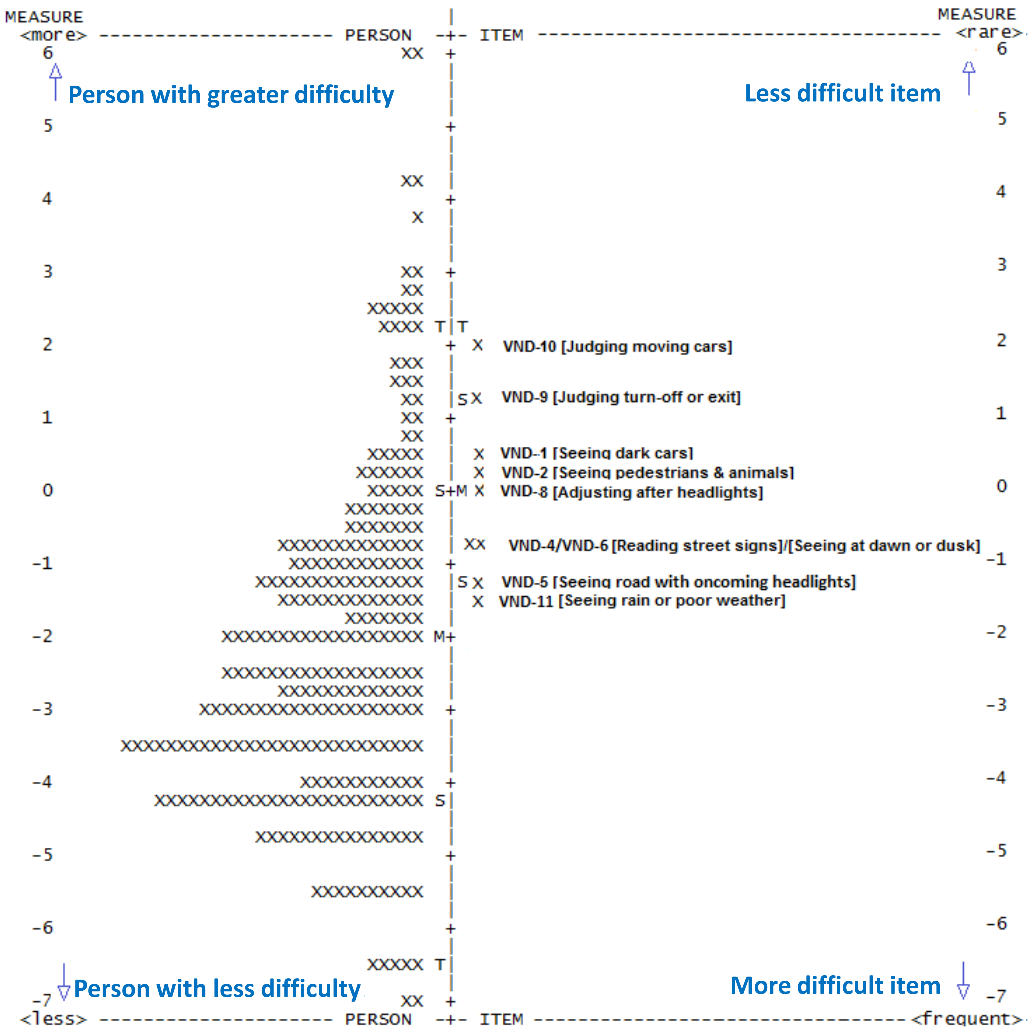


Figure 3-2: Person-Item map showing targeting of the nine item VND-Q and separation of the person and item means (M).

3.4.3 Questionnaire construct validity

The mean (±SD) VND-Q score for respondents was -2.07 ± 2.34 logits, corresponding to a mean score of 19 out of a maximum 45 points. In the multivariable regression models including age, gender and night driving exposure (Table 3-7), age was not significantly associated with difficulty levels. Multivariable analyses showed that female respondents reported significantly more night driving difficulties than males and respondents who reported less night driving exposure (<25 km per week) also had more difficulties. In addition, those who had previously reported their difficulties to an eye care practitioner had more vision-related night driving difficulties. These findings did not differ for univariable analyses (Table 3-7).

Construct validity was supported, whereby respondents who self-reported bilateral eye disease had significantly greater vision-related night driving difficulties for both univariable and multivariable models, compared to those who reported no eye disease; although, there were no significant differences between those with unilateral eye conditions and no eye disease (Table 3-7). Respondents with better self-rated general distance vision (good to excellent) and less difficulty under low-light and glare (little to no difficulty) had significantly less vision-related night driving difficulties in the univariable and multivariable regression models (Table 3-7).

3.4.4 Categorisation of open question responses

Table 3-6 summarises the broad themes identified in the open question responses completed by 100 (35%) respondents. The predominant problem identified was glare from oncoming headlights, followed by vision in poor lighting when driving at night. Importantly, no additional content areas were identified, which provides evidence that the VND-Q items reflect the predominant visual difficulties experienced by older drivers at night. Although difficulties with night driving in unfamiliar areas and on highways were reported, these situations are infrequent and situation specific therefore not necessarily relevant to all drivers.

Table 3-6: Open responses regarding vision-related night driving difficulties.

Night Driving Difficulties	**Number of comments**
Problems with oncoming headlight glare, halos or starbursts, seeing lane markings	71
Concerns about visibility in poor lighting, difficulty seeing pedestrians, animals, curb, road lane markings	25
Avoidance of night driving	24
Discomfort, aching, pain, anxiety, related to night driving	21
Difficulty seeing in poor weather	15
Prolonged time to regain vision after headlights	12
Concerns about clarity of vision, difficulty reading signs	10
Difficulty driving at night in unfamiliar surroundings because of vision	6
Problems judging distance to turnoff because of vision	5
Problems judging distance to other vehicles because of vision	5
Difficulty with vision when driving on highways at night	3

Table 3-7: Demographic and vision univariable and multivariable regression outcomes with VND-Q as the dependent variable.

Variable	n (%)	Mean logit score (95% CI) for reference group[a]	Univariable Analyses		Multivariable Analyses[b]	
			Regression coefficient (95% CI)	p-value	Regression coefficient (95% CI)	p-value
Total sample	283 (100%)	-2.07 ± 2.34 (SD)				
Self-reported demographics						
Age						
<60 (reference)	179 (63.3%)	-2.12 (-2.58 to -1.67)				
≥60	104 (36.7 %)		-0.32 (-0.88 to 0.25)	0.27	-0.21 (-0.76 to 0.34)	0.45
Gender						
Male (reference)	98 (34.5%)	-2.68 (-3.15 to -2.21)				
Female	185 (65.4%)		**1.19 (0.64 to 1.75)**	**<0.001**	**0.90 (0.33 to 1.47)**	**0.002**
Amount of night driving (km/week)						
< 25km (reference)	152 (54.1%)	-1.71(-2.10 to -1.31)				
≥25km	129 (45.9%)		**-1.22 (-1.75 to -0.69)**	**<0.001**	**-1.05 (-1.58 to -0.51)**	**<0.001**
Self-reported vision						
Eye disease						
None (reference)	196 (69.2%)	-2.38 (-2.70 to -2.06)				
Unilateral condition	41 (14.5%)		0.30 (-0.49 to 1.08)	0.50	0.36 (-0.76 to 1.48)	0.53
Bilateral conditions	46 (16.3%)		**0.80 (0.06 to 1.55)**	**0.03**	**0.76 (0.05 to 1.47)**	**0.04**
General distance vision						
Good to Excellent (reference)	227 (80.2%)	-2.45 (-2.76 to -2.15)				
Fair to Very Poor	56 (19.8%)		**1.27 (0.60 to 1.93)**	**<0.001**	**1.23 (0.58 to 1.88)**	**<0.001**
Difficulty in low-light						
A little to no difficulty	185 (65.4%)	-2.83 (-3.14 to -2.52)				
Moderate to extreme difficulty	98 (34.6%)		**1.96 (1.44 to 2.49)**	**<0.001**	**1.79 (1.29 to 2.30)**	**<0.001**
Difficulty with glare						
A little to no difficulty	117 (58.7%)	-3.41 (-3.77 to -3.04)				
Moderate to extreme difficulty	166 (41.3%)		**2.28 (1.80 to 2.77)**	**<0.001**	**2.12 (1.65 to 2.59)**	**<0.001**
Difficulty reported to practitioner						
No (reference)	128 (46.5%)	-2.72 (-3.01 to -2.33)				
Yes	147 (53.5%)		**0.91 (0.36 to 1.46)**	**<0.001**	**0.95 (0.43 to 1.47)**	**<0.001**

[a] more negative score represent less vision-related night driving difficulties

[b] models include age, gender and night driving exposure

3.4.5 *Questionnaire repeatability*

The two-way, single-measure ICC for test–retest reliability was 0.89 (95%CI, 0.78–0.95). The repeatability coefficient, Rc=2.07, demonstrated excellent repeatability of the VND-Q score. This suggests that the sample of 30 participants used for the repeatability analysis was appropriate as published guidelines confirm that only 15 participants would be necessary given the ICC = 0.89 and the 95% CI range = 0.17.[193] The Bland-Altman plot (Figure 3-3) showed the data to be distributed within the 95% limits of agreement (LOA) with mean difference ± 95% LOA = 0.27 ± 2.0 logit. Given the VND-Q score range for the repeatability sample (n=30) from -5.49 to 5.26 logit (full sample range = -7.72 to 7.54 logit), the mean elevation of Rasch score upon retesting was considered negligible.

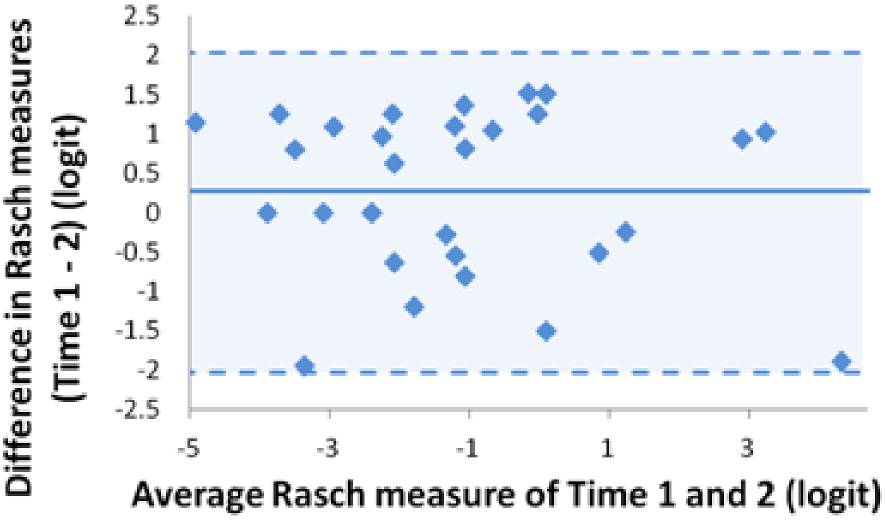


Figure 3-3: Bland-Altman plot of VND-Q Rasch scores for test-retest (n=30).

3.5 DISCUSSION

This study describes the development of a vision and night driving difficulties questionnaire (VND-Q), which comprised a nine-item, unidimensional, interval-level scale for use in a general population of older drivers. The psychometric properties of the questionnaire were established using Rasch analysis to inform item selection and to validate the questionnaire in a large sample of older drivers who experienced varying degrees of night driving difficulties.

The VND-Q is the first questionnaire designed to specifically investigate vision-related night driving difficulties. Importantly, it was developed for use in a general older population, rather than for those with specific eye diseases and is therefore highly applicable and relevant for the ageing driving population. The VND-Q covers a range of driving tasks and includes items that vary in difficulty from easier tasks, such as judging the distance to other moving cars, through to more difficult tasks, such as driving in poor weather at night.

The construct validity of the VND-Q was supported in the present study, where respondents with poorer self-reported general vision in low-light and with glare had more vision-related night driving difficulties. Notably, respondents who self-reported bilateral eye conditions had more difficulties, which provides additional support of construct validity of the VND-Q, given that conditions such as glaucoma[113], AMD[41,69] and cataract[24,194] are known to impair mesopic vision and increase glare sensitivity. However, the majority of respondents did not report any eye disease (69%), therefore the ability to generalise these results for glaucoma, AMD and cataract populations is limited.

Higher levels of vision-related night driving difficulty for female participants concurs with previous findings, where females reported higher levels of discomfort and difficulty when driving at night compared to males.[195,196] Our findings also showed that a larger proportion of the males drove more at night than females (>25 km: 62% vs 39%, respectively); greater exposure to night driving may improve males' night driving confidence,[197] as well as decrease the perception of discomfort associated with night-driving.[195] Among all respondents, VND-Q scores were significantly lower for those who reported driving more at night than those who had less exposure. Correspondingly, females also reported more night-driving avoidance than males. This concurs with previous research, where females are less likely to drive at night than males,[6] who tend to attribute more importance to their driving status and stop only when physical health has declined substantially.[6,195]

A key strength of the current study was the use of Rasch analysis to develop an interval measure of vision-related night driving difficulties, without the category spacing assumption inherent in classical test theory.[159] The Rasch generated questionnaire demonstrated unidimensionality, confirming a consistent underlying latent trait, and demonstrated well-ordered thresholds. According to published criteria-based recommendations for Rasch analysed vision-related PROMs,[107] the properties of the VND-Q would be considered to be high quality (grade A) in areas of item identification, response categories, dimensionality, measurement precision, item fit statistics, concurrent validity, test-rest reliability and known group validity. Item selection, differential item functioning and targeting would be considered medium quality (grade B). Overall the quality assessment of the VND-Q, according to these recommendations, supports the validity of this PROM.

There are, however, some limitations of the study that should be considered when interpreting the results. Construct validity was evaluated using self-reported vision and eye conditions; Study 2 and 3 of this PhD program (Chapters 4 and 5) explored the validation of the VND-Q further and determined how self-reported night driving difficulties as assessed by the VND-Q relate to clinical measures of visual function and actual measures of closed-road night driving performance. The current study was not powered to detect differences in night driving difficulties between subgroups of eye conditions, so future work including cohorts of older adults with specific age-related eye diseases known to affect mesopic vision should be undertaken. Future research is also required to determine responsiveness of the VND-Q to potential treatment options, such as cataract surgery, contact lens, or IOL options, which might improve the capacity of older adults to drive at night.

Targeting of the VND-Q was sub-optimal according to criteria-based recommendation indicating that the VND-Q may be more applicable to drivers with greater levels of vision-related night driving difficulties, such as those with specific eye conditions likely to impact on visual function at night. The inclusion of more difficult night-driving items to improve the targeting of the questionnaire would be difficult, as it already includes challenging driving tasks (driving in poor weather at night). Based on these considerations, targeting of the VND-Q was considered satisfactory for a general population of older drivers with night driving concerns. Testing the VND-Q in a population with eye disease is important, although it is likely that many individuals with greater visual impairment due to eye disease may have restricted their night-time driving or avoid it altogether, given that night driving has been shown as one of the first visual tasks to be restricted due to eye disease.[5]

The VND-Q has the capacity to provide important and relevant information to clinicians, particularly when combined with clinical vision data. For example, this information could potentially be used to inform clinical decisions about referral for cataract surgery or license renewal assessments if the VND-Q was shown to be sufficiently sensitive. Our findings show that around half of the participants had reported their difficulties to an eye-care practitioner, even though all reported some degree of vision-related difficulties with night-driving. While individuals with greater night driving difficulties were more likely to have reported their concerns, the VND-Q could help clinicians identify older drivers who may be more hesitant to report their difficulties to eye-care providers, potentially due to concerns about losing their licence. In a research setting, the VND-Q could be combined with other established driving questionnaires, such as the Driving Habits Questionnaire,[84] to provide comprehensive self-reported driver information regarding driving habits self-rated driving ability and vision-related night driving difficulties.

3.6 CONCLUSIONS

In conclusion, this study developed and validated a 9-item VND-Q to quantify the degree of vision-related night driving difficulties of older drivers, using a well-established Rasch analysis protocol to confirm its unidimensionality and reliability for use in clinical and research settings. The development of the VND-Q is an important step in providing a reliable and validated instrument to assist clinicians and researchers in better understanding and tailoring treatment options for older drivers reporting vision-related night driving difficulties. Vision testing is primarily conducted under photopic light levels, which do not reflect the level of visual ability under low luminance or glare conditions, therefore questionnaires such as the VND-Q may provide important information for the detection of difficulties that older drivers experience in low-light conditions, in the presence of glare sources and when adapting to changing in light levels. Application of the VND-Q is demonstrated in Chapters 4 and 5 where further support for the validation of the new questionnaire is provided using measures of visual function and night driving performance.

Chapter 4. STUDY 2 - INVESTIGATION OF VISUAL FUNCTION TESTS FOR NIGHT DRIVING DIFFICULTIES

4.1 INTRODUCTION

As ambient light levels in the environment change, either gradually or suddenly, the visual system adapts both optically (via pupil size) and neurally in order to optimise visual performance.[37,198] The use of both cone and rod photoreceptors enables vision across a broad spectrum of light levels extending from photopic conditions through to scotopic conditions, including the intermediate level mesopic conditions typically experienced when driving at night.[30] The night-time driving environment is unique because it presents challenging conditions such as poor street lighting, intense oncoming headlight glare, and the need to adapt across a wide range of lighting conditions – all are aspects of vision that are not currently examined in a standard clinical examination.

A standard clinical eye examination typically involves assessment of visual function under photopic light levels; however, this does not necessarily reflect visual function under other lighting conditions.[23,43,113,114] Furthermore, standard clinical testing commonly includes HCVA as the only measure of visual function, which is a poor indicator of overall quality of vision and does not provide adequate information about complex real-world environments such as those encountered when driving at night.[115,116]

Recent studies highlight the limitations of using measures of photopic vision as surrogates for vision in mesopic and glare lighting conditions.[41,113,194] Measurements of photopic VA, for both high and low contrast targets, do not show a substantial visual decline in early AMD, whereas measures of mesopic VA are more sensitive and are significantly affected even in the early stages of the disease.[41] Photopic VA is also a poor predictor of self-reported activity limitations in patients with early cataract, yet chart based measures of disability glare better reflect patients' self-reported activity limitations due to their vision.[194] In addition, while photopic CS has been shown to reveal visual deficits above and beyond VA,[199–201] there is also evidence that photopic testing of CS fails to detect significant losses of visual function under mesopic conditions.[113] Thus for some patients, the assessment of photopic vision does not capture visual function under mesopic or glare lighting conditions and this may be an important limitation when assessing patients who report vision-related night driving difficulties.

The low-luminance conditions evident on night-time roads present considerable visibility challenges for drivers.[3] Furthermore, the presence of glare from headlights and street lighting can cause visual disability through increased intraocular light scatter,[202] as well as via neural processes, resulting in prolonged disability even after removal of the glare source.[14] Night-time driving conditions are particularly problematic for older drivers due to age-related pupil miosis,[15,203] increased crystalline lens opacities and light scatter,[204,205] and neuro-visual degenerations.[206] These changes can result in impaired contrast sensitivity, increased disability glare and delayed adaptation to fluctuating light levels.[40,115,207] In addition, age-related eye diseases, such as cataract, AMD, and glaucoma, can reduce night-time visual function, with cataracts resulting in reduced contrast sensitivity and increased disability glare,[208] and retinal diseases, such as AMD and glaucoma, resulting in reduced mesopic vision[41,42] and prolonged recovery after exposure to glare sources.[209,210]

One quarter to one third of older adults report problems with glare and low-luminance conditions in relation to night driving,[3,12] yet there are currently no standardised or well validated tests for assessing fitness to drive at night. As previously discussed in the literature review (Chapter 2), some European countries have implemented a vision assessment for night driving using the Mesotest. However, it is questionable whether the Mesotest pass/fail criteria (0.02 logCS; 1:23), in the presence and absence of glare, for a private vehicle licence) can discriminate between safe and unsafe drivers,[131] Furthermore, the small 0.1 logCS difference between drivers who would be considered eligible to drive at night and those that would fail the test has been recognised as a limitation of the test, given that the repeatability values for the glare and no glare conditions are 0.07 logCS and 0.17 logCS, respectively.[113,132] Only one study has shown crash statistics that validate a previous and more difficult German Ophthalmological Society's vision standard (0.1 logCS in the presence and absence of glare (one level better than the revised standard)), to demonstrate a greater crash risk for drivers failing the test than those that pass.[29]

Given the absence of any validated tests that assess mesopic vision and disability glare which have been shown to be associated with night driving safety, licenced drivers are eligible to drive under both day and night conditions in most countries, with authorities relying on drivers to self-regulate their own night driving. This lack of vision standards for night driving is problematic given that drivers are known to underestimate their visual limitations at night[17–19] and often have limited insight into their own driving abilities.[20,21] Therefore, it is critical to examine the associations between vision-related night driving difficulties and performance on clinical tests of visual function, to guide the assessment and management of vision for night driving. The following sections describe the standard and non-standard tests of visual function that are included within the experimental study presented in this chapter.

4.2 ASSESSMENT OF VISUAL FUNCTION

4.2.1 Visual acuity

Visual acuity assessments have the advantage of being familiar, inexpensive and adaptable for testing using either high or low contrast targets at various light levels. Visual acuity is typically measured using high contrast letters under photopic luminance; however, varying the contrast and luminance for VA measurement has been shown to provide additional information about visual function. For example, photopic LCVA is more sensitive to age-related media opacities than photopic HCVA, and mesopic HCVA shows an age-related decline about one decade earlier than photopic HCVA, being more sensitive to age-related vision loss.[23,211,212] Visual acuity varies according to chart luminance and letter contrast as shown in Figure 4-1.

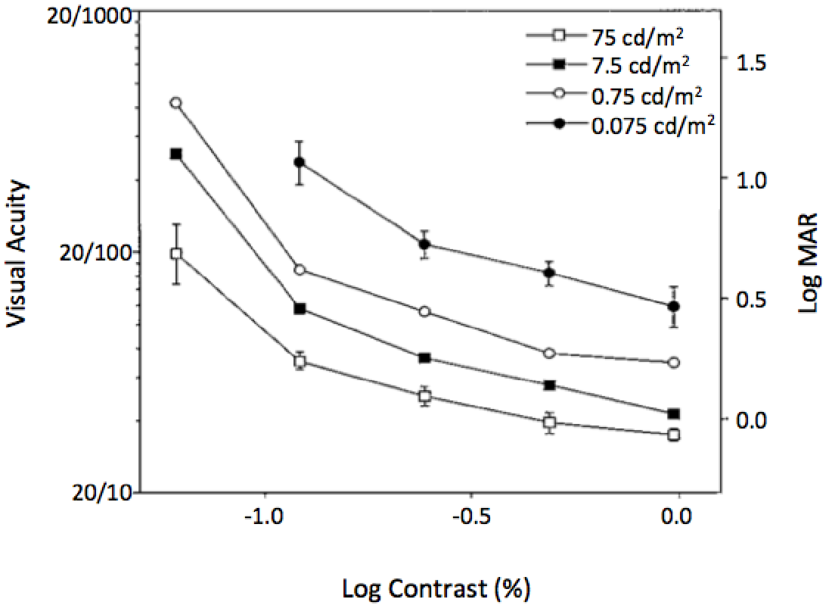


Figure 4-1: Log MAR (best corrected VA) as a function of Log Contrast for four subjects (0.075cd/m^2 to 75cd/m^2). Source: Johnson & Casson[213]

Notably, VA is significantly reduced by a combination of low contrast and low luminance that commonly occurs under night-time driving conditions, such as with darkly clothed pedestrians crossing a poorly lit road or low-contrast hazards against the night sky and road. Two large population studies have demonstrated that a one to two line decrease in habitual HCVA, predicts greater self-reported night driving difficulties[112,214] although a combination of mesopic and photopic VA better predicts night-time driving performance than a standard measure of HCVA alone.[26]

The difference between high contrast photopic (75cd/m^2) and mesopic VA (0.75cd/m^2) is approximately three lines on a standard letter chart, and up to five lines for low contrast letters (24% contrast).[213] Significant declines in mesopic VA occur during the sixth decade of life and beyond, whereas significant age-related declines in photopic VA occur about a decade later.[23] Thus mesopic VA may be a more sensitive measure than photopic VA for detecting subtle age-related changes in visual function that potentially affect night driving. The need for standardised lighting conditions and adaptation time, however, limit the clinical application of mesopic VA until stronger evidence for its value becomes available.

In order to overcome lighting and adaptation limitations, the SKILL card (Smith-Kettlewell Institute Low Luminance) was developed that combined low reflectance and low contrast in a near acuity chart card.[211] The SKILL score, or the difference between near VA measured on the white and dark grey side of the card, has been shown to be significantly affected by increasing age and diseases such as optic neuritis.[215] However, it has not been used extensively and there is no published evidence of its value for investigating functional measures of mesopic vision such as vision-related night driving difficulties.

4.2.2 Contrast Sensitivity

Alongside VA, CS has also been shown to be important for performing everyday tasks.[216] This is not surprising given that the natural visual environment contains objects of varying size and contrast. As previously mentioned, the ability to detect subtle levels of contrast is a particularly important aspect of vision in low-light conditions when driving, for example, detection of a pedestrian wearing dark clothing on night-time roads.[17,26]

The use of CS testing in addition to measures such as VA that assess the resolution capabilities of the eye, has been advocated by many authors to provide a better representation of visual performance than a single measure of photopic HCVA.[115,116,200,201,217–219] Indeed, VA can appear normal while CS is markedly reduced, particularly in neuro-pathological conditions such as optic neuritis,[199] multiple sclerosis,[200] or glaucoma.[201] Essentially, VA measures only a narrow portion of the contrast sensitivity function, where high contrast VA corresponds to the high frequency CS cut-off. Chart-based tests of CS typically measure only a limited range of spatial frequencies at a range of contrast levels. Thus, it is important to note that chart-based tests of VA and CS capture only a portion of the entire contrast sensitivity function.

Contrast sensitivity is significantly associated with night-time driving difficulty as assessed by the ADVS subscale[220], and improvement in CS post-cataract surgery has also been shown to relate to a reduction in night driving difficulties as derived from the ADVS subscale.[221] However, if night driving difficulty is rated using the single relevant NEI-VFQ question, CS does not significantly predict drivers' self-reported difficulties.[214] More critically though, evidence shows that the avoidance of night driving is predicted by poor CS[6] and closed road driving studies also provide evidence of the value of CS testing in conjunction with VA for predicting driving performance under both day and night-time conditions.[26,222,223]

There are various instruments that measure different components of contrast sensitivity, such as the Vistech VCTS charts, Cambridge Gratings, Melbourne Edge Test and the Pelli-Robson letter chart, all of which can be used at both photopic and mesopic levels. [116] Photopic CS has been shown to relate to mesopic VA,[24,26] but testing cone-mediated vision might not be an appropriate substitute for assessing true mesopic vision, where the rods and cones both contribute to visual functioning.[15] If vision-related night driving difficulties arise from underlying neural dysfunction or pupil size, the adaptation state during testing may be critical and it may be necessary to measure visual function specifically under mesopic light levels in order to replicate typical night driving conditions.

The Pelli-Robson chart is a widely used CS test, particularly within the driving field, and has good repeatability under photopic[224] and mesopic conditions.[118] However, there is limited normative data for CS measured at low luminance levels. A recent study reported reductions in log CS, measured using the Pelli-Robson chart, for normally-sighted adults under mesopic conditions (1.04 lux illuminance) of 0.004 log CS per year.[75] As previously mentioned, the Mesotest also measures CS and has the advantage of using standardised mesopic conditions. It has been used consistently by the German driving authority[225] and by several research groups to evaluate mesopic vision and fitness to drive at night,[24,28,119,132,133,152,226] despite the lack of evidence supporting its validity as a predictor of night driving safety.

4.2.3 Intraocular Scatter and Disability Glare

High levels of intraocular scatter are common in older adults due to cataract and other disturbances to the ocular media.[47,65] The importance of evaluating disability glare and intraocular scatter has therefore been emphasised and numerous attempts have been made to develop clinically useful tests for their assessment.[227–231] It is important to note that slit-lamp examination of media opacities involves an objective estimate of the amount of light scattered back from the ocular media (known as back scatter); however, a patient's symptoms may be more closely related to the light scatter reaching the retina (known as forward scatter). The relationship between forward scatter and back scatter is complex and therefore it is difficult to predict one from the other.[67]

A recent advance in straylight evaluation was the development of the C-Quant (Oculus GmbH, Wetzlar Germany) which is one of the most reliable options for predicting straylight and related glare sensitivity.[232] It allows determination of a straylight parameter and has an established reference database.[68] C-Quant straylight measures are significantly related to reported symptoms of glare in photorefractive keratectomy patients[233] and to night and general driving scores of the NEI-VFQ in an elderly population, although the association between self-reported night driving difficulties and straylight is relatively weak.[234]

Unlike the C-Quant which provides an actual measure of intraocular straylight, disability glare tests examine the reduction in visual function, such as VA or CS, in the presence of a glare source. Tests include the Brightness Acuity Tester,[235] Berkeley Glare Test[228] and the Mesotest with the addition of a glare source.[132] The Berkeley glare test is a chart-based measure of LCVA with the addition of a diffuse glare source for assessing the change in LCVA under induced glare.[228] It is reported to be sensitive to subtle media disturbances and allows standardisation of luminance levels, glare positioning and viewing conditions also having high reliability.[229] The Mesotest II, works similarly except that it uses a single point glare source and a single Landolt C target (size 6/60) to determine the effect of glare on visual function.[132]

Another option for assessing the effects of glare is to use a halometer which measures the size of the radial glare or halo surrounding a point glare source known as the photopic scotoma.[227] This is also an indirect measure of the visual disability caused by glare.[227] Halo measurement has been achieved by a range of methods including drawing a boundary around a light source extent, by defining a glare source size compared to an object of known size, and more objectively, by using target recognition to define the boundaries of the glare scotoma.[227] The Vision monitor[236], Halometer DG test[128], and Aston Halometer[129] are similarly designed instruments that use glare boundaries based on the recognition of optotypes for measuring the extent of glare surrounding a light-emitting diode.

Scores from the Halometer DG test have demonstrated significant associations with self-reported night driving difficulties (Driving Habits Questionnaire) in cataract patients[128] and the Aston Halometer has been used to investigate outcomes of refractive surgery, including multi-focal IOL implantation.[227,237] However, there is no evidence from on-road studies demonstrating that halometer scores can predict the ability to cope with headlight glare when driving at night.

4.3 RATIONALE

There is currently limited information regarding the relationship between self-reported vision-related night driving difficulties and performance on standard and non-standard measures of visual function. It is not known whether individuals that report vision-related night driving difficulties also perform poorly on currently used photopic clinical tests and whether tests conducted under mesopic conditions may be better at identifying these individuals.

Self-reported difficulties alone are not sufficient for clinical decision-making as they may be influenced by many factors other than visual impairment. For example, an individual who is less insightful regarding the extent of their visual function may rate their difficulties as relatively low in comparison to a more insightful observer. Similarly, someone with high tolerance to visual impairment would rate difficulties as relatively low compared to someone who is not tolerant of any impairment in visual functioning. In addition, self-reported difficulties may be reflective of a person’s daily visual requirements (high or low demand) rather than actual visual ability. Self-reported difficulties, however, do provide important cues for alerting clinicians to the need for further investigations via clinical assessment, although evidence is required regarding which clinical tests are most appropriate for guiding decisions about night driving.

For this study, the battery of visual function tests was selected according to those that have previously shown associations with driving difficulties or actual measures of night driving performance. They were also selected to reflect a range of assessment types including acuity, contrast, and disability glare. Variations within each visual function category were included so that a comparison between similar tests could be undertaken. For example VA was measured using high and low contrast targets and photopic and mesopic luminance levels; the Pelli-Robson Chart and Mesotest II provided different assessment techniques for measuring contrast sensitivity, and the Berkeley Glare Test, Aston Halometer, and the Mesotest II with glare, provided different techniques for measuring disability glare.

4.4 AIMS AND HYPOTHESES

This study aimed to examine which photopic, mesopic and glare-based tests of visual function were most strongly associated with self-reported vision-related night driving difficulties, as quantified by the VND-Q. Particular emphasis was placed on mesopic and glare-based tests of visual function to determine if performance on these tests was more strongly associated with difficulty levels than the results of tests of photopic visual function, particularly the standard clinical test of photopic HCVA. An important aim of the study was to determine if non-standard tests of visual function, such as those conducted under mesopic luminance levels or glare conditions, could reveal reduced visual function for participants who reported having moderate to high levels of vision-related night driving difficulties, despite having normal photopic HCVA.

It was hypothesised that (articulated as alternate hypotheses):

- Reduced visual function, as assessed by photopic, mesopic, and glare-based tests of visual function, would be associated with higher levels of self-reported vision-related night driving difficulties and higher (more positive) VND-Q Rasch scores.

- Mesopic and glare-based tests of visual function would be more strongly associated with self-reported vision-related night driving difficulty, as quantified by VND-Q Rasch scores, than outcomes of visual function tests conducted under photopic luminance levels.
- The associations between VND-Q scores and outcomes of mesopic and glare based visual function tests would be stronger for participants who have good photopic HCVA yet report moderate to high levels of vision-related night driving difficulties compared to participants with lower levels of difficulties.

4.5 METHODS

4.5.1 Sample Size

Participants included those who had previously provided their contact details as part of the larger questionnaire-based study of vision-related night driving difficulties (Study 1, Chapter 3) who were invited to take part in this vision testing component of the PhD program. All prior participants were eligible to participate if they had provided consent to be contacted. Individuals with the greatest vision-related night driving difficulties (greatest VND-Q Rasch scores) were contacted first until the required sample size was obtained. This was determined using G-Power 3.1[238] for a study that that would involve multiple regression analyses using a two-tailed test, medium effect size of 0.15, α of 0.05 and a conservative estimate of four predictor variables. This analysis indicated that 73 participants should be tested in order to obtain 90% power.

Participants were required to be currently driving at night (or have driven at night within the past year) and to have self-reported concerns about their vision for night driving including either difficulties in low-light, glare or with adaptation when driving at night. Individuals self-reporting systemic conditions that could affect driving or cognition were not eligible for participation, eg. Parkinson's disease, dementia or physical frailty. Ethical approval for the study was obtained from the QUT Human Research Ethics Committee (QUT HREC #1300000459) and informed consent obtained prior to commencement. The study adhered to the tenets of the Declaration of Helsinki.

4.5.2 Questionnaire data

Vision-related night driving difficulties were measured using the VND-Q as developed in Study 1 (Table 4-1). The raw scores for each item were converted to an overall Rasch score for each participant, according to the VND-Q Rasch scale generated in Chapter 3. A higher or more positive score indicated greater vision-related night driving difficulties whereas a lower more negative logit score indicated fewer difficulties. As in Chapter 3, the extent to which participants felt comfortable with night driving, how frequently participants avoided driving at night because of their vision, and exposure to night driving were also recorded for each participant. In addition, general ratings of vision under different lighting conditions and for night driving, consistent with Chapter 3, were also collected. This was important for assessing the visual function tests that best reflected VND-Q Rasch scores for patients who have substantial difficulties yet would appear to have good vision based on a standard measure of photopic HCVA.

Table 4-1: 9-Item Vision and Night Driving Questionnaire (VND-Q)

How much difficulty do you have or would you have with the following night driving tasks:

Q1 Seeing dark coloured cars when driving at night?

Q2 Seeing pedestrians or animals on the road side when driving at night?

Q3 Reading street signs when driving at night?

Q4 Seeing the road because of oncoming headlights when driving at night?

Q5 Seeing because of glare when driving at dusk or dawn?

Q6 Adjusting after passing headlights from oncoming cars when driving at night?

Q7 Judging the distance to your turnoff or exit while driving at night?

Q8 Judging the distance between you and other moving cars while driving at night?

Q9 Seeing the road in rain or poor weather when driving at night?

Rating scale:
(1) No difficulty; (2) A little difficulty; (3) Moderate difficulty; (4) A lot of difficulty; (5) Extreme difficulty

4.5.3 Vision Assessment

Slit-lamp assessment of the external eye and intraocular lens, fundus photography and monocular central 22° threshold visual fields (Medmont M700; Medmont Pty Ltd., Camberwell, Victoria, Australia) were conducted to assess ocular health status. Participants were eligible to participate if they held a current Australian drivers' licence and had best corrected binocular HCVA of better than or equal to 0.3 logMAR (6/12), as per the Australian standard, measured using a standard logMAR chart.

After vision screening, a comprehensive series of visual function assessments was conducted under photopic, mesopic and induced glare conditions as outlined in Table 4-2. To balance the effects of fatigue and practice on test outcomes, the order of photopic and mesopic testing was randomised, with the glare assessment being undertaken immediately following mesopic examination. Participants were given a ten minute adaptation period to the mesopic light level based on previous studies that have used a 5-10 minute timeframe.[114,118,120,121,127] Halogen room lighting in the testing laboratory provided a photopic luminance level of 100 ± 6 cd/m^2 as confirmed by five measurements (each corner and the centre of the chart) using the BM7 Luminance Colorimeter (Topcon, Tokyo, Japan). This level was consistent with recommended photopic lighting requirements for each of the vision tests.[116,239]

Mesopic conditions were produced using dimmable halogen lighting at 0.38 ± 0.02 cd/m^2 level using the mean of five measurements from the BM7 Luminance Colorimeter. This luminance level was selected as it falls within the range of mesopic testing levels used in previous studies (0.1-1cd/m^2)[23,41,123,240] and has also been shown to enable reliable and repeatable visual function test results.[121] The illuminance measured at the eye for typical driving on poorly lit night-time roads was confirmed to be within the low mesopic zone through on-road pilot investigations that included six night-time drives (each 25 minutes in duration) in dry and wet weather road conditions (refer to Appendix A).

All visual function assessments were conducted binocularly using the participants' habitual driving correction (if any), given that the aim of the study was to assess associations with self-reported vision at night-time which is likely to reflect participants' habitual binocular viewing experience. The tests of visual function were selected because they have previously demonstrated reliable and repeatable results, except for the Mesotest which has been suggested to have suboptimal reliability given the small difference in contrast between levels, as described below.[132] Nevertheless, the Mesotest was considered to be a key test to include in this study as it is the only instrument specifically used for determining visual fitness for night driving in some countries.

Photopic and mesopic pupil diameter were measured during the photopic and mesopic visual function testing protocols to investigate whether differences in retinal illumination had any significant effects on self-reported vision-related night driving difficulties or visual function test outcomes. The C-Quant straylight parameter was determined immediately after the mesopic testing protocol to assess whether age-related lens changes were significantly associated with night driving difficulties.

Photopic Testing

Visual Acuity: HCVA (90%) and LCVA (10%) were measured and scored on a letter by letter basis,[241] where each letter represented 0.02 logMAR and one line was 0.1 logMAR. Participants were encouraged to guess letters that were near threshold and VA was determined when four or more errors were made on a line.[241]

Near VA was measured during the photopic protocol using the SKILL card (Figure 4-2).[211] The double-sided chart provided a SKILL score of the difference in logMAR acuity for high contrast black letters on a white background and when measured for the reduced reflectance side of the chart with low contrast black letters on a dark grey background.

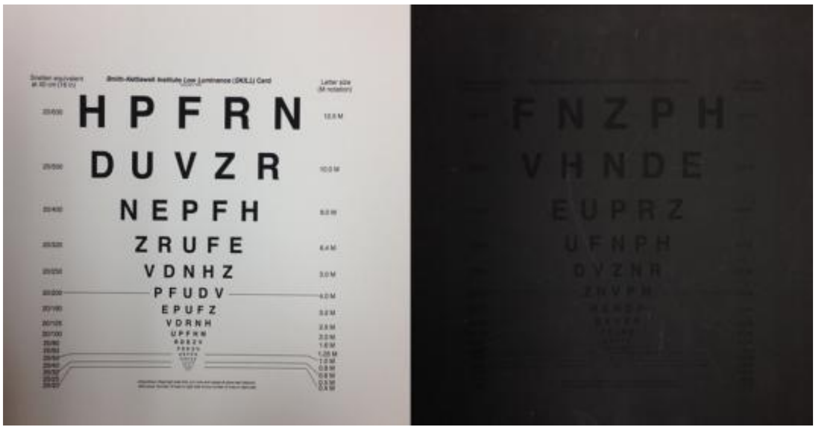


Figure 4-2: SKILL card for measuring reduced reflectance near visual acuity.

Contrast sensitivity: Photopic CS was measured using the Pelli-Robson chart (Clement Clarke International Ltd.; Harlow, U.K.) under the same luminance conditions as for VA testing. The test consists of eight rows of Sloan letters equivalent to a spatial frequency of approximately 1cpd which is near the peak of the contrast sensitivity function at a one metre test distance.[242] Contrast decreases by 0.15 log units between each of sixteen triplets of letters. Participants were given time and encouraged to guess letters until a full triplet was answered incorrectly. Contrast sensitivity was scored on a letter by letter basis (0.05 log units for every correctly identified letter) with O and C being accepted interchangeably as this improves repeatability of the test.[243]

Table 4-2: Visual function test specifications

Instrument specifications				Light levels	Test distance[a]
Photopic	High contrast visual acuity logMAR chart	90% contrast[b] optotypes	Range: -0.20-1.10 logMAR	Chart luminance: 100 ± 6cd/m^2	3.2 metres
	Low contrast visual acuity logMAR chart	10% contrast[b] optotypes	Range: -0.20-1.10 logMAR	Chart luminance: 100 ± 6cd/m^2	3.2 metres
	Pelli-Robson contrast sensitivity chart	6/36 sp freq 1cpd optotypes	Range: 0.00-2.25 logCS	Chart luminance: 100 ± 6cd/m^2	1 metre with +1.00DS
	SKILL card	>90 & 14% contrast[b] optotypes	Range: -0.10-1.40 logMAR	Chart luminance: 100 ± 6cd/m^2	40cm with +2.50DS
Mesopic	High contrast visual acuity logMAR chart	90% contrast[b] optotypes	Range: -0.20-1.10 logMAR	Chart luminance: 0.38 ± 0.02cd/m^2	3.2 metres
	Low contrast visual acuity logMAR chart	10% contrast[b] optotypes	Range: -0.20-1.10 logMAR	Chart luminance: 0.38 ± 0.02cd/m^2	3.2 metres
	Pelli-Robson contrast sensitivity chart	6/36 sp freq 1cpd optotypes	Range: 0.00-2.25 logCS	Chart luminance: 0.38 ± 0.02cd/m^2	1 metre with +1.00DS
	Mesotest II without glare	Landolt C 6/60 sp freq 3cpd	Range: 0.02-0.30 logCS	Background luminance: 0.032 ± 0.003cd/m^2	5 metres virtual image
Glare	Mesotest II with glare	Landolt C 6/60 sp freq 3cpd	Range: 0.02-0.30 logCS	Background luminance: 0.1 ± 0.01cd/m^2 Glare source: 0.35 lux at pupil	5 metres virtual image
	Aston Halometer	0.4 logMAR optotypes	Range: 8 directions 0-360°	Room lighting off Glare source: LED[c] 5000K, 40 mA, 3.7 V	2 metres
	Berkeley Glare Test	18% contrast[b] optotypes	Range:-0.3-0.90 logMAR	Chart luminance: 100 ± 2cd/m^2 Diffuse glare: 750 cd/m^2	1 metre with +1.00DS

[a] Habitual distance refractive correction when no working distance lens is specified

[b] Weber contrast

[c] Light-Emitting Diode

Mesopic Testing

Visual Acuity: Mesopic HCVA and LCVA were measured using methods identical to the equivalent photopic VA assessment, an alternative chart to that used for photopic testing was used to avoid any familiarity with the test letters.

Contrast Sensitivity: Pelli-Robson CS was also measured in the same way as for photopic testing but under the mesopic lighting levels and using an alternative chart.

Mesotest II without glare: The Mesotest II (Oculus, GmbH, Wetzlar, Germany) without glare provided an alternative measurement of mesopic CS. The specifications were designed to simulate night driving conditions;[65] however, the mesopic background luminance of 0.032cd/m^2 is much lower than current night-time road lighting levels which range between 0.1-0.5cd/m^2 and at the lowest levels, have been measured at 0.1cd/m^2 on wet country roads illuminated only by headlights.[34] The Mesotest II (Oculus, GmbH, Wetzlar, Germany) (Figure 4-3) is a free-space viewing instrument that presents an image of a Landolt C at a virtual distance five metres from the viewer who is wearing their distance refractive correction (if any).

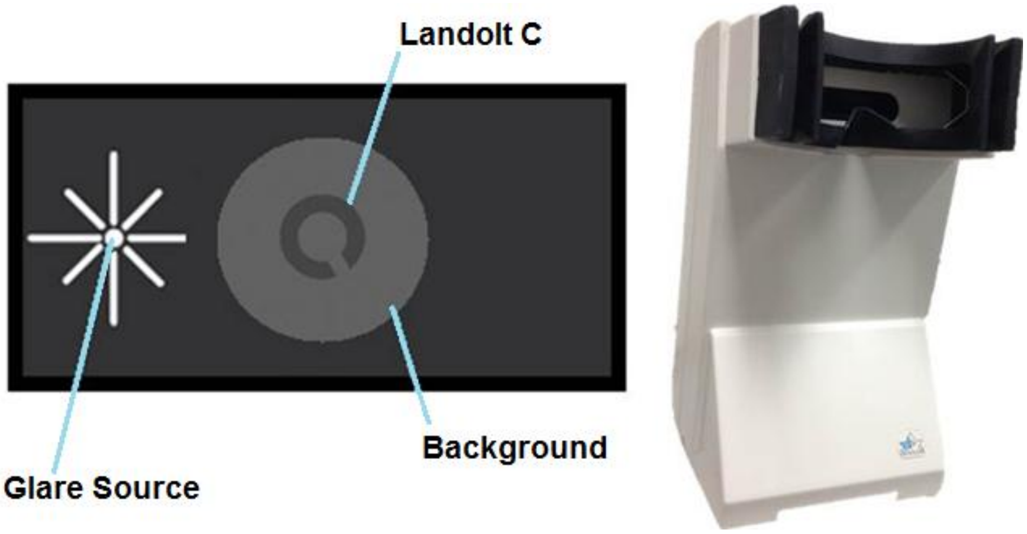


Figure 4-3: Mesotest II instrument and visual stimulus

Participants commenced the test having already undergone a ten minute adaptation period and approximately ten further minutes of testing under mesopic conditions. Participants were required to judge the direction of a 6/60 Landolt C gap (equivalent to a spatial frequency of 3 cycles/deg) from a choice of six positions (up, up-right, down-right, down, down-left, up-right) for each of five presentations at four decreasing levels of contrast. The four contrast levels vary by 0.1 log units with the ratio of the optotype to background being 1:23 (log 0.02), 1:5 (log 0.1), 1:2.7 (log 0.2) and 1:2 (log 0.3), corresponding to 95, 80, 63 and 50 percent of the contrast threshold, respectively.[133]

The test commenced with the easiest level of contrast (1:23) and if the participant correctly identified the direction of the Landolt C gap for three out of the five presentations for that level, they scored a pass and then progressed to the next level. When five incorrect responses were given for a contrast level, the test was stopped although testing was always conducted for both the no glare and glare conditions. The 95% repeatability coefficient for the Mesotest conducted in the absence of glare is 0.66 after correction for floor and ceiling effects.[132] This means that 95% of the time a repeat score on the Mesotest without glare would be within 0.66 levels of the original measurement. Given this repeatability level, a change between passing and failing a level could easily occur upon repeat testing.

Glare tests

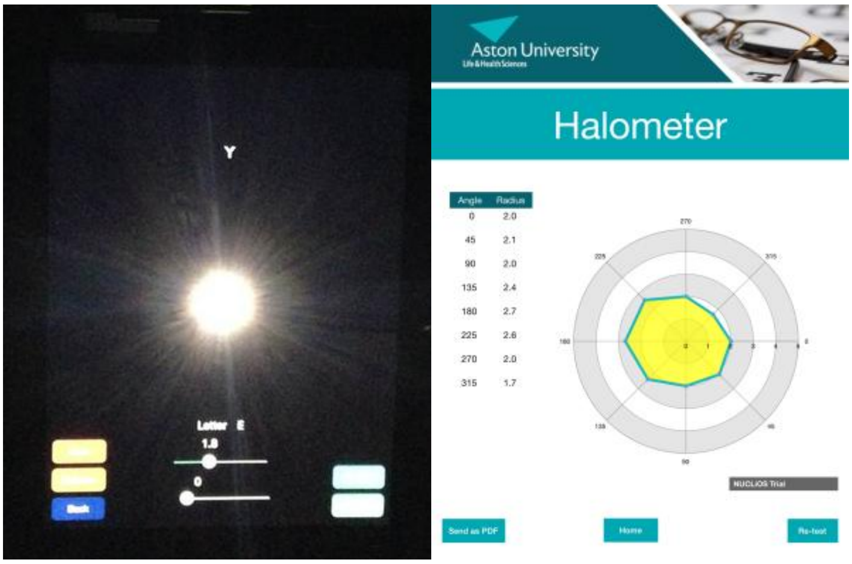
Mesotest II with glare: The participants' task for the Mesotest II conducted in the presence of glare was identical to that for the Mesotest without glare, but with the addition of a white LED glare source positioned at a visual angle of 3° to the left of the Landolt C target. The glare source is designed to simulate glare from the headlights of an oncoming vehicle at the low-beam setting. The source has an intensity of 0.35 lux at the pupil plane and results in a background luminance of 0.1cd/m^2.[24] The 95% repeatability coefficient of the Mesotest II with glare is 1.67 which is poorer than that measured for the no glare test. Therefore a change in score of 1-2 levels between exams would be expected 95%

of the time, which has led to some researchers questioning whether discrimination between safe and unsafe drivers can be accurately achieved using the Mesotest.[132]

Aston Halometer: The Aston halometer (Figure 4-4)[129] measures the area obscured by glare induced by a bright white LED (5000K colour temperature; pulse width modulation duty cycle of 15.6%, forward current 40 mA, 3.7 V; Osram Licht AG) attached to the centre of an LCD (iPad4, Apple) with a 2048 x 1536 pixel resolution and a 240 x 169.5 mm size screen (Figure 4-5). The only light in the room during testing was that of the LED glare source; the test was performed immediately following the mesopic protocol so participants were already adapted to mesopic conditions prior to this test.

The boundary of the photopic LED scotoma was recorded at eight eccentricities (0˚, 45˚, 90˚, 135˚, 180˚, 225˚, 270˚, 315˚) as the position closest to the LED at which participants correctly identified 2 out of 3 presentations of a randomised high contrast (100% Webber contrast) Sloane letter equivalent to a size of 6/15 (0.4 logMAR, UK driving standard). This seen-to-not-seen approach was used to ensure that participants could see the letter at the maximum distance from the LED before it was moved toward the source in 0.1˚ steps. If the participant was unable to identify the letter at the maximum distance, the glare source was turned off to confirm that the participant understood the task. If upon the second trial the participant was still unable to see the letter at the extreme position, they were assigned a maximum distance for that eccentricity and the test was continued until all eight directions were measured.

Halo area was calculated using the sum of the area of eight triangles with side lengths as measured along each of the eccentricities. The Aston halometer is reported to have high repeatability and to provide a valid measure of glare difficulties that arise from IOL implantation.[129]



Angle	Radius
0	2.0
45	2.1
90	2.0
135	2.4
180	2.7
225	2.6
270	2.0
315	1.7

Figure 4-4: Aston Halometer showing instrument and data output.

Berkeley Glare Test: The Berkeley glare test consists of a set of plexiglass letter charts with opaque triangular letter charts mounted over a 30 X 27 cm light box. It is used to measure the reduction in LCVA that occurs with the addition of glare (Figure 4-5). In the current study, the low contrast letter chart was used for measurements without glare and subsequently with glare on a medium setting. The disability glare index (DGI) was calculated by determining the difference between low contrast acuity (logMAR) with and without the glare source.[229] The Berkeley glare test is reported to be sensitive to subtle media disturbances and allows standardisation of luminance, glare positioning and viewing conditions.[229]

Figure 4-5: Berkeley glare test

Ocular Characteristics

Pupil Size: The NeurOptic pupillometer (model 79101) (NeurOptics, Inc.) was used to measure pupil sizes of both eyes under photopic and mesopic lighting conditions. The monocular device fits against the patient's orbit and uses infrared technology and digital imaging to autocalibrate and autofocus. The mean and standard deviation of multiple measurements provides a reliable and accurate measure of pupil diameter.[244] The right and left eye pupil sizes were averaged for analysis.

Straylight Index: The C-Quant (Oculus GmbH, Wetzlar Germany) was used to assess ocular scatter for right and left eyes. It uses a compensation comparison technique where the surround of a central field flickers out of phase with a flickering bipartite central field.[231] A two alternative forced choice paradigm is used for each of twenty-five presentations, where patients report which half of the central bipartite field flickers the most. The point at which the central flicker is not detectable is when compensation has been reached. A computer generated frequency of seeing curve is used to calculate the single straylight parameter (s). The right and left eye values were averaged for analysis.

4.5.4 Statistical analysis

Statistical analyses were performed using SPSS version 21.0 (SPSS, http://www-01.ibm.com) and p-values <0.05 were used to indicate statistical significance. For all statistical tests, residuals were assessed to confirm the model assumptions of normality, linearity and homoscedasticity. Data was also screened to identify any outliers, missing data or errors. Generalised linear regression models were used to determine the associations between age, gender, eye conditions, amount of night driving, and VND-Q scores to determine how they affected participants' ratings of their night driving difficulties on the VND-Q.

Pearson correlation analyses were used to assess the relationships between tests of visual function. A specific investigation of the relationship between age and each of the four tests of visual acuity (photopic HCVA, photopic LCVA, mesopic

HCVA, Mesopic LCVA) was conducted using generalised linear regression models. To determine if the VA tests were differentially affected by the effects of age, the interaction between age and test condition was explored using linear mixed models, with random intercept for participants and unstructured covariance.

Finally, generalised linear regression models were used to determine the associations between tests of visual function and VND-Q scores, and the association between ocular characteristics and VND-Q scores, adjusting for relevant factors and covariates. The residuals of models were used to calculate the difference in VND-Q score variance explained using models with and without each vision test.

4.6 RESULTS

4.6.1 Participants

Participant demographics and eye conditions that were assessed during ocular health screening are summarised in Table 4-3. Visual field screening did not reveal any gross deficits that could impact upon driving. Data are shown for the full sample of 72 participants and for a subgroup of 29 participants who reported substantial night driving difficulties yet had VA at expected levels for their age (within three letters on the Bailey-Lovie logMAR chart[245] <75yrs <0.00 logMAR; ≥75yrs <0.02 logMAR[246]) Substantial difficulties were classified as general vision ratings of 'a lot' or 'extreme difficulties' in low-luminance or glare conditions, or a rating of vision for night driving that was 'fair', 'poor' or 'very poor'.

Figure 4-6 provides a visual representation of the subgroup of participants (n=29) with good photopic VA yet high levels of vision-related night driving difficulties. The right side of the figure includes those patients who are likely to report night driving difficulties to their eye care professional (high difficulties). The highlighted subgroup of participants were of particular clinical interest because they have normal vision based on a standard assessment of photopic HCVA but report high levels of night driving difficulties and thus would not be identified in a standard clinical examination. It was hypothesized that mesopic and glare based tests would be particularly valuable for revealing deficits in these participants.

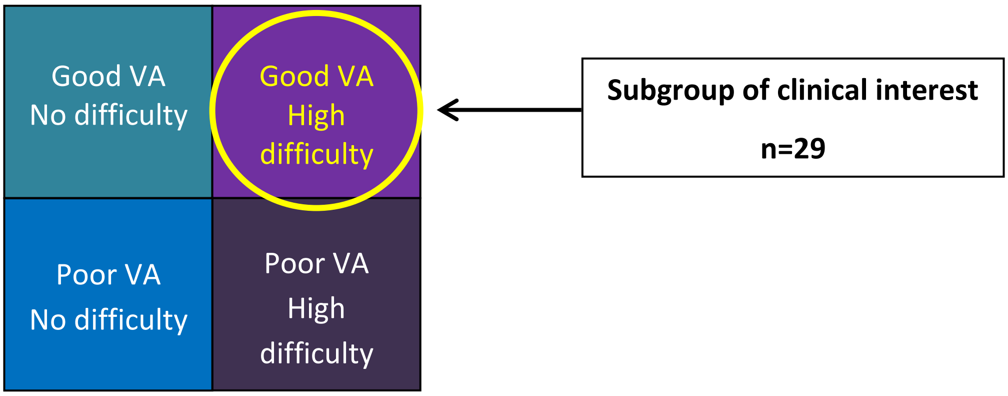


Figure 4-6: Visual representation of VA and difficulty levels combinations

Table 4-3: Demographics and eye conditions for the full sample and subgroup of clinical interest.

		Full sample n=72	**Subgroup n=29**
Age (yrs)	Mean ± SD (range)	65.1 ± 8.7 (50-83)	65.0 ± 8.4 (50-82)
Gender	Male (n, %)	24 (33%)	10 (34%)
	Female (n, %)	48 (67%)	19 (66%)
IOL (monofocal)	No (n, %)	60 (83%)	24 (83%)
	Yes (n, %)	12 (17%)	5 (17%)
	Unilateral	2 (3%)	-
	Bilateral	10 (14%)	5 (17%)
Habitual correction	Optimally corrected (n, %)	64 (89%)	29 (100%)
	Suboptimal[a] (n, %)	8 (11%)	-
Eye conditions	Nil (n, %)	32 (44%)	17 (59%)
	Unilateral (n, %)	20 (28%)	7 (24%)
	Cataract (LOCS III>3)[b]	7 (10%)	3 (10%)
	Corneal scarring[b] or microcysts	5 (7%)	3 (10%)
	Amblyopia (R-L VA ≥2 logMAR)	3 (4%)	-
	Dry AMD	2 (3%)	-
	Epiretinal membrane	2 (3%)	-
	Adies tonic pupil	1 (1.4%)	1 (3.4%)
	Bilateral (n, %)	22 (31%)	5 (17%)
	Cataract (LOCS III>3)[c]	14 (19%)	4 (14%)
	Diabetic retinopathy[c]	3 (4%)	1 (3.4%)
	Early glaucoma	2 (3%)	1 (3.4%)
	Prior retinal tear	2 (3%)	1 (3.4%)
	Epiretinal membrane	1 (1.4%)	-
	Early dry AMD	1 (1.4%)	1 (3.4%)

[a] VA difference between best and habitual correction ≥0.1logMAR

[b] One participant had both conditions (same eye) for n=72

[c] One participant had both conditions for n=72 and n=29

4.6.2 Questionnaire data

Across all 72 participants the mean VND-Q score was -2.10 ± 1.48 logit (calibrated from Study 1), equivalent to a score of 19 out of a total of 45, which was a similar level of difficulties to the larger sample in Study 1 (-2.07 logit, Chapter 3). Figure 4-7 illustrates the responses for each item of the VND-Q. Twenty-four percent of participants indicated little overall difficulty (for all nine items), while 76 percent indicated moderate or greater difficulties in at least one of the VND-Q items.

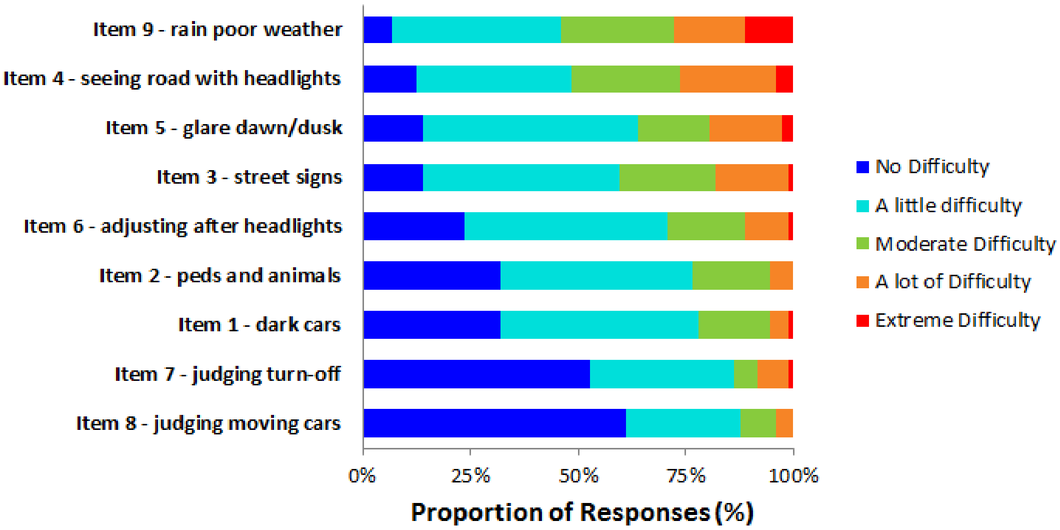


Figure 4-7: Responses to the 9-Item VND-Q.

Male gender was associated with less vision-related night driving difficulty (regression coefficient=0.99 logits, p<0.005), as was more night driving exposure (regression coefficient=0.34 logits, p<0.05), although most participants (82%) reported driving 50 kilometres or less at night in a typical week. Age did not significantly affect VND-Q Rasch scores even when participants with IOLs were excluded (p>0.05). Ocular disease status was also not significantly associated with participants' difficulty levels. Participants reported driving 2.1 ± 1.5 nights (after dusk or before dawn) in a typical week. Twenty-nine percent of participants reported being completely comfortable driving at night, while the others had at least a little reservation; thirty percent of participants reported avoiding night driving because of their vision, at least some of the time.

4.6.3 Visual function test outcomes

Table 4-4 summarises participants' performance on the tests of visual function conducted under photopic and mesopic conditions, and in the presence of glare. Data are shown for the full sample and for the subgroup that reported greater difficulties (according to general vision ratings) yet had age normal levels of HCVA.[246] The subgroup's mean VND-Q Rasch score was -1.47 ± 1.48 logit which demonstrated significantly more vision-related night driving difficulties than the full sample ($t=-11.63$, $p<0.001$).

Reduced letter contrast and lower luminance levels decreased VA and there was a wider range of VA for both photopic LCVA and mesopic HCVA and LCVA in comparison to photopic HCVA. The mean differences between HCVA and LCVA for photopic and mesopic conditions were 0.2 logMAR (2 lines) and 0.3 logMAR (3 lines) on the letter chart, respectively (mean ± SD = 0.18 ± 0.07 logMAR, 0.28 ± 0.15 logMAR, respectively). The mean difference between photopic HCVA and mesopic HCVA was 0.4 logMAR (4 lines) on the letter chart (mean ± SD = 0.40 ± 0.14 logMAR). Age-related declines in VA were evident for all VA tests, where there was a significant linear decline for photopic HCVA ($\chi^2=5.65$ $p=0.017$), photopic LCVA ($\chi^2=20.47$ $p<0.001$), mesopic HCVA ($\chi^2=25.53$ $p<0.001$) and mesopic LCVA ($\chi^2=38.60$ $p<0.001$). There was also a significant interaction between age and VA test type ($F_{3,72} = 5.02$ $p = 0.003$) where there was a greater age-related reduction in VA for low contrast letters at mesopic luminance levels than for high contrast and photopic conditions (Figure 4-8).

Interestingly, photopic Pelli-Robson CS showed little variation between participants yet mesopic Pelli-Robson CS demonstrated a larger range, with some participants exhibiting marked reduction in CS under the lower luminance condition. There was a mean difference between photopic and mesopic CS of 0.4 logCS.

Table 4-4: Summary of visual function test outcomes under photopic, mesopic and glare conditions. Data shown for the full sample and the subgroup who had greater difficulties yet clinically normal VA (<0.1 logMAR). Arrows represent the direction of better scores for each test of visual function.

Visual Function Variable		**Full Sample (n = 72)**		**Subgroup b (n = 29)**^{b}	
		Mean (±SD)	**Range**	**Mean (±SD)**	**Range**
Photopic	High Contrast Visual Acuity (logMAR)$^{\vee}$	-0.03 ± 0.12	-0.20 - 0.30	-0.07 ± 0.07	-0.18 - 0.08
	Low Contrast Visual Acuity (logMAR)$^{\vee}$	0.15 ± 0.15	-0.10 - 0.62	0.12 ± 0.11	-0.06 - 0.40
	Contrast Sensitivity (logCS)$^{\wedge}$	1.92 ± 0.12	1.40 - 2.25	1.93 ± 0.07	1.65 - 1.95
	SKILL Score$^{\vee}$	31.94 ± 9.10	16.00 - 62.00	28.9 ± 7.38	16.00 - 44.00
Mesopic	High Contrast Visual Acuity (logMAR)$^{\vee}$	0.36 ± 0.18	0.02 - 0.96	0.32 ± 0.16	0.02 - 0.76
	Low Contrast Visual Acuity (logMAR)$^{\vee}$	0.64 ± 0.21	0.16 - 1.40	0.59 ± 0.18	0.22 - 1.10
	Contrast Sensitivity (logCS)$^{\wedge}$	1.52 ± 0.31	0.75 - 1.95	1.54 ± 0.26	0.95 - 1.95
	Mesotest -glare (levels passed)$^{\wedge}$	2.68 ± 1.56	0.00 - 4.00	2.83 ± 1.54	0.00 - 4.00
Glare	Mesotest +glare (levels passed)$^{\wedge}$	1.67 ± 1.70	0.00 - 4.00	1.86 ± 1.62	0.00 - 4.00
	Halo Area (cm^{2})$^{\vee}$	7.16 ± 5.81	1.10 - 18.50	6.53 ± 5.39	1.10 - 18.50
	DGI Berkeley Glare Test (VAR^{a})$^{\vee}$	3.74 ± 4.30	-5.00 - 18.00	1.83 ± 3.25	-5.00 - 9.00

[a] Visual Acuity Rating (VAR) = 100-50(logMAR)

[b] high self-rated difficulties with VA<0.1

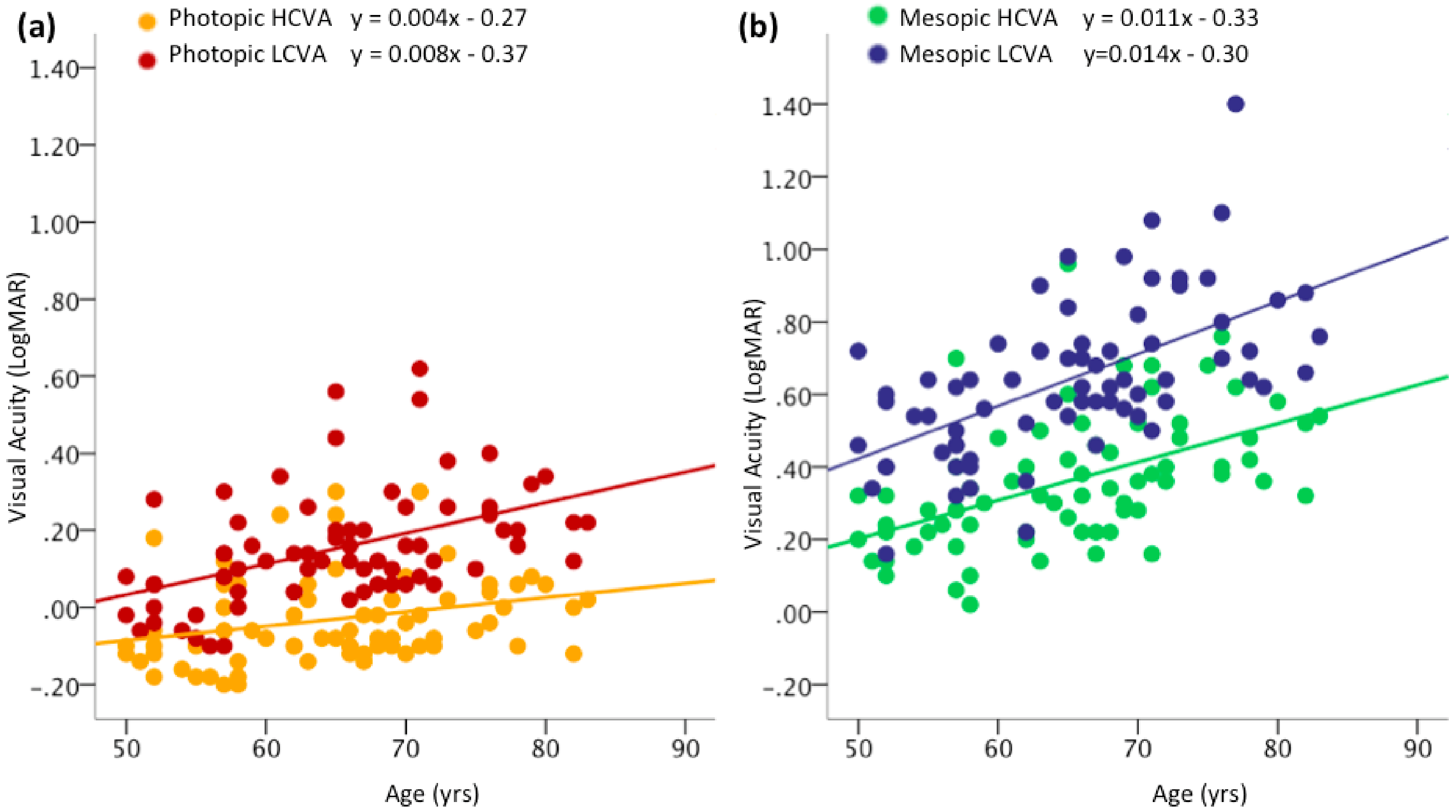


Figure 4-8: Relationship between age and binocular habitual high and low contrast visual acuity under (a) photopic (100 ± 2cd/m^2) and (b) mesopic (0.38 ± 0.02cd/m^2) luminance level.

The effects of glare varied greatly between participants as evidenced by the Mesotest, Halometer area, and Berkeley DGI data for both the full and subgroup samples (Table 4-4). Twelve of the participants in the full sample, including three from the subgroup, were assigned the maximum halo area because they could not identify the optotype at the outermost edge of the iPad screen.

The percentage of participants who would be eligible for night driving, and passed the Mesotest II level 1 required for a private vehicle licence according to German Ophthalmological Society's guidelines, are shown in Table 4-5. From the full sample, almost half of the drivers would not be eligible to drive at night. Even though the subgroup reported greater vision-related night driving difficulties, the proportion of drivers who were ineligible to drive at night according to German Ophthalmological Society standards decreased to just under a third for the subgroup who all had VA better than 0.1logMAR.

Table 4-5: Percentage of participants passing Mesotest II level 1 and eligible for night driving according to German Ophthalmological Society night vision criteria.

	Full sample n = 72	**Subgroup n = 29**
Pass (n, %)	42 (58%)	21 (72%)
Fail (n, %)	30 (42%)	8 (28%)

4.6.4 Correlations between visual function tests

Table 4-6 shows Pearson correlation coefficients (r) between the tests of visual function that were measured. It can be seen that photopic LCVA was more strongly correlated with mesopic tests than either photopic HCVA and Pelli-Robson CS. Pelli-Robson CS tested under mesopic conditions was strongly correlated with the number of Mesotest levels passed both in the presence and absence of glare. Further important findings included that the Aston Halometer halo area was significantly correlated with acuity measures and the correlation between halo area and the Mesotest with glare was stronger than the association with the Berkeley glare test which uses a diffuse glare source.

Table 4-6: Pearson correlation coefficients (r) between visual function variables and ocular characteristics. All visual function variables were performed binocularly and under habitual viewing conditions.

	Photopic HCVA (logMAR)	**Photopic LCVA (logMAR)**	**SKILL Score**	**Photopic Pelli-Robson CS (logMAR)**	**Mesopic HCVA (logMAR)**	**Mesopic LCVA (logMAR)**	**Mesopic Pelli-Robson CS (logMAR)**	**Mesotest - glare (levels passed)**	**Mesotest +glare (levels passed)**	**Berkeley Glare DGI**	**Aston Halo Area (cm^2)**
Photopic HCVA (logMAR)	1										
Photopic LCVA (logMAR)	0.87**	1									
SKILL Score	0.37**	0.54**	1								
Photopic Pelli-Robson CS (logMAR)	-0.46**	-0.57**	-0.47**	1							
Mesopic HCVA (logMAR)	0.64**	0.72**	0.59**	-0.34**	1						
Mesopic LCVA (logMAR)	0.52**	0.65**	0.57**	-0.35**	0.73**	1					
Mesopic Pelli-Robson CS (logMAR)	-0.41**	-0.57**	-0.54**	0.46**	-0.70**	-0.78**	1				
Mesotest -glare (levels passed)	-0.46**	-0.57**	-0.57**	0.33**	-0.62**	-0.56**	0.70**	1			
Mesotest +glare (levels passed)	-0.38**	-0.52**	-0.46**	0.29*	-0.53**	-0.54**	0.62**	0.70**	1		
Berkeley Glare DGI	0.38**	0.50**	0.46**	-0.45**	0.35**	0.43**	-0.36**	-0.43**	-0.34**	1	
Aston Halo Area (cm^2)	0.67**	0.72**	0.45**	-0.44**	0.64**	0.48**	-0.47**	-0.57**	-0.53**	0.43**	1

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

4.6.5 Analyses of VND-Q scores and visual function test outcomes

Full sample analysis (n=72)

Table 4-7 shows the generalised linear regression model outcomes with VND-Q score as the dependent variable for unadjusted models. Additional models were adjusted for gender because, as previously discussed, males reported significantly less vision related night driving difficulties. Data were not adjusted for night driving exposure (amount of night driving) as few participants drove more than 50 km/week at night and night driving exposure is also likely to vary according to drivers' visual function.

Photopic VA and halometer area were significantly associated with VND-Q scores in the unadjusted models. In the gender-adjusted models, photopic LCVA, mesopic CS and Mesotest outcomes were also significantly associated with VND-Q scores. The significant tests of visual function independently accounted for between 5-13% of the variation in VND-Q score in the adjusted models (Table 4-7). The strongest predictors of VND-Q scores were photopic HCVA, Mesotest in the absence of glare, and halometer area. There was no significant difference in VND-Q scores between participants that passed the Mesotest and those that failed, regardless of whether the models were unadjusted or gender-adjusted (unadjusted χ^2=0.44 p=0.51; adjusted χ^2=2.48 p=0.11).

Generalised linear regression outcomes with VND-Q score as the dependent variable and the difference between photopic and mesopic high contrast VA as the independent variable, showed a significant relationship where those with a greater difference between photopic and mesopic HCVA reported greater vision related night driving difficulties (χ^2=5.05 p=0.025). However, when the data was adjusted for gender the relationship was no longer significant (χ^2=1.55 p=0.21). In models using the difference between photopic and mesopic low contrast VA as the independent variable, there was no significant relationship with VND-Q scores for unadjusted or gender adjusted outcomes (unadjusted χ^2=2.01 p=0.16; adjusted χ^2=0.81 p=0.37). Gender was significant in each of the models that were tested ($p<0.05$).

Table 4-7: Associations between VND-Q Rasch scores and measures of visual function tests for the full sample and subgroup of participants using generalised linear models. Univariable (unadjusted) and multivariable (adjusted) data are shown for the full sample and the subgroup.

		Full sample n = 72					**Subgroup n = 29**				
		Unadjusted		***Adjusted***[a]			***Unadjusted***		***Adjusted***[a]		
	Visual Function Variable	**Wald Chi-Square**	**p-value**	**Wald Chi-Square**	**p-value**	**R-sq**[b]	**Wald Chi-Square**	**p-value**	**Wald Chi-Square**	**p-value**	**R-sq**[b]
Photopic	High Contrast Visual Acuity (logMAR)	8.62	**0.003**	9.83	**0.002**	11	0.38	0.54	0.62	0.43	-
	Low Contrast Visual Acuity (logMAR)	3.67	**0.055**	6.42	**0.011**	7	0.15	0.70	0.52	0.47	-
	SKILL score	2.85	0.09	3.02	0.08	-	1.06	0.30	0.88	0.35	-
	Contrast Sensitivity (logCS)	2.10	0.15	0.09	0.76	-	0.00	0.98	0.39	0.53	-
Mesopic	High Contrast Visual Acuity (logMAR)	0.05	0.82	1.36	0.24	-	0.14	0.70	0.75	0.39	-
	Low Contrast Visual Acuity (logMAR)	0.00	0.95	1.07	0.30	-	0.92	0.34	1.88	0.17	-
	Contrast Sensitivity (logCS)	0.77	0.38	3.48	0.06	-	5.01	**0.025**	8.46	**0.004**	20
	Mesotest -glare (levels passed)	3.24	**0.072**	10.56	**0.001**	11	5.52	**0.019**	12.01	**0.001**	30
Glare	Mesotest + glare (levels passed)	1.05	**0.305**	4.45	**0.035**	5	6.55	**0.010**	9.68	**0.002**	23
	Halo area (cm^2)	5.75	**0.017**	11.82	**0.001**	13	0.24	0.62	0.76	0.38	-
	DGI Berkeley Glare Test (VAR[c])	0.57	0.45	0.08	0.78	-	0.00	0.96	0.21	0.65	-

[a] Gender, included as factor, was significant in all models p<0.05

[b] Proportion of total variance in VND-Q Rasch scores accounted for by the vision test component of adjusted models

[c] Visual Acuity Rating (VAR) = 100-50(logMAR)

Subgroup analysis (n=29)

For the subset of participants who reported substantial levels of vision-related night driving difficulties yet had normal VA for their age, mesopic CS and Mesotest outcomes (in the absence and presence of glare) were significantly associated with VND-Q Rasch scores for both unadjusted and gender adjusted models (Table 4-7). Figure 5-10, Figure 5-11, and Figure 5-12 show the relationship between these tests and VND-Q Rasch scores.

Importantly, no photopic tests were significantly associated with VND-Q scores for the subgroup. The percentage of variation explained by the mesopic tests, including mesopic CS and the Mesotest in the presence and absence of glare, was between 20-33% and this was approximately 2-3 times the variance accounted for by any test in the equivalent full sample analyses (Table 4-7).

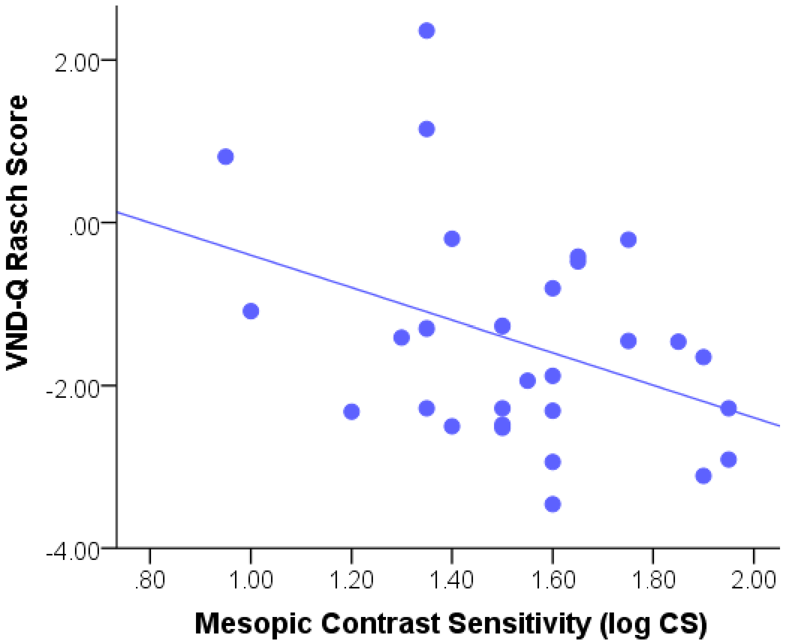


Figure 4-9: Relationship between mesopic Pelli-Robson contrast sensitivity and VND-Q Rasch scores (n=29; unadjusted data)

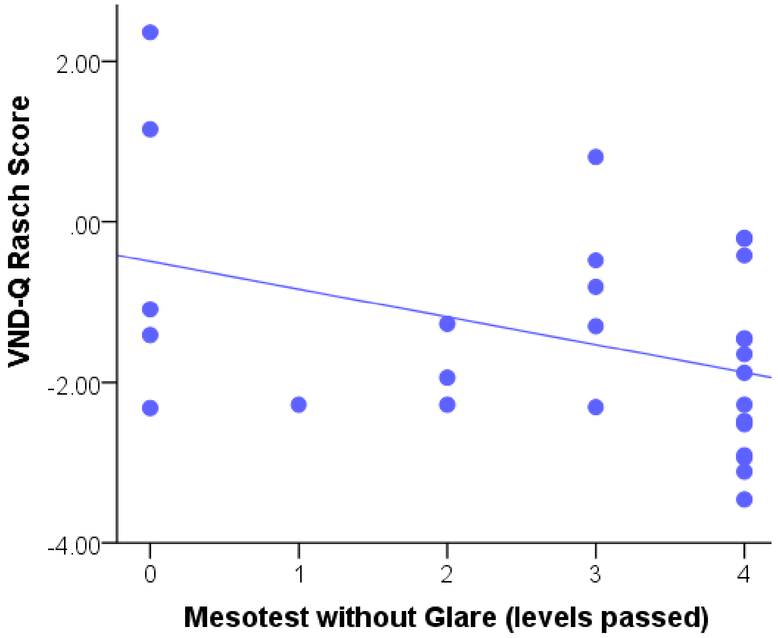


Figure 4-10: Relationship between levels passed of the Mesotest without glare and VND-Q Rasch scores (n=29; unadjusted data).

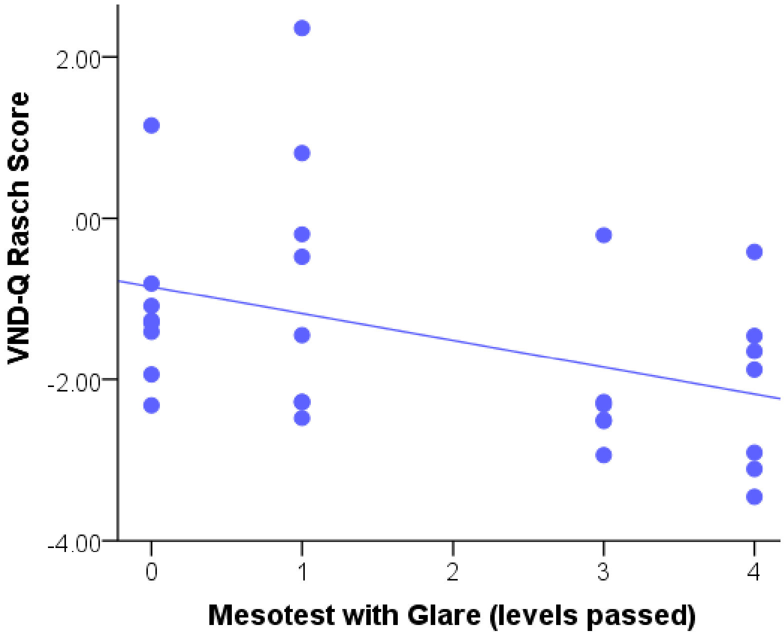


Figure 4-11: Relationship between levels passed of the Mesotest with glare and VND-Q Rasch scores (n=29; unadjusted data).

4.6.6 Ocular characteristics outcomes

Pupil size and straylight characteristics for the full sample and subgroup are shown in Table 4-8. Pupil size and the straylight parameter were not significantly associated with VND-Q scores for either the full sample (photopic pupil diameter χ^2=1.52 p=0.22; mesopic pupil diameter χ^2=1.69 p=0.19; straylight parameter χ^2=0.41 p=0.71) or the subgroup sample (photopic pupil diameter χ^2=0.008 p=0.93; mesopic pupil diameter χ^2=0.037 p=0.85; straylight parameter χ^2=0.005 p=0.94). Adjusting for gender did not change this outcome. There was also no significant effect of pupil size on the outcomes of any of the visual function tests. This finding indicates that differences in retinal illumination or adaptation states (via pupil size) is unlikely to confound the associations between the visual function tests and VND-Q scores.

Table 4-8: Pupil size and straylight parameters for the full group and subgroup.

	Full sample (n=72)		**Subgroup (n=29)**	
	Mean ± SD	Range	Mean ± SD	Range
Photopic pupil diameter (mm)	3.61 ± 0.59	2.50 - 5.40	3.66 ± 0.60	2.50 - 4.75
Mesopic pupil diameter (mm)	5.10 ± 1.00	3.30 - 7.40	4.95 ± 0.87	3.55 - 7.40
Straylight parameter (s)	1.29 ± 0.25	0.83 - 2.01	1.24 ± 0.25	0.83 – 1.82

4.7 DISCUSSION

In this study, the VND-Q was used to quantify vision-related night driving difficulties of older drivers who identified themselves as having difficulty in low luminance or glare conditions. Photopic, mesopic and glare-based measures of visual function were compared with the vision-related night driving difficulty ratings, and demonstrated that photopic tests commonly used in clinical eye examinations do not always reflect self-reported vision-related night driving difficulties. Photopic HCVA was significantly associated with VND-Q scores for the full sample and non-standard tests did not appear to be of added value for assessing self-reported difficulties. Importantly, for participants who reported substantial difficulties with their vision under low-luminance conditions, in glare or for night driving, yet had good VA for their age, the mesopic tests were more strongly associated with VND-Q scores in comparison to photopic measures which were not significantly associated with VND-Q scores. Thus the assessment of visual function under photopic conditions is not likely to detect individuals who have vision-related difficulties under low-luminance or glare conditions when driving at night.

The age-related associations between loss of VA with decreased contrast and luminance support those of previous studies;[23,213] these results reinforce the notion that age-related changes preferentially affect VA under low luminance and low contrast conditions, such as those encountered when driving at night. It was interesting that there was no significant association between VND-Q Rasch scores and age despite the decrease in visual function in this sample with age. The uneven distribution of eye conditions, presence of IOL in some participants and differences in night driving exposure may confound the age associations with VND-Q scores; however, even models adjusting for these factors failed to demonstrate that older drivers in this sample reported greater vision-related night driving difficulties. The study was designed to include drivers who specifically reported visual difficulty driving at night, therefore a selection bias might account for the lack of the expected association between vision-related night driving difficulties and age.[112]

The lack of association between the C-quant straylight parameter and self-reported vision-related night driving difficulties was expected. A large study (n=2422 drivers; 20-89 yrs) by Michael et al.[214] demonstrated that intraocular straylight measured by the C-quant had a statistically significant but only weak association with self-reported difficulties based on NEI-VFQ mean overall scores and the NEI-VFQ single question regarding night driving difficulty. Michael et al. found significant differences in straylight parameter values for the night driving difficulty categories of “no difficulty” and “little difficulty”, but no significant difference between the categories “little difficulty” and “moderate difficulty”; there was also a wide range of straylight parameter values for the participants who reported extreme difficulty or had stopped driving at night. The latter findings provide support for the current study, given that the participants were recruited because they reported at least some level of night driving difficulty. Although this study did not set out to investigate underlying mechanisms related to reported night driving difficulties, these findings suggest that age-related lens changes and the resultant increase in straylight within the eye are not the primary mechanisms underlying night driving difficulties. Tests of visual function, which are effective regardless of underlying mechanisms, are therefore vital for identifying patients who may not be safe to drive at night.

Full sample analysis (n=72)

In the full sample of 72 participants, the association between photopic HCVA and night-driving difficulty was not surprising, given that closed-road driving studies have demonstrated significantly worse night driving performance scores due to even small amounts of optical defocus that degrade photopic VA.[138,141] The current study findings also concur with previous studies demonstrating significant associations between photopic VA and self-reported night driving difficulty (assessed using a single question about difficulty driving at night),[247] and between photopic VA and night-time crash risk.[29] However, the relationship between photopic VA and both self-reported and actual night driving performance is unclear as other research reports poor correlations between photopic VA and perceived night driving difficulty, assessed using a single question about night driving[248] and between photopic VA and closed-road night driving recognition scores (e.g. road signs and pedestrians).[26,249]

A closed-road driving study also demonstrated that pedestrian recognition distances at night-time are significantly reduced in the presence of headlight glare for conditions of induced blur compared to optimal refractive correction.[138] This finding is supported by the current data showing a relatively strong correlation between photopic VA and halo area ($r=0.67$, $p<0.01$), where glare and haloes from oncoming headlights would be significantly greater with defocus or with reduced VA, although the relationship may vary depending on whether the cause of VA loss was refractive or neurological.

Seventy-eight percent of the study population were optimally corrected. However, several of the participants commented that they had updated their spectacles or started wearing their previously prescribed spectacles in response to the experimental testing and were now experiencing less vision-related night driving difficulties. This anecdotal evidence suggests that the introduction of testing under low luminance and glare conditions could alert patients to visual deficits that may be affecting their night driving difficulties. Further research in this area is warranted to investigate whether night driving performance and crash risk can be improved by increasing drivers' awareness of their visual limitations at night through testing vision under non-standard lighting conditions.

The use of LCVA, CS and testing vision using mesopic lighting conditions has been advocated for older adults due to the greater and earlier decline of vision measured under low luminance levels or using low contrast targets. [26,28,240,250,251] A recent study demonstrated significant reductions in CS in older adults with early and intermediate AMD, compared to healthy controls, and this effect was most apparent under mesopic conditions.[75] For the full participant sample, this study failed to demonstrate that photopic LCVA and photopic Pelli-Robson CS and mesopic tests were more strongly associated with self-reported vision-related night driving difficulties than photopic VA. Studies have demonstrated that photopic CS is associated with self-reported visual function[220] and is an important predictor of night-time driving recognition performance, particularly in relation to pedestrian detection.[26,27] Furthermore, in a study of night driving avoidance the value of photopic CS and LCVA were demonstrated, where photopic CS was the visual function most closely associated with avoidance of night-time driving in males, and LCVA in the presence of glare was most closely associated with driving for females.[6] However, the current study concurs with the findings of a previous study that Pelli-Robson CS does not have added value for the prediction of night driving difficulties as assessed by the ADVS in large cohort study.[214] In the present study, when the data was adjusted for gender, photopic LCVA was significantly associated with VND-Q scores which supports the evidence that it may be useful for assessing night-driving difficulties.

Photopic CS has also been shown to relate to mesopic VA,[24,26] so for this reason may be particularly useful for predicting night driving ability. However, testing cone-mediated vision might not be an appropriate substitute for assessing true mesopic vision where the rods and cones both contribute to visual function.[15] If vision-related night driving difficulties arise because of underlying neural dysfunction or pupil size, the adaptation state during testing may be critical and it may be necessary to measure VA and CS specifically under mesopic light levels to gain a true measure of vision under night-time driving conditions.

With regard to the glare tests in the present study, several glare tests demonstrated significant associations with the VND-Q Rasch scores. These included the Mesotest II (with glare) and the Aston Halometer but not the Berkeley glare test. It is likely that the diffuse lighting of the Berkeley test does not simulate headlights as effectively as the point glare sources of the other tests and that the near test distance is not optimal for simulating driving conditions. Night driving studies have not previously shown the Berkeley Glare DGI to be a particularly strong predictor of driving performance, albeit having some association with driving recognition performance and hazard avoidance scores.[138]

Future work should focus on determining whether glare measures, such as the Aston halometer or the Mesotest II (with glare) are significant predictors of actual night driving performance measures. It should be noted however, that the halometer test on the small LCD screen limited testing to those individuals with moderate or lower glare problems (maximum score was assigned to 17% of participants) and therefore may need to be adapted for use with older patients with cataracts or other ocular diseases. It should also be noted that the testing of mesopic LCVA also posed difficulties for some participants who needed to move to a closer working distance to see even the top line of the letter chart. The combination of 0.38cd/m^2 and 10% letter contrast may not be optimal for assessing Mesopic LCVA and is a further issue requiring investigation.

Subgroup analysis (n=29)

When the study sample was restricted to drivers with good VA for their age and substantial self-reported night driving difficulties, tests of mesopic visual function had particular value for revealing visual deficits in those with normal photopic HCVA. Importantly, this study is the first to specifically examine a cohort with substantial low-luminance, glare, or vision-related night driving difficulties, but who had relatively normal photopic VA with no visual impairment. For this subgroup of individuals, a key finding was that mesopic CS and the Mesotest II outcomes, in the presence and absence of glare, demonstrated a significant association with VND-Q Rasch scores while photopic testing did not.

The findings of the current study are in accord with the only other study reporting on the association between subjective night-time driving disability and mesopic vision, where Mesotest II outcomes, in the presence and absence of glare, were significantly associated with the difference between self-rated day-time driving difficulty and difficulty driving at night and in poor weather.[248] The data here, also support studies reporting that photopic and mesopic tests provide different information about vision, such that photopic measures of visual function are not surrogates for mesopic measures of visual function.[23,113] Mesopic VA is more sensitive to age-related degenerations and specifically, to declines in visual function caused by optical factors such as nuclear opalescence or wavefront aberrations.[23] Photopic measures of CS or LCVA have also been shown to be poor predictors of equivalent mesopic test outcomes, indicating that mesopic testing reveals different information about visual function.[113]

For the subset of 29 participants who had good VA and CS based on a routine eye-examination under photopic conditions, a clinician may dismiss the possibility of night-driving difficulties related to vision. This outcome may have important consequences for driver safety and could also impact on rapport between the patient and clinician. The assessment of mesopic visual function using tests such as the Mesotest and mesopic CS would be more valuable for the assessment of such patients and could be potentially useful for providing advice to patients about their visual fitness to drive at night.

Further exploration of mesopic tests in relation to actual driving performance and safety when driving at night, is necessary to confirm these preliminary findings and to confirm the value of mesopic vision testing. Determining the length of adaptation that is necessary prior to testing under mesopic conditions would also be a valuable avenue for future investigation as it would reinforce the practical usability of mesopic tests in a clinical setting. Future study is critical because the implications of the current study also reach beyond those with no deficits in VA or CS: if photopic testing does not inform clinicians of potential night driving difficulties in normally-sighted individuals, the extent of reductions in mesopic visual function for drivers with some visual impairment might similarly be unknown and at a level that might seriously impair night driving performance and safety.

Strengths and limitations of the study

A major strength of this study was the investigation of a wide range of both standard and non-standard visual function tests that are practical for clinical use. By including participants who had concerns about their vision for night driving, it was possible to investigate whether non-standard testing using mesopic or glare-based tests better reflected patients' subjective reports than a standard assessment of photopic VA.

However, there were some limitations to this study including the inherent subjectivity of self-reported data. Drivers have been shown to overestimate their ability to see at night,[20] therefore it is possible that the participants may have underestimated rather than overestimated their difficulties. Although, regarding headlight glare, discomfort can inflate difficulty ratings because patients can confuse discomfort and actual visual disability.[16] Furthermore, the participants in this study mostly drove less than 50 kilometres at night per week, therefore their capacity to accurately rate their night driving performance may be limited by their relatively low levels of exposure to night driving. Alternatively, the low level of night driving may reflect that the cohort was insightful about their visual limitations and hence would be relatively insightful when rating their night driving difficulties. As previously suggested, future study is necessary to confirm these findings by assessing the associations between mesopic tests of visual function and actual driving performance; therefore, Study 3 (Chapter 5) was designed to explore these relationships.

4.8 CONCLUSIONS

Driving is important for older adults' independence and quality of life[1] so the presence of vision-related night driving difficulties and their assessment should be carefully considered. The results from this study add to the growing evidence that the photopic VA standards for drivers licencing may be inadequate for assessing visual fitness to drive at night. Study 3 (Chapter 5) further explored how actual closed-road driving performance relates to VND-Q scores and tests of visual function. Importantly, in the present study, non-standard mesopic vision testing protocols were found to better reflect self-reported vision-related night driving difficulties than standard photopic tests in older adults with good VA.

Examination of vision under mesopic conditions may alert patients to the fact that extra caution is required at night and may prompt better self-regulatory practices. In addition, mesopic vision testing may be useful in aiding clinical decisions regarding timing of cataract extraction or for other interventions that may positively impact on visual quality and reduce night driving difficulties. Rigorous investigations of the level of mesopic vision that affects actual night-time driving performance and safety are necessary to determine if mesopic testing should be routinely assessed for fitness to drive at night. The data presented in this study will guide the development of protocols for the assessment of mesopic vision function for older drivers, and are an important basis for research presented in Study 3 (Chapter 5) regarding night driving performance.

Chapter 5. STUDY 3 - NIGHT DRIVING PERFORMANCE OF OLDER ADULTS

5.1 INTRODUCTION

Driving at night is hazardous; as discussed throughout this thesis, crash risk is increased at night compared to daytime,[9] especially for vulnerable road users such as pedestrians.[8] Fatigue, excessive speed, and alcohol consumption play a role in these increased risks, especially for younger adults;[10,87,88] however, reduced visibility under night-time conditions is a primary factor contributing to pedestrian and cyclist collisions,[8,10] and can cause significant reductions in aspects of driving performance such as road sign recognition[17,252] and hazard detection.[17,26] The effect of the age-related deterioration in visual function on crash-risk is unclear, although the decrease in driving performance due to low luminance levels and glare at night is known to be exaggerated in older drivers compared to their younger counterparts.[17,27,137,252]

The important role of vision in driving has been widely discussed.[7] However, questions have been raised as to whether the current measurement of photopic HCVA is optimal for determining fitness to drive, particularly at night-time.[26,253,254] Currently, licenced drivers in most countries are eligible to drive under both day and night conditions despite the fact that the visual tests included in licensing are generally VA measured under photopic conditions which is not necessarily relevant to night-time driving. Given the absence of specific visual requirements for night driving, drivers make their own judgements regarding their ability to drive at night and self-regulate their driving behaviour accordingly. This reliance on the self-regulation of night driving and the self-reporting of night driving difficulties is not ideal because, as previously described, drivers are known to underestimate their visual limitations at night,[17–19] poorly assess their own driving abilities,[20,21] and self-restrict their night driving based more strongly on confidence levels than visual impairment or true driving ability.[134]

A key finding by Lachenmayr et al.[29] was that drivers with poorer visual function under low-luminance conditions and in the presence of glare had a three times increased crash risk at night compared to drivers with better vision under these conditions. Other crash analyses also show that visibility is one of the primary determinants of safe driving at night, being the main factor contributing to the seven times increased risk of pedestrian fatalities at night compared to daytime.[8]

The relative preservation of visual guidance ability at night (according to the selective degradation hypothesis described in Chapter 2, section 2.5) has been postulated as an underlying reason why many drivers have falsely high perceptions of visibility and high levels of confidence when driving at night.[139] It has been suggested that drivers are comfortable driving at day-time speeds at night even though they exceed the theoretical 25-50 km/hr speed necessary for successful avoidance of road hazards using low-beam headlights.[255] Stopping distances are however, dependent on road lighting, surface conditions and drivers' individual reaction times and visibility distances. Drivers also tend to be reluctant to use high-beam headlights which may also be an indication that they are unaware of their visual limitations at night,[89] given that high-beam headlights can increase visibility by a factor of up to 3.5.[137] The benefits of brighter headlights, however, may be out weighed by the impact of glare for oncoming traffic and this is likely to contribute to drivers' decisions to drive primarily with their low-beams.[89]

Glare has been shown to be a particular problem reported by drivers at night.[86] However, self-rated visual disability resulting from glare tends to be greatly overestimated, where drivers' judge the intensity of glare that will impair their visual acuity at levels that are 88% less than the actual intensity required.[89,90] Paradoxically, drivers also overestimate the distances at which they can identify targets and pedestrians in the face of oncoming headlights, particularly for low intensity glare sources such as low-beam headlights.[18,256] It is evident that self-rated glare difficulties are complex and this is likely to be because they incorporate both the perception of disability and discomfort glare. Notably, discomfort glare increases for smaller angles of glare incidence at the eye, for larger or more numerous glare sources and for more difficult tasks, even without a change in illuminance at the eye.[16] One study demonstrated that very low levels of glare which were expected to cause no visual impairment resulted in poorer pedestrian detection purely from the effects of discomfort (e.g. aversion from the light source) in the presence of glare.[143]

In closed road studies, older drivers have been shown to drive more cautiously and at slower speeds at night than younger drivers.[17,143] This may suggest at least some awareness of the difficulties associated with vision when driving at night, although these behaviours do not fully compensate for the reduced visibility resulting from the low luminance levels[17] or glare[143] of the night driving environment. Furthermore, there is evidence that under real world road conditions, average driving speeds are not significantly different between day and night-time,[257] and it is difficult to adjust driving speed when driving with the flow of real-world traffic.

As discussed in the literature review, few studies have investigated the link between visual function and night driving performance. Crash analyses show that photopic VA is more likely to be reduced in drivers with a history of a state-reported night-time crashes compared to drivers without a crash history, although mesopic CS and glare sensitivity appear to be reduced to an even greater extent than photopic VA in these drivers.[29,126] These studies, however, have not been replicated and there is a need for further investigation in order to confirm the link between visual function and night-time crash risk. Clinicians cannot confidently determine if mesopic vision and glare sensitivity are appropriate for age and subsequently whether a patient is visually fit to drive at night without having clear evidence of a relationship between tests of visual function and objective measures of driving performance.

This experimental study conducted as part of this PhD program aimed to build upon previous findings in order to provide a clearer understanding of the relationships between photopic, mesopic and glare based measures of visual function, vision-related night driving difficulties, and closed-road night driving performance. Section 5.2 below outlines the range of driving study design options that could have been adopted for the current study, to provide context for the experimental method that was chosen.

5.2 DRIVING STUDY DESIGN

There are five main outcome measures that have been used as indices of driving performance and safety. These include: (1) driver reported data on perceived driving ability and behaviours, (2) analysis of crash data, (3) driving simulator performance measures, (4) closed-road driving performance measures, and (5) open-road driving performance measures.[258] Each methodology has both unique advantages and limitations for the assessment of various aspects of driving performance. Thus understanding the differences between study designs is important as different methodological approaches may result in apparently inconsistent outcomes which need to be interpreted appropriately. Table 5-1 summarises some examples of studies that have explored the relationship between tests of visual function and night driving for driver reported data, crash analyses, closed road condition, simulator studies, and open-road investigations. Sections 5.2.1 to 5.2.5 below explain each of the five main driving study designs in further detail.

Table 5-1: Links between visual function and night driving study outcomes

	Study Population	Relationship between visual function and night driving	Source
Driver reported data	257 older drivers (56-90 yrs)	The avoidance of night driving (DHQ) was weakly correlated with photopic VA, photopic CS, and VF mean defect ($p \leq 0.05$).	Ball et al. 1998[5]
	297 drivers (21 to >70 yrs)	45% of drivers who reported avoidance of night driving were unable to perform any level of the Mesotest with glare compared to 14% of drivers who still drove at night ($p<0.01$). 20% of drivers who avoided driving at night were unable to perform any level of the Mesotest without glare compared to 5% of drivers who still drove at night ($p<0.01$). Drivers with poor photopic VA and self-reported avoidance of night driving had worse mesopic CS and greater glare sensitivity.	Puell et al. 2004[24]
	752 older drivers (58-96 yrs)	Females: self-reported night driving cessation (modified VAQ) was significantly related to low contrast VA in the presence of glare (OR = 1.84, no p-value specified). Males: self-reported night driving cessation (modified VAQ) was significantly related to photopic CS (OR = 2.72, no p-value specified).	Brabyn et al. 2005[6]
	16 drivers (18-33 yrs)	Estimates of night-time recognition distances in the presence of glare were more closely related to subjective reports of glare induced discomfort (deBoer scale) than to actual recognition distances ($p=0.01$).	Balk & Tyrrell 2006[89]

Table 5-1: Links between visual function and night driving study outcomes (continued)

Driver reported data	1605 drivers (65-84 yrs)	Worse baseline scores in CS and central and lower peripheral VFs were individually associated with a greater odds of night driving cessation 2 years later.	Freeman et al. 2006[153]
	1543 older drivers (≥75 yrs)	Night driving avoidance (DHQ) was not significantly associated with UFOV scores ($p=0.428$).	Okonkwo et al. 2008[259]
	990 drivers (≥68 yrs)	Exposure to night driving (odometer recordings) was significantly associated with higher photopic CS and VF ($p=0.02$, 0.05, respectively); photopic VA was not ($p=0.12$).	Kaleem et al. 2012[260]
	17 younger drivers (18-21 yrs) 11 older drivers (65-80 yrs)	Older participants overestimated their own VA and the disabling effects of headlight glare on pedestrian recognition ($p<0.05$).	Stafford Sewall et al. 2014[261]
Crash analyses	432 with history of night crash (30-59 yrs) 432 control persons (30-59 yrs)	Almost 20% of professional drivers involved in night-time collisions with other road users had severely diminished twilight vision (Mesotest without glare); 25% had increased susceptibility to glare (Mesotest with glare). The risk of collision for these drivers was greater than for those who fully satisfied the minimum requirements for these visual functions ($p\leq0.01$).	Von Hebenstreit 1984[126]
	261 drivers with state recorded crash history (56 ±12 yrs) 250 drivers no state crash or insurance claim (58 ± 10 yrs)	Photopic VA, Mesopic VA, and glare sensitivity, were significantly reduced in those with a history of night-time crashes compared to a control group ($p<0.001$, $p<0.001$, $p<0.01$, respectively); VF mean defect was not associated with night-time crash risk (no p-value specified).	Lachenmayr et al. 1998[29]

Table 5-1: Links between visual function and night driving study outcomes (continued)

Simulator studies	A: 9 drivers (28-55 yrs) B: 8 young drivers (21-29 yrs) 8 older subjects (67-78 yrs)	Steering accuracy was degraded by visual field reduction but not blur or low luminance. Low luminance degraded the steering of older drivers more than younger drivers whose steering accuracy was preserved under low luminance.	Owens & Tyrrell 1999[139]
	21 drivers (20-65 yrs)	Decreased background luminance from 0.1-1cd/m^2 and increased target eccentricity were associated with poorer target detection and overall driving performance. Off-axis targets on the left-hand side tended to be missed at high driving speeds and low luminance.	Alferdinck 2006[262]
	10 driving instructors (51 ± 11 yrs) 11 learner drivers (21 ± 2 yrs)	Visual search strategies were poorer under night-time conditions compared to day-time driving conditions.	Konstantopoulos et al. 2010[263]
Closed-road studies	12 young drivers (20 ± 3 yrs) 12 older drivers (70 ± 4 yrs)	Photopic VA did not account for the age-related differences in night-time traffic sign legibility distances (p>0.05).	Sivak et al. 1981[249]
	6 young drivers (23 ± 4 yrs) 6 older drivers (68 ± 6 yrs)	There was no significant difference in traffic sign legibility distance for young and older subjects when matched for high-contrast low-luminance VA.	Sivak & Olsen 1982[264]

Table 5-1: Links between visual function and night driving study outcomes (continued)

Closed-road studies	8 young drivers (22 ± 3 yrs) 8 middle aged drivers (47± 4 yrs) 8 older drivers (72 ± 3 yrs)	Photopic VA did not predict measures of night-time driving recognition performance (p>0.05).	Wood & Owens 2005[26]
	20 drivers (28 ± 6 yrs)	CS predicted a greater proportion of night-time driving performance than photopic VA and both were significant predictors of performance (p=0.001).	Wood et al. 2010[265]
	28 drivers (20-36 yrs)	Pedestrian detection and recognition distances were significantly impaired by simulated visual impairment (p<0.001) and glare (p<0.035). The effect of simulated cataract was greater than blur despite having matched VA (p<0.001).	Wood et al. 2012[138]
	12 young drivers (17-33 yrs) 12 older drivers (66-80 yrs)	Pedestrian recognition distance was predicted by a test of motion sensitivity even when controlling for driver age.	Wood et al. 2014[27]
Open-road studies	990 drivers (75.7 ± 5.2 yrs)	Driving at night was associated with better contrast sensitivity (p = 0.02) and visual field detection (p = 0.05). Photopic visual acuity was not significantly related to whether participants drove at night or not (p = 0.12).	Kaleem et al. 2012[260]

5.2.1 Driver reported data

Chapter 3 described the advantages of self-reported difficulties obtained through questionnaires and interviews, in terms of providing a drivers' perspective of the functional effects of visual difficulties. This includes any compensatory behaviours and impacts on quality of life.[258] Drivers can be asked about specific task difficulties, comfort and confidence, driving habits (e.g. exposure to different road conditions, amount of driving), and driving errors (e.g. crashes or near misses).[258] This approach enables a comprehensive profile of attitudes and beliefs regarding drivers' perceptions of their own driving abilities and behaviours to be obtained, although can be influenced by tolerance to discomfort and visual disability, confidence levels, personality, accessibility to other transport options and lifestyle choices.[5,186,258]

The other type of self-reported data in relation to driving involves an individual rating their own driving abilities. It is important to note that this type of self-reported data are not surrogate measures for driving performance or safety as drivers typically demonstrate limited insight into their own driving abilities, because unless a near miss or crash occurs, there is no feedback on which to base a judgement of ones' own driving ability. Interestingly though, drivers who are overconfident of their ability, as compared to on-road assessments of actual driving ability, are more likely to report being involved in a previous crash.[20]

5.2.2 Analyses of crash data

Crash data are the gold standard for determining the safety of drivers and can indicate driver ability or impairment when at-fault data is used.[258] Where all crashes are used, regardless of fault, larger sample sizes can be obtained because the data is not limited to only crashes where fault is known. In these types of studies, any association between visual impairment and driving performance is usually diminished since some of the crashes are not due to the visual characteristics of the driver. There is a hierarchy of crash data, ranging from the most valuable data being at-fault and state-recorded, through to self-reported crash data which lacks an objective assessment of fault and may be affected by memory lapses or unwillingness to admit to wrong-doing due to social or privacy concerns.[266] The use of police-recorded incidents or state-reported crashes can enable greater accuracy and eliminate bias; however, this type of data may be difficult to obtain since access to state records is governed by laws and regulations.[258] There is only a moderate correlation between state-recorded and self-reported crash data,[266] which is not only due to the factors mentioned above but also due to self-reported data capturing additional incidents that would not usually be recorded in the state crash record. In examining and comparing crash data it is therefore also important to consider the particular type of crashes that are relevant, such as for different environmental conditions (e.g. day or night),[147] road situations (e.g. turning across an intersection)[267] and crash outcomes (e.g. fatal or minor).[267]

5.2.3 Driving Simulator Studies

There are many complexities involved in the night-time driving environment making it difficult to accurately replicate, although numerous studies have attempted to use driving simulators for investigating vision and aspects of night driving performance.[139,152,262,263,268–270] The simulation of night-time driving must take into account ambient illumination, the headlights of the driver’s vehicle and those of oncoming headlights.[271] Visual performance is highly dependent on these lighting conditions,[135,136] therefore replicating on-road conditions as closely as possible is important for the validation of night driving simulator study outcomes. In addition, and particularly at night, variations in road type, traffic density, street lamp source, headlight designs, and weather conditions are also important complexities to be taken into consideration for night driving simulators.[271] Simulator studies currently have limited value due to the difficulty accurately replicating a true night driving environment. However, simulator studies carry lower risks for participants than road-based studies and if better designs are developed, could arguably provide easier manipulation of environmental conditions than in real world settings, which are affected by natural weather cycles and the need to perform testing at night.

5.2.4 Closed-Road Driving Studies

Closed-road studies are undertaken on driving circuits where access is restricted and there is no other traffic on the road. The main advantage of these types of studies is that driving conditions can be standardised across participants and task difficulty can be manipulated without compromising safety.[258] For example, participants can be asked to drive around an experimental circuit with added distracters and obstacles, allowing assessment of driving performance for measures such as the capacity to recognise road signs, recognise and avoid road hazards, and perform judgements and manoeuvring tasks.[265] Furthermore, ambient lighting and glare sources can be manipulated. Using an instrumented vehicle, measures such as lane keeping, reaction times, pedestrian detection distances, vehicle speed, and eye movements can also be recorded.[27,272] Driving using simulated visual impairment can also be undertaken in a safe and controlled environment with the possibility for repeated measures designs without the variations in traffic that would otherwise occur on the open-road.[258]

5.2.5 Open-road Driving Studies

Open-road studies occur on public roadways, usually following a standard route that includes opportunities for the assessment of simple and complex aspects of driving performance and safety.[273–276] Performance and safety ratings can include scores for interaction with other road users, driving behaviours (e.g. following distances, anticipation and reaction times, speed regulation), and manoeuvres (e.g. merging, turns).[274] Minor errors such as drifting within the lane, failing to check blind spot and mirrors, and hazardous errors such as exceeding the speed limit, disobeying signs, drifting across lanes and sudden braking, can also be recorded and used in standardised scoring systems.[273] Hazardous errors requiring intervention from the driving instructor (applying brakes, taking hold of the steering wheel, explicit verbal guidance) are often scored as reasons for poor driving performance and safety scores.[273–275]

In open-road studies, it is difficult to standardise experimental conditions between participants; however, the presence of other vehicles, pedestrians and the complexities of real-world driving environments make this type data more valid for making inferences about driver ability and safety compared to the other driving study designs.[258] The gold standard for assessment is by a certified driving rehabilitation specialist who is often also an occupational therapist, with a dual-brake vehicle and qualified instructors being essential for monitoring and maintaining safety. Importantly, to date there has been a lack of open road studies that have been conducted under night-time driving conditions. Naturalistic driving experiments that use measuring devices to observe participants' normal driving habits, in their own vehicle, over longer period of time (e.g. weeks, months) avoid many of the limitations of open-road assessments,[260] although are rather impractical and tend to generate large amounts of data to be analysed and interpreted. With more sophisticated data collection and analysis techniques being developed in the future, these approaches are likely to provide useful data on night-time driving which will complement already existing approaches.

5.3 RATIONALE

Given there has been so little research specifically focusing on night driving and so many unknown factors it was felt that the use of a closed-road approach permitting standardization and a high level of environmental control, would be the most appropriate design for this PhD study. While there is evidence in the literature to suggest that visual function is associated with night-time driving performance, the critical visual function tests that can predict safe night driving are unclear. Determining these tests is important because self-regulation of night-driving is not always appropriate due to drivers' poor abilities to judge whether, and to what extent, they should self-regulate their night driving.

There is a clear need to identify which visual function tests best predict night driving performance. This study was therefore designed to provide an objective measure of night driving performance that could be assessed against self-reported difficulties explored in Chapter 3 and tests of visual function that were assessed in Chapter 4 and have previously demonstrated links with aspects driving performance.

5.4 AIMS AND HYPOTHESES

The primary aim of this study was to explore night driving performance in older adults who report night-time driving difficulties and to investigate the specific effect of intermittent glare on night driving performance for older adults who report having difficulty driving at night. The study was also designed to examine whether measures of mesopic and glare-based visual function were better predictors of night-time driving performance than photopic measures of visual function such as the commonly used standard measurement of photopic HCVA. Furthermore, the study aimed to evaluate how closely older drivers' perceived levels of vision-related night driving difficulty, as quantified by the VND-Q Rasch scores, were associated with objective measures of closed-road night driving performance.

It was hypothesised that (articulated as alternate hypotheses):

- Greater self-reported vision-related night driving difficulty levels, as quantified by VND-Q Rasch scores, would be associated with poorer night-time driving performance.

- The presence of intermittent glare would result in significantly reduced night-time driving performance, particularly in drivers those reporting greater difficulty scores on the VND-Q.

- Poorer outcomes on photopic, mesopic, and glare-based visual function tests would be associated with poorer night-time driving performance, in the absence and presence of intermittent glare.

- Mesopic and glare-based tests would explain a greater amount of variation in driving performance compared to photopic tests of visual function, including the standard clinical test of photopic HCVA.

5.5 METHODS

5.5.1 Sample size considerations

The methodology used in this experimental study was based on previous closed-road research conducted by the Queensland University of Technology's Vision and Driving team.[141,253,277] These studies have demonstrated that between 11 to 24 participants is an adequate sample size for these repeated-measures designs where $p<0.05$ indicates statistical significance. Using a conservative estimate of the maximum sample size ($n=24$) and allowing 10% for participant drop-out or equipment failure, it was determined that 26 participants should be recruited.

5.5.2 Participants

Twenty-six drivers aged between 63 and 88 years who reported various levels of vision-related night driving difficulties were recruited as a convenience sample from the Study 2 participants (refer to section 4.5.1); those with the greatest levels of night driving difficulties (greatest VND-Q Rasch Scores) were recruited first. All participants were licensed drivers and reported that they had driven at night within the past year. The study followed the tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology Human Research Ethics Committee (QUT HREC # 1200000401). Participants were given detailed information about the study and informed consent was obtained with the option to withdraw from the study at any time. The study was conducted over two sessions including one session for visual function testing and questionnaires, followed by a night driving component at the Mt Cotton Driver Training Centre.

5.5.3 Questionnaires

Participants repeated the vision-related night driving questionnaire (VND-Q) to provide a measure of self-reported difficulties in logit. Similar to Study 2 (Chapter 4) participants were also asked about their exposure to day and night driving in a typical week over the past month, the type of roads they drove on at night and the amount of time they avoided driving at night. Discomfort due to oncoming headlights was also rated before the driving runs according to a five option deBoer scale ranging from just noticeable to unbearable in response to the question "How disturbing do you find oncoming headlight glare?" (Table 5-2: deBoer scale used to subjectively rate discomfort from oncoming headlight glare.Table 5-2);[278] which has been widely used as a scale for rating discomfort glare.[143,256,278–280]

Table 5-2: deBoer scale used to subjectively rate discomfort from oncoming headlight glare.

Just noticeable	5
Satisfactory	4
Just permissible	3
Disturbing	2
Unbearable	1

5.5.4 Assessment of visual function

An optometric screening examination was performed prior to the visual function assessment. This included a slit-lamp examination of the anterior segment and retinal photography to assess the posterior segment to determine the presence of any ocular disease. Photopic binocular HCVA with habitual correction was also screened to ensure participants met the Australian driving VA standard (binocular VA 6/12 (0.3logMAR) or better). Monocular 40-point screenings (Humphrey Visual Field Analyser; Carl Zeiss, Meditec Inc., Dublin. CA) were performed to ensure that participants had no visual field defects that could affect driving performance.

The visual function assessment included the tests used in Study 2 (Chapter 4), except for the SKILL card and mesopic LCVA. The SKILL card was not included after consideration of Study 2 results as it demonstrated poor associations with self-reported night driving difficulties and mesopic LCVA was found to be too difficult for some participants (described in Chapter 4, section 4.7) so was also not included in this study protocol. A dot motion test was additionally included in Study 3 as the importance of motion sensitivity for driving, particularly at night, has been demonstrated in numerous studies.[149,222,281–283] The dot motion sensitivity test included in the current protocol, has been shown to relate to night-time pedestrian detection distances in a previous closed-road driving study,[27] and correlates with laboratory-based measures of driving performance, such as response time to hazards on video simulations of dynamic driving scenes in a hazard perception test.[149]

The tests of visual function were performed according to previously described methods in section 4.5.3 of Study 2 (Chapter 4), while the motion sensitivity test is explained in detail below. Specific lighting levels and test specifications are presented in Table 5-3. All measurements were performed binocularly using the participants' habitual driving correction (if any), with the addition of an appropriate working distance lens where necessary. Adaptation time to mesopic conditions was 10 minutes in accordance with the 5-10 minute timeframe used in previous studies.[114,118,120,121,127]

Motion Sensitivity

A computer-based random dot kinematogram was used to measure motion sensitivity at a test distance of 3.2 metres.[27,149] Participants were required to identify the direction of movement of a central panel of dots (subtending a visual angle of 2.9° x 2.9°) which moved randomly in one of four cardinal directions (up, down, left or right). The dot density was 0.43% and the test was conducted under mesopic lighting conditions using an average screen luminance measured as 0.36 ± 0.02 cd/m^2 (BM7 Luminance Colorimeter, Topcon, Tokyo, Japan). The minimum dot displacement threshold detected by participants (Dmin) was determined using the mean of the last 6 reversals, using a two-down one-up staircase algorithm. Dmin was defined in terms of pixel displacement.

Table 5-3: Visual function assessment: instrument specifications, light levels and test distances.

Instrument specifications			Light levels	Test distances[a]
Photopic	High contrast visual acuity LogMAR chart	90% contrast[b] optotypes Range: -0.2-1.1 LogMAR	Chart luminance: 100 ± 2cd/m^2	3.2 metres
	Low contrast visual acuity LogMAR chart	10% contrast[b] optotypes Range: -0.2-1.1 LogMAR	Chart luminance: 100 ± 2cd/m^2	3.2 metres
	Pelli-Robson contrast sensitivity chart	6/36 sp freq 1cpd optotypes Range: 0-2.25 logCS	Chart luminance: 100 ± 2cd/m^2	1 metre with +1.00DS
Mesopic	High contrast visual acuity LogMAR chart	90% contrast[b] optotypes Range: -0.2-1.1 LogMAR	Chart luminance: 0.38 ± 0.02cd/m^2	3.2 metres
	Pelli-Robson contrast sensitivity chart	6/36 sp freq 1cpd optotypes Range: 0-2.25 logCS	Chart luminance: 0.38 ± 0.02cd/m^2	1 metre with +1.00DS
	Motion sensitivity computer program	Dot panel visual angle 2.9°x2.9° Staircase stepsize: 1-2 pixels	Screen luminance: 0.36 ± 0.02 cd/m^2	3.2 metres
	Mesotest II without glare	Landolt C 6/60 sp freq 3cpd Range: 0.02-0.3 logCS	Backgound luminance: 0.032 ± 0.003cd/m^2	5 metres virtual image
Glare	Mesotest II with glare	Landolt C 6/60 sp freq 3cpd Range: 0.02-0.3 logCS	Background luminance: 0.1 ± 0.01cd/m^2 Glare source: 0.35 lux at pupil	5 metres virtual image
	Aston Halometer	0.4 logMAR optotypes Range: 8 directions 0-360°	Room lighting off Glare source: LED[c] 5000K, 40 mA, 3.7 V	2 metres
	Berkeley Glare Test	18% contrast[b] optotypes Range:-0.3-0.9 logMAR	Chart luminance: 100 ± 2cd/m^2 Diffuse glare: 750 cd/m^2	1 metre with +1.00DS

a: with habitual distance refractive correction when no working distance lens is specified

b: Weber contrast

c: Light-Emitting Diode

5.5.5 Driving Assessment

Instrumented Vehicle

All driving assessments were conducted in an automatic transmission sedan (2015 Toyota Camry) with the halogen headlights set to low-beam for testing. The vehicle was instrumented with two roof-mounted cameras (HERO4 GoPro; San Meteo, USA) which recorded lane position (1080 pixels; 30 frames per second). An audio recording device (Apple iphone®) was also used to capture participants' verbal responses.

To provide the intermittent glare source, a dimmable 7.5cm diameter diffuse LED light fixture (maximum 12V, 10W; 2700K) was mounted on the driver side of the car bonnet (Figure 5-1). The glare source was switched on and off at specific locations around the driving circuit and remained at a constant level when it was turned on during the drive. Importantly, the intensity of the glare source was adjusted for each participant, so that the illuminance at the eye was 13 ± 2 lux, as measured with an illuminance meter (IM-2D; Topcon, Tokyo, Japan). This level was 650 ± 10 cd/m^2 at the driver's eye height if they were looking directly at the glare source. The illuminance level was chosen based on pilot study investigations as described in the following section.

Figure 5-1: Glare source location for the closed-road driving experiment

Pilot studies for selection of glare source intensity

<u>Pilot study 1:</u> The objective of the first pilot study was to measure the maximum illuminance at a driver's eye level when approached by oncoming traffic under real on-road night-time driving conditions. The headlight intensity from moving oncoming traffic at night was measured on a well-lit suburban road using an illuminance meter at the eye (IM-2D; Topcon, Tokyo, Japan). Figure 5-2 illustrates the position of the experimental vehicle where the examiner sat in the front passenger seat to measure illuminance from the single lane of oncoming traffic. Ten measurements were taken with the illuminance meter resting on the observer's forehead to record illumination at eye height.

The measurements ranged between 2.0 - 12.7 lux depending on the distance of the approaching vehicle and the exact direction of the headlight beams in relation to the parked car. The illuminance meter is specified as having an accuracy of ±5% for measurements between 0.1-19,990 lux.[284] Therefore, the maximum glare experienced at a driver's eye height due to oncoming headlights on a well-lit road, was determined as 12.7 ± 0.6 lux which is also consistent with earlier on-road illuminance measurements shown in Appendix A.

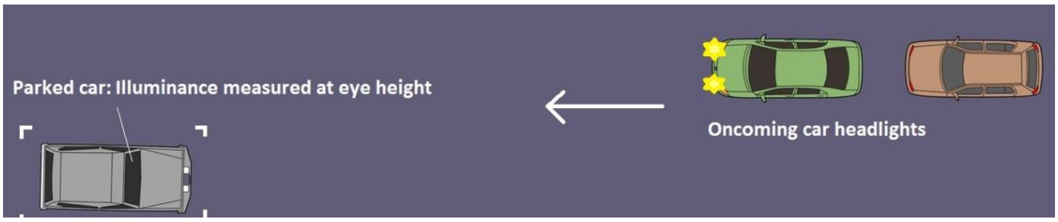


Figure 5-2: Position of experimental vehicle and oncoming traffic for measuring at-eye illuminance of oncoming headlights at night

<u>Pilot study 2:</u> The second pilot study aimed to determine the setting required for the artificial glare source that subjectively matched that from real car low-beam headlights. Subjective brightness matches of stationary low-beam headlights (Holden, Commodore) and the vehicle mounted glare source were determined for four observers (mean age = 42.3 ± 9.1 yrs) on the closed-road as shown in Figure 5-3. The distance between the observer and the car headlights was 50 metres according to the expected point of maximum glare within the headlight beam.[143] The subjective glare matches corresponded to an illuminance at the eye from the glare source of 12.8 ± 2.7, ranging from 9 to 15 lux. This level was comparable to the levels determined in pilot study 1 (12.7 ± 0.6 lux).

Figure 5-3: Position of glare source and real car headlights for subjective brightness matching

Pilot study 3: The aim of the final pilot study for determining the glare source intensity was to explore whether an illuminance level of 13 ± 1 lux at the observer's eye height (as established in the previous two pilot studies) impaired VA to the same extent as real oncoming vehicle low-beam headlights. On the closed road, a logMAR high contrast vision chart was positioned beside low-beam headlights at a distance of 20m from the observer as shown in Figure 5-4. This 20m distance was chosen based on the range of the acuity chart (i.e. the top line was equivalent to 0.5 logMAR (6/19) at the 20m distance).

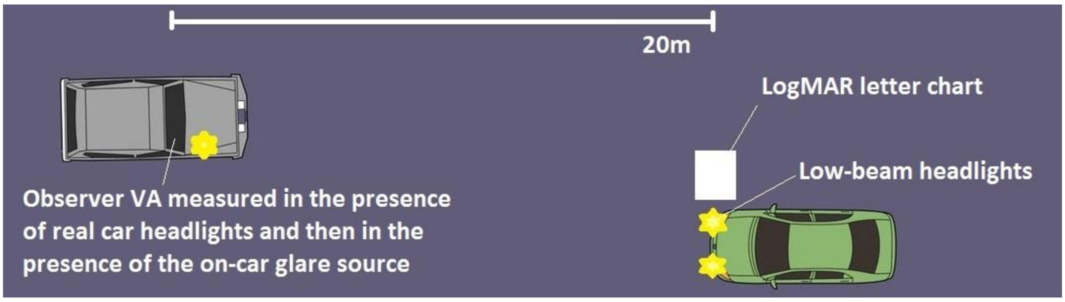


Figure 5-4: Position of the observer, on-car glare source, low-beam headlights and VA chart

The VA of three observers (mean age = 45.7 ± 7.4 yrs) was measured in the absence of glare, in the presence of real-car low-beam headlights and in the presence of the on-car glare source set at 13 ± 1 lux (Table 5-4). The results showed that VA was within one letter for the low-beam and on-car glare source confirming that this glare source setting effectively simulated the VA impairment of low-beam headlight glare.

Table 5-4: Visual acuity measurements for three observers in the absence of glare and in the presence of real car headlights and the on-car glare source

	VA (logMAR) Observer 1	VA (logMAR) Observer 2	VA (logMAR) Observer 3	Mean VA (logMAR)
No Glare	0.30	0.32	0.26	0.29 ± 0.03
Low-beam headlights	0.44	0.44	0.32	0.40 ± 0.07
On-car glare source	0.44	0.44	0.34	0.41 ± 0.06

The combination of these three pilot studies showed that the glare source resulted in a similar illuminance level at the drivers' eye height, perception of brightness and visual impairment to actual low-beam headlights, although it did not replicate the angular size of moving headlights which change constantly while driving.

5.5.6 Closed-Road Circuit

Night-time driving performance was measured on a closed-road circuit at the Mount Cotton Driver Training Centre, as used in previous studies.[17,26,141,265] The circuit comprises a multiple lane bitumen road, without any street lighting, is representative of a rural road setting and includes standard road markings and signs. Testing commenced at least 15 minutes after nautical twilight (sun 12° below horizon) and occurred only on nights when road surfaces were dry. The section of the circuit used for this study was 4.6 kilometres and included hills, curves, intersections and straight sections (Figure 5-5).

Figure 5-5: Aerial view of the closed road circuit

Four experimenters were involved in each driving session. Two were seated in the instrumented vehicle with one providing directions to the participant and the other scoring driving performance and activating the switch button for the glare light at positions marked by reflective cones. The other two experimenters acted as pedestrians and adjusted the location of the recognition and hazard tasks between runs.

Participants completed two runs of the circuit following a practice lap to familiarise the participant with the test vehicle and the required tasks. The practice lap was carried out in the reverse direction to the testing lap to reduce any learning effects. One of the runs of the circuit was undertaken in the absence of glare and the other when the vehicle mounted glare source was turned on intermittently at specific locations during the drive resulting in 30% of the drive being performed in the presence of glare. The order of the intermittent glare and no glare runs was counterbalanced to minimise learning effects. The two conditions varied only in the positioning of some road hazards and detection tasks; each included the same number of hazards (12), triangular road markings (12), pedestrians (4), animals (4) and speed signs (21). Schematic maps of the no glare and intermittent glare layouts are shown in Figure 5-6.

The total time taken to complete each of the runs was recorded. Runtime was not included as a performance measure as it was not considered to directly reflect driving performance, since driving speed may be affected by reasons unrelated to driving ability. For example, slowing down during difficult driving conditions may be beneficial for safety, and not necessarily correspond to poor driving performance. In addition, familiarity with driving the test vehicle and test anxiety could impact upon participants' driving speed regardless of their driving ability under real-world conditions. Nonetheless, it was important to adjust for driving speed as a covariate because driving slower could create an advantage by giving some participants extra time to detect and respond to recognition tasks and to avoid hazards. Furthermore, under real world traffic conditions drivers cannot always modulate their speed according to their needs therefore adjusting for driving speed would better reflect the true driving ability of participants.

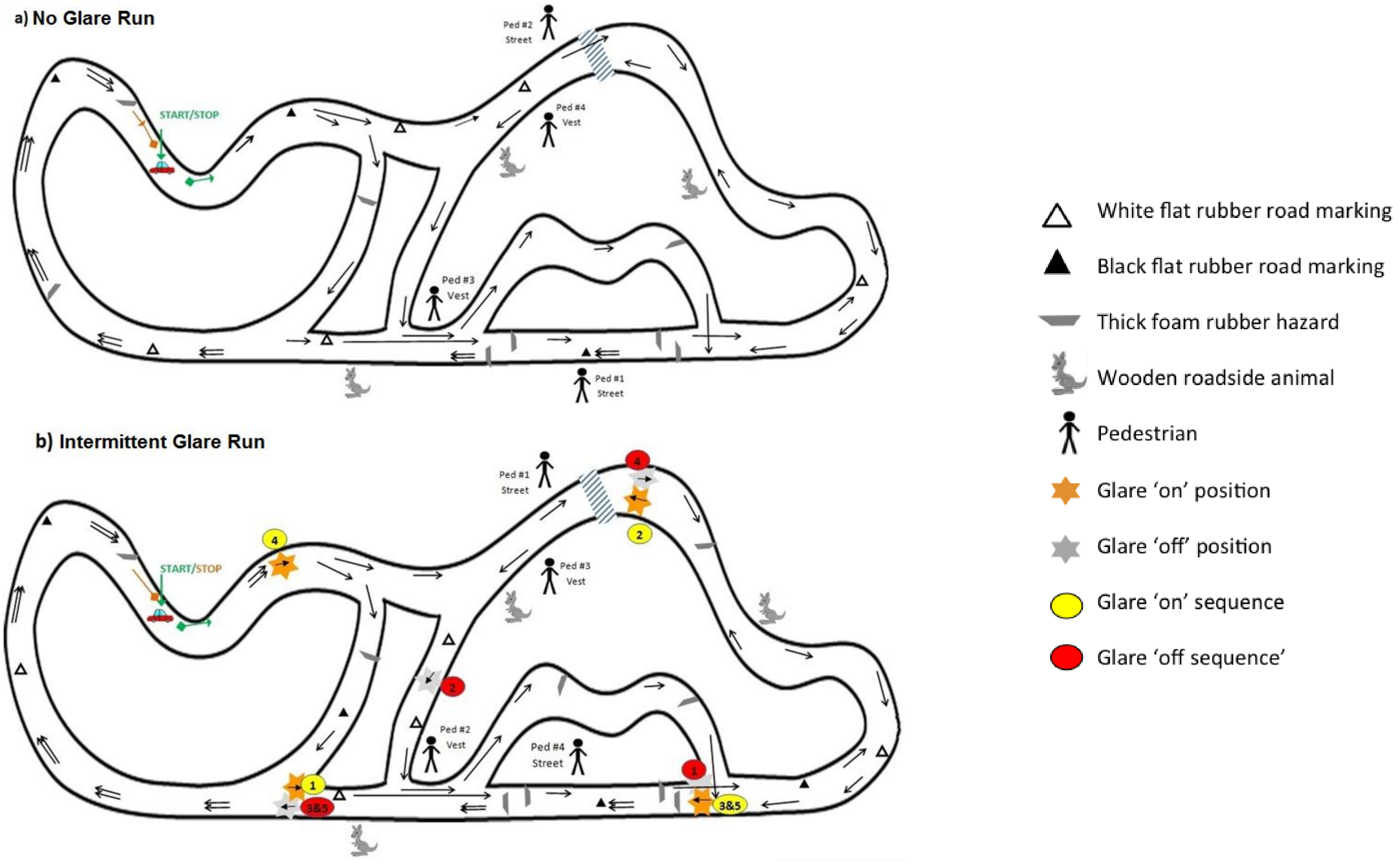


Figure 5-6: Track layouts a) no glare run b) intermittent glare run

Driving performance measures

Participants were instructed to drive at a comfortable speed and to keep in their lane as much as possible during the drives. They were required to attend to and verbally respond to five visual tasks while driving: identifying the speed signs, white and black triangular markers on the road, wooden roadside animals, real pedestrians walking in place on the roadside and thick grey foam rubber hazards positioned across the lane.

Speed signs: A total of 21 speed signs were present around the driving circuit for each of the glare conditions, including standard white signs with black letters and regulatory yellow speed signs with black letters. Participants were required to correctly report the sign content and the total percent recognised was calculated. No partial scores were allocated for detecting a sign yet incorrectly reporting speed.

Triangular road markings: Flat rubber white and black triangles measuring 40cm x 40cm x 0.5cm (height x width x thickness) were positioned in the centre of the lane at 12 positions (six black and six white) for each run (Figure 5-7a). Participants were asked to verbally respond to these targets but did not need to avoid them.

Roadside animals: There were four roadside positions where the wooden animals were located in each of runs. The animals were made from plywood measuring 80 centimetres in height and 41 centimetres in width (Figure 5-7b). Participants were required to verbally respond to their presence.

Roadside pedestrians: Four pedestrians were present on the roadside during each run. The pedestrians walked in place on the opposite side of the two-lane road wearing either street clothing (low contrast long-sleeved grey shirt) (2) or a reflective vest (2) and black pants and shoes (Figure 5-7c). These pedestrian clothing selections have been used in previous closed-road investigations.[137,138,285] Participants were again required to respond verbally to the presence of a pedestrian and the percent of pedestrians recognised was scored. Two pedestrians were positioned along the straight section of the road and the other two positioned near the pedestrian crossing.

Foam hazards: Thick grey foam rubber hazards (reflectance of approximately 10%) measuring 220 cm x 80 cm x 15 cm (length x width x thickness) were positioned at 12 locations for each run (Figure 5-7a). Drivers were required to report their presence and to steer around them if they saw them in time to do so safely. If the hazard could not be avoided, it was safe to drive over them as this had minimal effect on vehicle control and felt similar to a small speed bump. Hazards that were seen and successfully avoided were given a score of one, whereas hazards that were seen but were clipped on the side (less than half-way across) scored only 0.5 points. In situations where the driver did not successfully avoid the road hazard and ran across the hazard at or beyond the horizontal half-way point, a score of zero was recorded.

Lane keeping: Video playback of the right and left hand side lane crossings was scored manually using a stopwatch to determine the percent of the total time spent driving within the lane and driving on or outside of the lane markings. The proportion of time spent within the lane was used rather than the number of lane crossings, as this gave a better indication of whether a driver tended to drive consistently outside lane markings in each of the driving conditions.

Figure 5-7: a) foam hazard and black triangular road marking, b) wooden roadside animal, c) pedestrians wearing reflective and low contrast clothing (pedestrians appeared only one at a time in the experiment)

5.5.7 Statistical Analysis

The driving performance measures, as a percent of the total possible score, were each converted to a z-score with the data for lane keeping being transformed so that a positive z-score represented better performance as was the case for the other variables. A mean z-score of each of the component measures was derived to form an overall composite z-score separately for each of the no glare and intermittent glare runs. This overall score captured each participant's night driving performance relative to the group as a whole, as has been used in previous closed-road studies.[141,222,286] The overall composite z-score is an important measure used to account for differences in how participants' prioritised the different driving tasks, whereby some components may have been performed better to the detriment of other components and vice versa.

Statistical analyses were performed using SPSS version 21.0 (SPSS, http://www-01.ibm.com) and p-values <0.05 were used to indicate statistical significance. For all statistical tests, residuals were assessed to confirm the model assumptions of normality, linearity and homoscedasticity. Data was also screened to identify any outliers, missing data or errors.

Paired t-tests were used to assess differences between the driving performance scores for no glare and intermittent glare conditions for each of the individual driving performance components, as well as for overall driving performance. Generalised linear mixed models (GLMM) with a maximum likelihood estimation (MLE) allowing the intercept to vary across participants, was used to investigate the relationship between driving performance in the two glare conditions and self-reported difficulties. In the GLMM, runtime was included as a covariate and glare condition as a repeated factor. Adjusting for runtime ensured that the task was comparable for all participants by providing a measure of driving performance regardless of their driving speed. The associations between self-reported measures (VND-Q and deBoer scale) were assessed using ANOVA.

For assessing which tests of visual function were most strongly associated with overall night driving performance, a series of GLMM models (MLE, random intercept for participants) for each vision measure separately was conducted, including glare condition as the repeated factor and runtime as a covariate. Residuals were used to calculate the additional percent of the variation explained in driving performance with the inclusion of each significant visual function tests within models adjusted for runtime.[287] Lastly, a GLMM was also used to determine the ability of the German Ophthalmological Society (July 2011) Mesotest II pass/fail criteria for discriminating between better and poorer night drivers.

5.6 RESULTS

5.6.1 Participant demographics and characteristics

Table 5-5 provides a summary of the participant demographics and eye conditions that were assessed during the ocular health screening. Three participants had bilateral ocular conditions, while five participants had unilateral ocular conditions. Central retinal conditions included epiretinal membrane, early AMD and a macular hole. Peripheral retinal conditions included prior retinal detachment and branch vein occlusion. Seven participants had previous cataract surgery and intraocular lenses (IOL) (6 bilateral and one unilateral); none of the participants had multifocal IOL designs. Visual field screening did not reveal any gross visual field defects that could affect driving performance.

Table 5-5: Summary of participant demographics and eye conditions (n=26)

Age (mean yrs ± SD)	71.8 ± 6.3
Gender (n (%))	
- Female	12 (46%)
- Male	14 (54%)
Eye conditions[a] (n (%))	
- Nil	18 (69%)
- Cataract (LOCS III>3)	2 (8%)
- Corneal	1 (4%)
- Central retina	4 (15%)
- Early glaucoma	2 (8%)
- Peripheral retina	3 (12%)

[a]four participants had multiple conditions

Participants driving exposure is shown in Table 5-6. Participants were all regular drivers but most (81%) drove less than 50 kilometres at night per week over the past month. Participants reported driving an average of 1.8 ± 1.7 nights per week and 25 percent of participants' total driving exposure was at night. Participants' night driving was primarily on main or local suburban roads. Just over half of the participants did not report avoiding night driving; the others reported avoiding night driving at least 'a little' of the time due to their visual difficulties. About a quarter of the participants reported that they avoided night driving most or all of the time because of their vision, although all reported that they had driven at night within the past year.

Table 5-6: Summary of participant driving exposure (n=26)

Daytime driving exposure (mean km ± SD)[a]	212 ± 219
Night driving exposure (mean km ± SD)[a]	72 ± 161
Road types driven on at night (n (%) yes)[ab]	
- Freeway	15 (58%)
- City	9 (35%)
- Main suburban	23 (89%)
- Local suburban	24 (92%)
- Rural	1 (4%)
Avoidance of night driving because of vision (n (%)[c]	
- None of the time	14 (54%)
- A little of the time	4 (15%)
- Some of the time	1 (4%)
- Most of the time	5 (20%)
- All of the time[c]	2 (8%)

[a] reported for a typical week during past month
[b] night was defined as after sunset or before dawn
[c] but have driven at night in the past year

5.6.2 Driving performance and effects of intermittent glare

Table 5-7 shows the mean overall driving performance z-scores and component driving outcome measures for the no glare and intermittent glare driving runs. Overall driving performance (z-score) was significantly worse in the presence of intermittent glare, compared to the no glare condition (t=3.48 p=0.002).

Table 5-7: Summary of participants' driving performance and comparison between no glare and intermittent glare run scores.

	No Glare		***Intermittent glare***			
Dependent Variables	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**	**t-statistic**	**p-value**
Overall z-score	0.15 ± 0.09	-0.98-1.4	-0.15 ± 0.11	-1.02-0.8	3.48	**0.002**
Component driving tasks						
- Low contrast hazards (% seen and avoided)	81.9 ± 15.6	42-100	78.2 ± 16.1	29-100	2.22	**0.035**
- Triangular road-markings (% seen)	60.8 ± 25.5	0-100	63.5 ± 23.5	8-100	-0.55	0.59
- Animals (% seen)	97.1 ± 8.1	75-100	93.9 ± 11.4	67-100	1.07	0.30
- Signs (% seen)	70.1 ± 20.1	5-95	67.4 ± 20.2	14-100	0.92	0.37
- Pedestrians (% seen)	48.1 ± 30.8	0-100	9.6 ± 15.9	0-50	6.88	**<0.001**
- Lane keeping (% of run-time keeping in lane)	82.4 ± 4.4	72-92	82.4 ± 5.2	69-93	0.03	0.98
Runtime (min)	8.3 ± 0.7	7.2-10.5	8.5 ± 0.7	7.5-10.3	-3.64	**0.001**

Of the individual driving components, pedestrian recognition was the most poorly performed overall and was most affected in the presence of the intermittent glare source, where there was a decrease in pedestrian recognition by an average of 38% compared to the no glare condition. There was no significant difference in recognition between the clothing conditions regardless of the glare condition (no glare: t=0.46 p=0.65 glare: t=0.93 p=0.54). However, in the no glare condition, pedestrians wearing the reflective vest were recognised by a greater proportion of participants than the pedestrians wearing street clothing. In the intermittent glare condition, the recognition of the reflective vest and grey street clothing pedestrians was zero for nearly all participants (vest 92%; street 96%); this floor effect explained why there was no difference between clothing conditions for the intermittent glare conditions.

Participants successfully avoided an average of 82% of the low contrast hazards for the no glare condition, while 78% of the hazards were avoided for the intermittent glare conditions which was significantly different. However, when driving score was adjusted for runtime, the difference between hazard avoidance between conditions was not significant. Nearly all participants recognised all of the wooden roadside animals and this was the task that was performed best for both the no glare and intermittent glare runs. The triangular road markings were detected on average slightly more of the time for the intermittent glare condition but there was no significant effect of glare condition. The recognition of the road surface markings was significantly worse for the black compared to the white markings (no glare: t=-7.60 p<0.001; intermittent glare: t=4.96 p<0.001) with a similar difference between outcomes, regardless of glare condition (t=1.56 p=0.13). On average, about two thirds of the road signs were recognised with no significant difference between the glare conditions.

Participants drove within the lane markings an average of 82% of the time regardless of the glare condition. When drivers deviated outside the lane markings, they spent significantly more time across the centre lane compared with the outside road edge (no glare: 11% vs 6.7% t =2.33 p <0.028; intermittent glare: 10.8% vs 6.8% t = 2.04, p =0.05), but there was no interaction between lane edge and glare condition (p=0.77).

The intermittent glare run time was slower compared to the no glare run. However, although statistically significant, the magnitude of the difference was only 20 seconds. Importantly, the difference between glare conditions for the overall z-score remained significant when adjusted for runtime ($F_{1,30.76}$=15.69 p< 0.001).

5.6.3 Self-reported night driving difficulty and night driving performance

The mean self-reported vision-related night driving difficulty for the participants, as determined using the VND-Q scores (calibrated from Study 1), was -2.04 ± 1.38 logit, corresponding to a score of approximately 19 out of a total possible score of 45. Participants had a range of self-reported difficulty, scoring from -4.25 logit to 0.72 logit on the VND-Q. Responses to individual VND-Q items are shown in Figure 5-8.

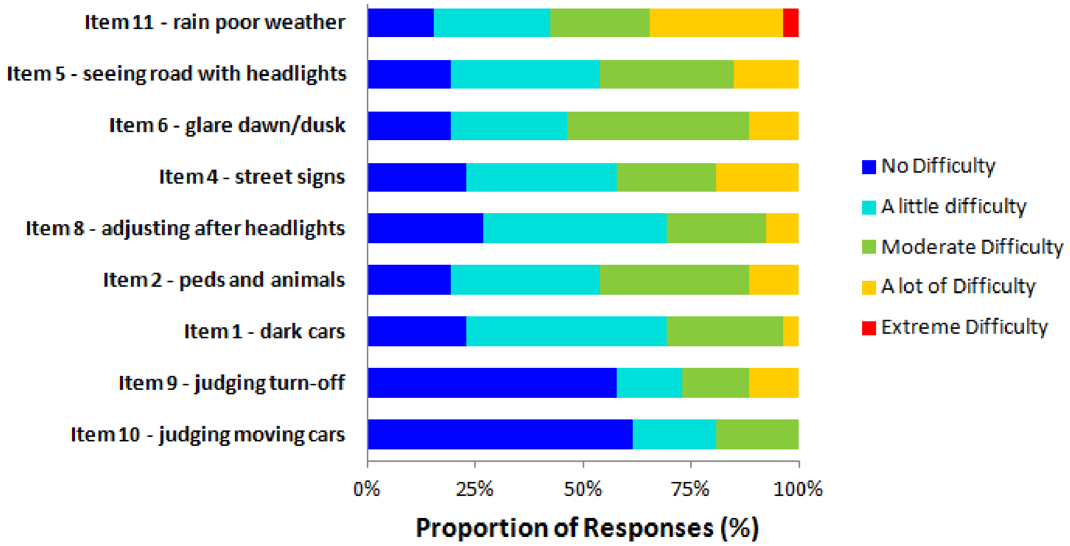


Figure 5-8: Proportion of respondents answering each category of the VND-Q.

Driving in the rain or poor weather at night was judged as the most difficult task, while judging the distance to turn-offs or to moving cars was reported to be less difficult. The level of self-reported difficulties in this study was similar to that of the overall levels in the larger samples in studies 1 and 2 (-2.07 logit Chapter 3, and -2.10

logit Chapter 4). In addition, a repeated measures generalised linear regression model demonstrated that those who participated in all three studies (n=23) did not differ in their self-reported difficulties (VND-Q scores) over time (Greenhouse-Geisser correction, F=0.136, p=0.80).

The deBoer ratings of participants' discomfort due to oncoming headlights, ranged from 'just noticeable' to 'disturbing' and on average, oncoming headlights were rated as 'just permissible' (Figure 5-9). The discomfort ratings from the deBoer scale showed a borderline significant association with difficulty ratings from the VND-Q Rasch scores (F = 3.01 p =0.05). Overall driving performance z-score was significantly associated with VND-Q Rasch scores but not significantly associated with the deBoer ratings (Table 5-8).

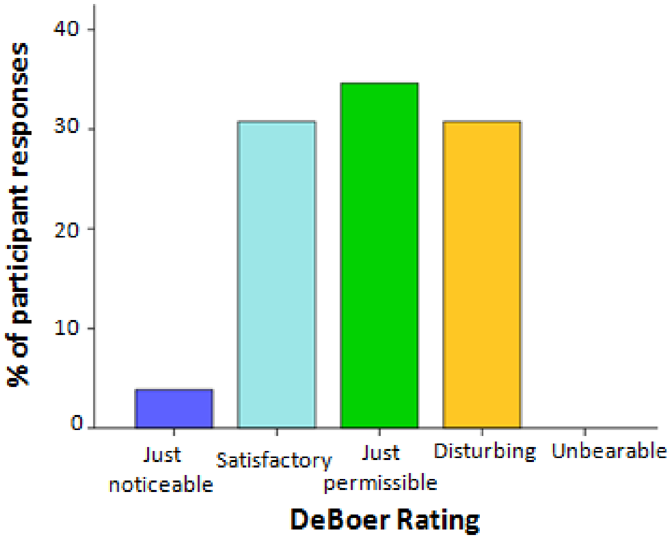


Figure 5-9: Proportion of respondents answering each category of the deBoer scale.

Table 5-8: Associations between VND-Q Score, deBoer rating and driving performance z-score. GLMM adjusted for runtime; glare condition as repeated factor.

	Mean ± SD	**Range**	**F_{df}**	**p-value**	**R^2_{GLMM}[b]**
VND-Q Rasch Score (logit)	-0.05 ± 0.09	-0.26 - 0.10	$F_{1,\ 26.00} = 9.19$	**0.005**	8%
deBoer Rating[a]	2.92 ± 0.88	1 - 4	$F_{1,\ 26.34} = 1.62$	0.21	-

[a] discomfort scale: just noticeable (1), satisfactory (2), just acceptable (3), disturbing (4),

[b] percent of total variance explained by the vision test component

The relationship between self-reported VND-Q scores and driving performance was much stronger for the intermittent glare driving run than the run performed in the absence of glare (Figure 5-10).

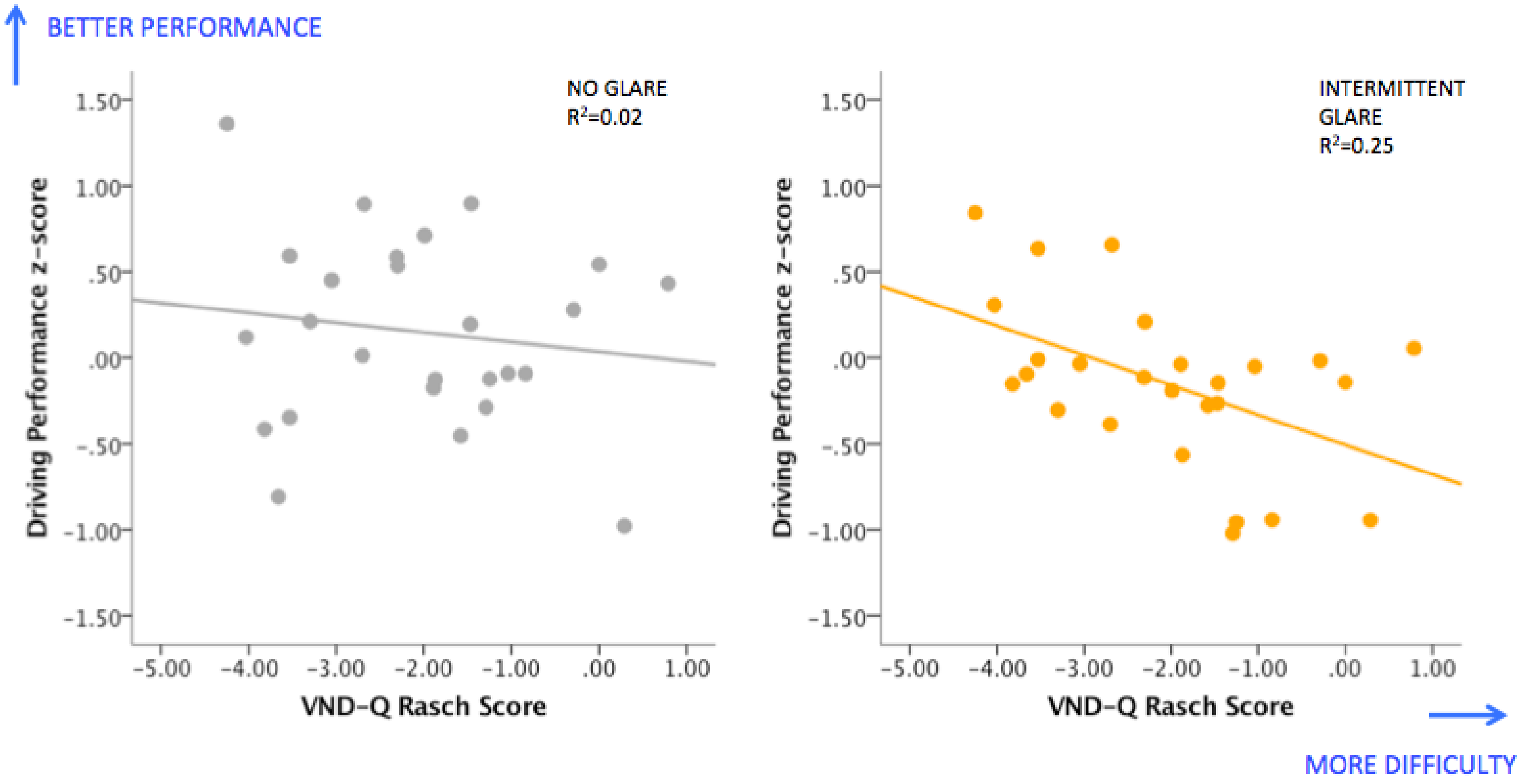


Figure 5-10: Association between VND-Q Rasch scores and driving performance z-score for no glare and intermittent glare conditions.

5.6.4 *Visual function tests and night driving performance*

While standard measures of photopic VA were significantly associated with night driving performance z-scores, stronger associations were found for non-standard tests of visual function, such as those conducted using low contrast letters, mesopic light levels or in the presence of glare (halometer area). The mean measures of participants' visual function and associations with night driving performance are summarised in Table 5-9. All participants had habitual photopic binocular HCVA that was ≤0.1 LogMAR (6/7.5) which is well within the 0.3 logMAR (6/12) driving standard.

Photopic tests

LCVA had the strongest association with driving performance for the photopic tests, explaining 13% of the driving z-score variation. Photopic HCVA was also significantly associated with driving performance although to a lesser extent. Pelli-Robson CS was not associated with night driving performance.

Mesopic tests

Motion sensitivity demonstrated the strongest association with driving scores out of both the mesopic test selection and the entire battery of tests, it accounted for one fifth (20%) of the variation in the participants' night driving performance. Mesopic HCVA had the next highest association within the mesopic tests and overall battery, accounting for 17% of the variation in driving scores. These two mesopic measures accounted for a greater proportion of the variation in driving scores compared to either of the significant photopic tests. In addition, mesopic Pelli-Robson CS was significantly associated with driving performance unlike the photopic version of the, test although it did not demonstrate an advantage over a photopic measure of LCVA.

Glare tests

The Aston Halometer area was significantly associated with overall driving performance, whereas the Mesotest with glare and the Berkeley glare DGI were not. Whilst halo area was significantly associated with driving scores, it did not demonstrate an association as strong as the a measure of photopic HCVA.

Table 5-9: Associations between visual function tests and overall driving performance z-score. All models include runtime as a covariate and glare condition as the repeated factor for mixed models generalised regression models.

		Mean ± SD	**Range**	**F_{df}**	**p-value**	**R^2_{GLMM}[a]**
Photopic	High Contrast Visual Acuity (logMAR)	-0.05 ± 0.09	-0.26 - 0.10	$F_{1,\ 26.10} = 4.68$	**0.040**	9%
	Low Contrast Visual Acuity (logMAR)	0.15 ± 0.10	-0.04 - 0.36	$F_{1,\ 26.11} = 6.85$	**0.015**	13%
	Contrast Sensitivity (logCS)	1.93 ± 0.06	1.65 - 1.95	$F_{1,\ 27.00} = 1.73$	0.20	-
Mesopic	High Contrast Visual Acuity (logMAR)	0.33 ± 0.12	0.08 - 0.56	$F_{1,\ 26.00} = 11.44$	**0.002**	17%
	Contrast Sensitivity (logCS)	1.45 ± 0.25	0.95 - 1.95	$F_{1,\ 26.25} = 6.98$	**0.014**	11%
	Motion Sensitivity (Dmin)	-0.80 ± 0.15	-1.08 - -0.53	$F_{1,\ 26.55} = 11.66$	**0.002**	20%
	Mesotest -glare (levels passed)	2.19 ± 1.65	0 - 4	$F_{4,\ 27.02} = 2.53$	0.06	-
Glare	Mesotest + glare (levels passed)	0.88 ± 1.21	0 - 4	$F_{4,\ 26.42} = 2.27$	0.09	-
	Halometer area (cm2)	12.88 ± 5.16	3.48 - 18.47	$F_{1,\ 26.00} = 4.53$	**0.043**	10%
	DGI Berkeley Glare Test (logMAR)	0.13 ± 0.07	0.00 - 0.30	$F_{1,\ 26.18} = 2.51$	0.13	-

[a] percent of total variance explained by the vision test component

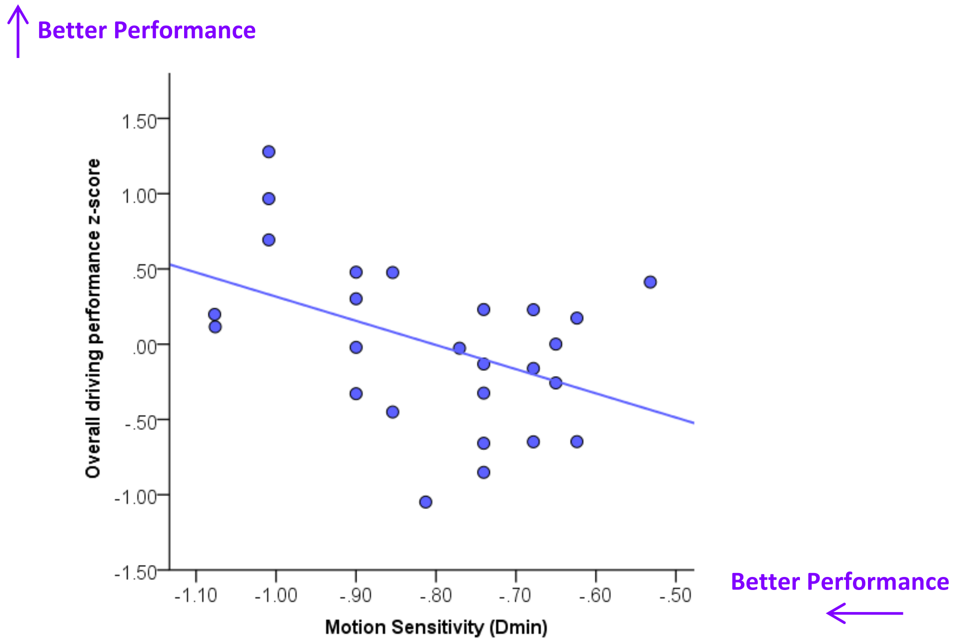


Figure 5-11: Association between motion sensitivity and night driving performance (no glare and intermittent glare condition combined; data unadjusted for runtime).

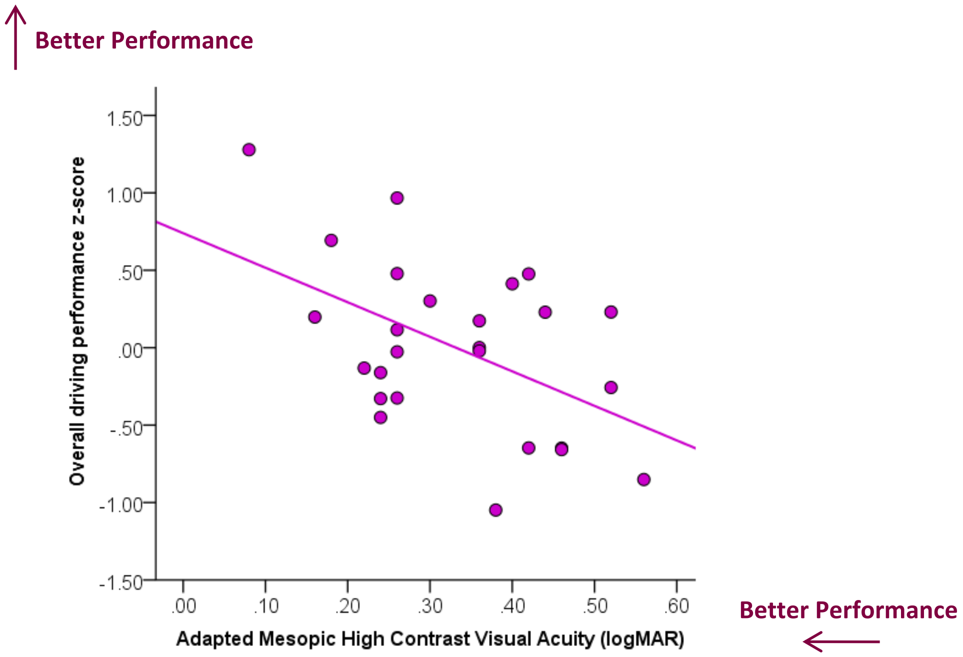


Figure 5-12: Association between mesopic high contrast visual acuity and night driving performance (no glare and intermittent glare condition combined; data not adjusted for runtime).

Mesotest

The Mesotest II pass/fail criterion set by the German Ophthalmological Society (July 2011), of a pass on level 1 for no glare and glare conditions, discriminated between drivers with better and worse driving performance scores ($F_{1,26.47} = 6.37$ $p = 0.018$). However, there were participants who would pass the Mesotest yet had the same overall driving performance as some of the participants who would fail the Mesotest and be classed as unfit to drive at night (Figure 5-13). The criterion of a pass on level 2 for the no glare and glare conditions, which existed prior to July 2011, showed only borderline significance for discriminating between better and poorer night drivers ($F_{1,26.48} = 3.71$ $p = 0.07$; adjusted for runtime).

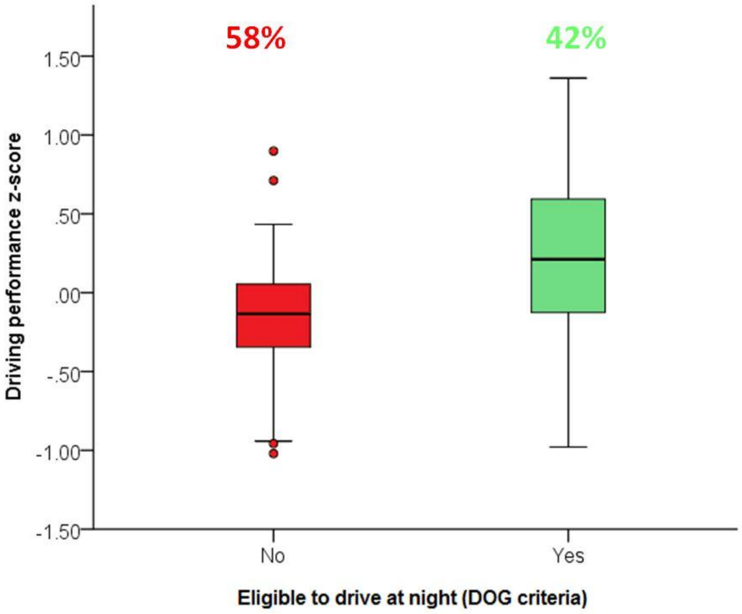


Figure 5-13: Overall driving performance z-score for participant's who would pass or fail the current German Ophthalmological Society's night driving standard.

5.7 DISCUSSION

Night driving performance for no glare and intermittent glare conditions

The data demonstrates that overall closed-road driving performance was degraded in the presence of glare, with poorer driving performance in the presence of glare for those who self-reported higher vision-related night driving difficulties. The task that was most affected by the presence of glare was pedestrian recognition, which was reduced by 38% on average between the no glare and intermittent glare conditions (48% vs 10%, respectively). This result was primarily for pedestrians wearing the reflective vests as the recognition of pedestrians wearing the low contrast grey street clothing was zero for nearly all participants (92%), regardless of the glare condition. The finding of poor recognition of pedestrians wearing dark clothing supports several previous investigations,[137,138,285] which have demonstrated the importance of retro-reflective clothing for improving pedestrian visibility at night, particularly when the reflective strips are positioned in the biomotion configuration.

Limited research has been conducted about the effects of headlight glare on driving performance, although it is clear that the presence of glare decreases pedestrian recognition distances[18,137,143] and varies according to pedestrian clothing,[138,144] from 10% in normally sighted older adults[137] to about a 40% for drivers with simulated cataract.[138] Thus the overall decline in pedestrian recognition due to the intermittent glare shown in the current study is at the upper limit and consistent with evidence that clearly shows a decrease in pedestrian visibility in the presence of glare.[17,18,137,138]

There are several possibilities as to why the recognition of pedestrians was the driving task most affected by intermittent glare. It was the most difficult of the tasks as evidenced by the lowest overall percentage of recognition and also posed the most challenging contrast conditions since the pedestrians were not within the direct headlight beam and did not wear biomotion clothing configurations that can greatly improve pedestrian recognition in the presence of glare.[138,144] Given that biomotion clothing is not a standard clothing condition it was not used as a clothing configuration for the pedestrians in the present study. Other evidence shows that the contrast sensitivity of moving targets declines by an estimated factor of six in the presence of glare, which supports the current finding that glare affected the visibility of roadside pedestrians.[146]

It is likely that the movement of the pedestrians and low contrast of their clothing caused poorer performance in the presence of intermittent glare, rather than their peripheral positioning, because there was no significant decrease with glare for performance on the only other peripheral driving task (recognition of roadside animals). However, another on-road study[143] of eight older participants (57-69 yrs), using simulated pedestrians (which do not replicate real world pedestrian movement), demonstrated that pedestrian detection can also be affected by discomfort glare and that the simulated pedestrians on the same side of the road as the glare source were less likely to be recognised. The authors suggested that older drivers in particular, looked away from the glare source to minimise their discomfort. The pedestrians in the present study were separated from the drivers by one lane (for safety purposes) and provided the only task positioned on the same side of the road as the glare source which could have been one of the factors contributing to the fact that pedestrians were more affected by the intermittent glare than the other driving tasks.

This experiment did not specifically investigate the cause of reduced performance in the presence of glare, and whether the reductions were due to true visual disability or compensatory behaviours such as squinting, light aversion and distraction. During the drive with intermittent glare, it was obvious that some participants averted their eyes from the glare source and moved their heads potentially to avoid discomfort or to improve their chances of detecting hazards and signs. Interestingly though, the deBoer discomfort ratings of the glare source were not significant predictors of driving performance whereas the VND-Q ratings were. This suggests that the reduced driving performance was due to disability glare rather than due to behaviours in response to discomfort glare. However, it is also possible that the VND-Q scores are also influenced by discomfort so this cannot be completely ruled out as a contributing factor to the detrimental effects of glare demonstrated in this study. Future work is necessary to investigate the eye movement patterns of drivers approaching glare sources, as this would confirm whether the effects of intermittent glare were primarily due to discomfort or true disability glare.

The results of this study also revealed that drivers slowed down in the presence of glare and that this behaviour may have improved their recognition and avoidance of low-contrast hazards on the road which was significantly poorer for the intermittent glare condition only when runtime was not taken into account. Runtime did not significantly contribute to driving performance for any of the other driving tasks that did not involve avoidance. Therefore, participants may have slowed down in the presence of intermittent glare, allowing more smooth steering patterns around the hazards and enabling them to manouevere around the hazard without hitting it. Similar to earlier closed-road research,[17] drivers did not fully compensate for the limitations in their vision. The detrimental effects of the intermittent glare were significant for pedestrian detection and for overall driving performance, regardless of driving speed. Further study is required to confirm whether these findings also occur for drivers who do not have vision-related night driving difficulties and are likely to be less affected by the presence of headlight glare.

Self-reported difficulties and night driving performance

The outcomes of this study also demonstrate a significant association between VND-Q Rasch scores and closed-road night-time driving performance. Participants were able to make better assessments of their visual limitations and driving ability compared to previous studies of self-reported daytime driving difficulties and on-road driving assessments,[20,21,288] and night studies that compared driver’s abilities to judge their own visual limitations at night against actual on-road visibility measures.[17,18] These previous studies clearly demonstrated that not all drivers have insight into their visual limitations or driving abilities. However, none have assessed the relationship between overall night driving performance and self-reported difficulty using a comprehensive questionnaire specifically focused on night driving.

The use of the Rasch analysed VND-Q and assessment of night driving performance (rather than daytime) provided the opportunity for a more detailed investigation of vision-related night driving difficulties. However, a large proportion of the participants in this study specifically sought participation because of their own difficulties, so the sample is likely to have been biased toward more insightful or more conservative drivers. Furthermore, participants had undergone extensive vision testing under mesopic and glare conditions during study 2 and had 6-12 months prior to participation in this study to observe their vision and night driving abilities before completing the survey for the final part of study series. Given that this additional time did not significantly alter participants' VND-Q scores, it suggests that participants' insight into their visual difficulties and night driving ability did not change as a result of participating in this series of studies. Therefore, including non-standard tests in examinations by eye-care professionals is not likely to help to educate patients about their night driving limitations or improve night driving self-regulation and behaviour. Owsley and colleagues[22] found that educational intervention for older drivers improved awareness of visual impairment and its impact on driving performance, so future work could explore the use of similar educational strategies for participants reporting night driving difficulties.

Further to Studies 1 and 2 (Chapters 3 and 4), the validity of the VND-Q is supported by the finding that the VND-Q Rasch scores were more valuable for the prediction of night time driving performance than the deBoer rating scale, consistent with other findings demonstrating the limited value of this discomfort glare scale.[143,261] The results of Study 2 (Chapter 4) also confirmed that there are significant associations between ratings on the VND-Q and measures of visual function such as photopic LCVA and mesopic CS, which were shown to significantly relate to closed-road night driving performance in the current study.

These results provide valuable preliminary evidence that the VND-Q has value for clinical or research settings when patients have particular visual concerns about night driving. Further studies including individuals who do not specifically have vision-related night driving difficulties are necessary to confirm these findings. Populations with eye diseases known to impair mesopic vision would also be useful to include in future investigations as this may provide a wider range of self-reported difficulties as reported on the VND-Q Rasch scale.

Relationship between visual function and night driving performance

This study found that several visual function tests conducted under mesopic luminance levels provide clear improvements upon a standard measurement of photopic HCVA for assessing vision-related night driving performance. Despite its pre-eminent role in clinical practice, a standard measure of photopic HCVA is not optimal for examining night driving capacity. Photopic HCVA accounted for only 9% of the variation in night driving performance, whereas photopic LCVA accounted for 13% of the variation in performance. Mesopic measures of motion sensitivity and mesopic HCVA accounted for about double the variation in participants' driving performance scores compared to photopic HCVA (17% and 20%, respectively). Mesopic Pelli-Robson was also significantly associated with driving performance although was only slightly better than photopic HCVA. Glare based tests and the Mesotest also did not prove to be more strongly associated with night driving performance than photopic HCVA.

These findings support previous investigations showing that photopic HCVA is not optimal for predicting day or night time driving performance.[26,29,223,289] The results are in accord with closed-road investigations by Wood and colleagues which showed the value of mesopic HCVA for predicting closed-road night driving performance,[26] and in another closed-road study, demonstrated that motion sensitivity was more strongly correlated with pedestrian detection distances at night than photopic HCVA and photopic CS.[27] Numerous other authors have also suggested that non-standard tests of visual function measured under low contrast or mesopic conditions are necessary because a measure of photopic HCVA overestimates visual ability in older adults due to the greater and earlier decline of vision for low contrast targets and low luminance conditions.[240,250,251,290]

Notably, this study is the first to comprehensively investigate the relationship between visual function and night time driving performance with a focus on the effects of glare. This was an important design feature given that Study 1 (Chapter 2) showed that one of the main night driving concerns of older drivers is with respect to glare from oncoming headlights. No other studies have found that glare tests are useful predictors of driving performance despite the fact that intuitively they might be expected to be better than tests that less closely simulate night-time driving conditions. In the present study halometer halo area was also significantly associated with driving performance, although none of the glare tests proved to be better predictors than mesopic HCVA or motion sensitivity. Importantly, these previously described tests of mesopic HCVA and motion sensitivity[26,27] remained the best predictors of night driving performance, even with this study's design which had about a third of the driving time in the presence of glare.

The inclusion of the Mesotest II, within the visual function test battery, is another novel component of the study. The test has been used to assess fitness to drive at night, in some countries, since twilight vision recommendations for driving were suggested by Aulhorn and Harms in 1970.[290] Critically, this is the first evidence that scores on the Mesotest relate to some aspects of night driving performance. The current study demonstrated that the German Ophthalmological Society's night driving pass/fail criteria for the Mesotest II (pass = level 1 in the presence and absence of glare), was able to discriminate between participants who scored better and worse on the closed-road circuit driving recognition and avoidance tasks. The previous pass/fail criteria for night driving had only borderline significance, therefore it appears that the new standard has an improved ability to assess visual fitness to drive at night. The finding that participants who fail the Mesotest II are poorer night drivers is consistent with crash studies indicating that those who fail the cut-off levels in the presence and absence of glare are more likely to be involved in a collision at night.[29]

Importantly, the Mesotest was not a better predictor of night driving performance than the other non-standard tests of mesopic visual function. Given the previously mentioned repeatability limitations of the Mesotest, the results of this study suggest that the best options for assessing visual capacity for driving at night are motion sensitivity and mesopic HCVA. Large-scale studies are, however, necessary to confirm these results including participants with eye disease who are more likely to experience vision-related night driving difficulties. The repeatability and clinical feasibility of implementing each of the potential options for assessing fitness to drive at night also need to be explored in future work.

Strengths and Limitations

A major strength of the current study was the unique measurement of night-time driving performance captured on the closed-road. Few research groups have access to closed road driving circuits which are essential for creating standardised driving conditions between participants. The testing of driving performance under night-time conditions was also an important feature of the study since the literature specifically exploring vision and night time driving performance is limited. Furthermore, the inclusion of the Mesotest in the testing protocol was an important strength because no closed-road studies have previously been conducted to support the validity of this instrument for discriminating between safe and unsafe night drivers, despite its current use in some countries to assess visual fitness to drive at night.

A particular advantage of the current study design was the ability to easily control the position and duration of the glare source. This enabled determination of the impact of glare on driving performance throughout a third of the driving run, including the ability of participants' to recover after repeated intermittent exposure to glare. The glare source duration (30% of the drive time) and frequency of glare exposure (5 sections of glare exposure) enabled simulation of oncoming or tailing headlights in real traffic conditions at night. The intensity of the glare source was also adjustable which controlled for variation that occurs between drivers of different heights so that the glare task was directly comparable for all participants; this was vital in order to compare visual function and driving performance between different participants.

Previous closed-road studies have used fixed position simulated or real car headlights positioned on the roadside.[17,18,26,137,251,277] Fixed position glare sources provide only limited exposure to glare within the driving circuit and only transient glare experiences, rather than simulation of conditions such as a stream of traffic or brightly lit freeway. Simulator studies that include glare sources[268–270] do not simulate real-world oncoming headlights nor do they match the cognitive or physical requirements of actual driving conditions, or the motion patterns of real pedestrians and night scenes. Therefore the current study design is likely to be the best currently available option for studying the effects of glare on driving performance without requiring long driving times to increase the exposure time to glare, or real on-road traffic conditions which can pose safety risks and lack the ability to control conditions between participants.

There were however, some limitations of the study. All of the participants self-identified some level of difficulty with their vision for night driving thus may have had greater insight about their driving abilities and visual limitations than the general older population. In addition, although the VND-Q indicated that the greatest difficulty experienced by participants was driving in rain and poor weather, this study was conducted in dry condition as a first step to investigating this issue. Dry conditions were necessary to ensure safety and also standardisation of experimental conditions. Given that the results of this study showed participants' driving performance was affected by glare under dry conditions, it is likely that driving performance may be even more impaired under more challenging conditions such as wet weather.

Investigations of open-road and night-time crash risk of individuals are necessary to confirm the findings that were demonstrated on the closed-road, although, the feasibility of open-road studies at night is limited by the need for driving instructors and occupational therapists to work during night-time hours. The results of this study may also have been confounded by the need for participants to adapt to an unfamiliar vehicle and driving environment. Naturalistic driving studies could reconcile these limitations although they tend to generate large amounts of data and are therefore involve complex data analysis requiring extensive resources.

Future research could include a wider range of participants including drivers who do not report difficulties with night driving and also specifically including drivers who already avoid driving at night or those who have a history of night-time crashes. It would also be beneficial to investigate study samples with a wider age range, specific eye diseases known to affect mesopic vision (e.g. AMD, Glaucoma, Diabetic Retinopathy) and patients prior to and post cataract surgery. It is likely that the capacity of tests of mesopic visual function for predicting driving performance would be even greater in populations with eye disease. Furthermore, there may be regional differences in vision-related night driving difficulties, where individuals who are exposed to more challenging night driving conditions more often have greater or less difficulty driving at night, as assessed by the VND-Q. Future studies could include drivers who frequently travel on rural roads and drivers from countries that experience a greater proportion of low luminance hours per day.

Further study using the Mesotest is also necessary because the results of this study show that other mesopic tests may be more valuable for assessing visual fitness to drive at night. In particular, motion sensitivity, mesopic HCVA, and the Mesotest should be assessed for their capacity to predict night driving performance in a wide selection of different cohorts to determine the best clinical assessment options for assessing visual fitness to drive at night. Given that the Mesotest is currently used to assess visual fitness to drive, the new standard implemented by the German Ophthalmological Society should also be investigated using crash analyses and open-road studies to confirm the results of this closed-road investigation.

5.8 CONCLUSIONS

The use of non-standard assessments of visual function for determining fitness to drive at night has been previously advocated,[24,26,28,29,240,265,290] but the limited on-road study data available has impeded the development of guidelines for eye care professionals about visual fitness to drive at night. Data from the current study suggest that achieving a photopic HCVA level of 6/12 or better does not guarantee that drivers can see adequately for driving under the low luminance and glare conditions of night-time roads. The standard assessment of photopic

HCVA for obtaining a drivers licence does not appear to be optimal for older people are optimally corrected for distance vision and have no major visual impairments due to eye disease.

Economic and time implications need to be taken into consideration when implementing driver screening practices therefore, it is important that a solid evidence basis is available. The evidence provided by this study clearly demonstrates the value of non-standard assessments of visual function and forms the basis for larger on-road explorations which could validate and justify the use of additional resources for assessing vision for night driving. The crash risk of drivers with reduced mesopic vision and increased glare sensitivity are elevated according to the limited information available,[29,126] therefore, ensuring that drivers have adequate vision for night time conditions is likely to be crucial for improving the safety of older drivers and other road users at night.

Chapter 6. SUMMARY AND CONCLUSIONS

6.1 OVERVIEW OF THE LITERATURE

Night driving poses high safety risks for drivers and other road users. Compared to day-time, there is at least double the risk of crashing at night[9] and significantly elevated risks of collisions with pedestrians and cyclists.[8] Importantly, the most common driver-related concern is regarding visual difficulties under the low light levels and glare conditions present on the road at night.[3–5] These concerns are particularly prevalent for older drivers due to age-related optical and neural degenerations that degrade vision specifically under mesopic conditions.[84,247,291]

The inter-relationships between self-reported vision-related night driving difficulties, tests of visual function and night driving performance have not previously been studied in a comprehensive program of research thus it remains unclear what constitutes an adequate level of vision for safe night-time driving. Subsequently, the determination of capacity to drive at night occurs via self-regulation, with drivers in most countries self-selecting whether they drive at night or not.[130]

Previous studies have demonstrated that self-reported difficulties with vision under low luminance and glare conditions are associated with older drivers' decisions to restrict and avoid driving at night.[3–6] Furthermore, reduced measures of visual function, such as Mesotest II outcomes in the presence and absence of glare, have been demonstrated to be associated with self-reported difficulty with driving at night.[248] In addition, photopic CS, photopic LCVA, and Mesotest outcomes relate to a greater likelihood of avoiding night-time driving.[6,24] However, drivers are known to under-estimate visibility at night-time in the presence and absence of glare,[17,89,90] and closed and open-road research show that drivers do not necessarily have insight into their own driving abilities.[20,21] Therefore, despite the encouraging associations between drivers' self-reported vision and measures of visual function, the current reliance on the self-regulation of night-time driving is not optimal.

Restriction or cessation of driving can have an enormous impact on older adults' independence, quality of life and long term health outcomes..[1,2] It is therefore critical that decisions regarding driving practices are guided by evidence-based objective determinants of fitness to drive at night so that older drivers do not unnecessarily restrict their driving. There is preliminary evidence that driver safety and performance at night is mediated, to some degree, by mesopic visual function, such as Mesotest outcomes[29,126] and mesopic VA.[26] Therefore, evidence-based objective determinants of fitness to drive at night will enable those drivers who are unsafe to drive at night to choose alternative transport options thus improving night-time safety, while allowing safe night drivers to continue to drive and maintain their mobility and independence.

Health professionals have a responsibility to investigate symptoms reported by patients, such as difficulties driving at night under low luminance or conditions of glare, and need to have access to tests of visual function that are known to reflect the ability to drive safely at night. Patients' self-reported difficulties are currently relied on as an indication for undertaking interventions such as cataract surgery[93] which can greatly improve patients vision for night driving.[292] This process could also be standardised and occur at more appropriate times with the introduction of measures of visual function that are known to reflect the ability to drive safely at night.

Understanding the role of vision in night driving has the potential to improve driving safety, and comprehensive studies are necessary to establish optimal methods for determining fitness to drive at night. This program of PhD research developed a questionnaire that will help quantify older adults' vision-related night driving difficulties. The research determined how standard and non-standard clinical tests of visual function are associated with self-reports of vision-related night driving symptoms and subsequently how these measures related to closed-road night-time driving performance. The remainder of this chapter will outline the major findings of the present investigations and will discuss their implications for older drivers and eye-care professionals.

6.2 SUMMARY OF MAJOR FINDINGS

The findings of this PhD research provide a strong foundation to help inform understanding of the level of vision necessary for safe night driving and in the implementation of well-validated measures of visual function that can assess fitness to drive at night.

Study 1 aimed to produce a valid and reliable instrument for capturing the vision-related night driving difficulties of older adults. The VND-Q is capable of identifying older drivers with reduced mesopic and glare-related visual function and is useful for alerting clinicians and researchers to patients who may have compromised night driving performance. Study 2 was designed to compare the capacity of standard and non-standard tests of visual function for predicting patients perceived levels of difficulties as assessed by the VND-Q. Finally, the objective of Study 3 was to provide a better understanding of night driving performance, particularly with respect to the effects of glare, for drivers who self-report difficulties with their vision at night. Study 3 included assessments of closed-road night driving performance in order to determine which tests of visual function were most strongly associated with the night driving performance of older drivers.

6.2.1 Development and Rasch analysis of a Vision and Night Driving Questionnaire

Twenty-five questionnaire items relating to vision and night driving were derived from in-depth review of the vision and driving literature and previous vision-related PROMs. These were categorised under six different difficulty areas including difficulties with low contrast, clarity of vision, glare, visual adaptation, motion and depth perception, and peripheral vision. Twelve unique items that covered all of these difficulty areas were formed with a single five-option response scale for difficulty, ranging from ‘no difficulty’ to ‘extreme difficulty’. Pilot investigations resulted in the elimination of the peripheral vision item and the formation of eleven items for distribution to the main study participants.

A total of 288 respondents completed questionnaires, most of whom (n=283, 98%) reported some vision-related night driving difficulty and were included in the analysis. Open responses from 100 participants regarding vision-related difficulties with night driving further confirmed that all areas of difficulty were represented in the final eleven items that were analysed using Rasch analysis and the Andrich rating scale model.

Rasch analysis enabled the development of a 9-item vision and night driving questionnaire that was unidimensional, repeatable and had excellent discriminant ability. A criteria-based quality assessment of the questionnaire according to recommendations from a previous review on vision-related PROMs[107] yielded high to moderate quality for all components of the VND-Q .

6.2.2 Validity of the VND-Q

It was demonstrated that drivers who reported greater levels of vision-related night driving difficulties with the VND-Q also reported poorer general visual function, vision for night driving, vision under low luminance and vision under conditions of glare. Respondents with self-reported binocular eye diseases such as glaucoma, AMD and diabetic retinopathy also reported greater levels of vision-related night driving difficulties supporting construct validity of the instrument.

Importantly, further support for the validity of the VND-Q was provided in Study 2 and Study 3 where it was shown that measures of visual function such as photopic high and low contrast VA, as well as mesopic and glare-based tests, were correlated with VND-Q Rasch scores, and that these objective measures and self-reported scores were associated with closed-road night driving performance.

6.2.3 Which standard and non-standard tests of visual function most strongly reflect self-reported vision-related night driving difficulties?

In Study 2, a range of standard and non-standard tests of visual function were administered to 72 older drivers, including a subset of 29 drivers who had good photopic HCVA yet reported substantial difficulties with their vision for night driving. The battery of visual function tests included photopic HCVA, LCVA, SKILL card and Pelli Robson CS; mesopic HCVA, LCVA, and Mesotest without glare; glare testing with the Berkeley glare test, Aston Halometer and Mesotest with glare.

The standard measurement of photopic HCVA was found to be significantly associated with VND-Q Rasch scores for the whole cohort, where participants with poorer VA were more likely to report greater vision-related difficulties with night driving. In addition, halo area was significantly associated with VND-Q scores, where participants who reported greater difficulties had larger areas of glare surrounding the LED of the Halometer. Photopic LCVA and the Mesotest (in the presence and absence of glare) were also significantly associated with VND-Q scores, after adjusting for gender, although they had similar associations with self-reported difficulty levels as a standard measure of photopic HCVA. For the full cohort, all of the significant visual function tests (photopic HCVA, photopic LCVA, Mesotest, Halometer) explained approximately 10% of variance in VND-Q scores.

Given these findings, an important question was to determine which vision tests best reflected VND-Q scores for participants who had normal photopic HCVA yet still reported relatively high difficulty with their vision for night driving. This is a critical issue to explore because it is a problem frequently faced by clinicians when a photopic HCVA fails to indicate any visual function difficulties. The findings demonstrated that for these patients, mesopic tests of visual function, such as Pelli-Robson CS conducted under mesopic luminance and the Mesotest II (in the presence and absence of glare), were significantly associated with their VND-Q scores. Furthermore, the amount of explained variance in VND-Q scores was increased by a factor of 2-3 compared to that which standard photopic HCVA explained for the full cohort analysis.

6.2.4 How closely do older drivers' perceived levels of vision-related night driving difficulties relate to actual measures of night driving performance?

In Study 3, measures of closed-road night driving performance were determined for 26 older drivers who reported a range of vision-related night driving difficulty. The recognition of signs, white and black road markings, pedestrians and road-side animals was scored, as well as the recognition and avoidance of on-road grey foam hazards. These driving tasks were performed over two runs of a 4.6 kilometre circuit, in the presence and absence of intermittent glare.

Self-reported difficulties, measured via the VND-Q, were significantly associated with night driving performance and were more strongly associated with driving performance in the presence of intermittent glare, suggesting that drivers were more insightful of their difficulties with glare than under general low luminance conditions. VND-Q scores showed similar associations with driving performance as the test of photopic HCVA. Therefore, the results of the present study demonstrate that the VND-Q would be useful for identifying poorer night drivers and a valuable measure for inclusion in research exploring potential interventions to improve night driving capacity.

The choice of self-report instrument is important in order to obtain a meaningful measure of vision-related night driving difficulties. This study also demonstrated that while the VND-Q instrument was associated with night driving performance, ratings of discomfort glare were not significantly associated with driving performance. This result is in accord with other studies that have also demonstrated that the deBoer rating scale for discomfort glare rating is not a useful predictor of night driving [143] or visual performance[18] outcomes.

6.2.5 How does intermittent glare affect night driving performance in older adults with vision-related night driving difficulties?

The presence of intermittent glare caused a significant reduction in overall driving performance for the 26 drivers tested on the closed-road, even when adjusted for time to complete the course. The overall composite z-score was important to account for differences in how participants prioritised different driving tasks. Of the individual driving components, pedestrian recognition was the most poorly performed and was the task most affected by the intermittent glare source, with a 38% decrease in pedestrian recognition compared to the no glare condition. The successful detection and avoidance of low-contrast hazards on the road was also significantly worse in intermittent glare conditions than in the absence of glare. However, in the runtime adjusted analysis, there was no significant difference between hazard avoidance in the different glare conditions. The results suggested that drivers were able to reduce the negative effects of glare by slowing down to facilitate the detection and avoidance of on-road hazards. However, slowing down is not always possible on the open-road, such as when driving in heavy traffic.

The findings of this study indicate that intermittent glare not only impairs the detection of roadside pedestrians, as has been previously demonstrated,[18,137,143] but also overall driving performance. The recognition and avoidance of low contrast on-road hazards was significantly impaired and other driving performance measures such as sign detection and the detection of roadside animals also tended to be poorer in the presence of glare but these reductions did not reach significance.

6.2.6 Are mesopic and glare based assessments of visual function better predictors of night driving performance than a standard measure of photopic visual acuity?

The tests of visual function that were included in the protocol for Study 3 included photopic HCVA, LCVA, Pelli-Robson CS; mesopic HCVA, Pelli-Robson CS, motion sensitivity, Mesotest without glare; and glare tests including the Mesotest with glare, Aston Halometer, and Berkeley glare test.

Reduced photopic HCVA was associated with reduced overall night driving performance although it accounted for only 9% of the variation in driving scores. Several non-standard tests of visual function were able to account for a greater proportion of the variation in night driving performance. The test of motion sensitivity was shown to be the strongest independent visual function test associated with night driving performance. It accounted for 20% of the variation in driving performance when data was adjusted for driving speed. Mesopic HCVA was also strongly associated with night driving performance, explaining 17% of the variation in performance when data was adjusted for driving speed. The best photopic assessment for night driving performance was LCVA but this only accounted for 13% of the variation in driving performance.

Consideration of the findings of Studies 2 and 3 in combination with current literature suggests that, photopic LCVA, Mesopic HCVA and CS and motion sensitivity all provide additional information about potential safety when driving at night in comparison to a standard measurement of photopic HCVA. These tests would be valuable additions to clinical assessments to help advise patients about their visual fitness to drive safely at night.

6.2.7 Are the Mesotest cut-off levels defined by the German Ophthalmological Society predictive of poorer night-time driving performance?

The Mesotest was a particularly important inclusion in the protocols for Studies 2 and 3 because of its use in some countries to assess visual fitness to drive at night and the limited evidence confirming validity of the instrument. There are also no previous closed-road studies to support its ability to discriminate between drivers' fitness to drive at night.

In Study 2, the Mesotest was one of the mesopic tests that was most strongly associated with participants' self-reported difficulties when photopic HCVA could not. In Study 3, it was found that the number of levels passed on the Mesotest II in the presence and absence of glare was not significantly associated with night driving performance; however, the current DOG standard of a pass on level 1, for the glare and no glare conditions, was significantly associated with night driving performance. Thus, when the instrument is used in this pass/fail capacity it does appear to discriminate between better and poorer night drivers.

Nonetheless, a limitation of using the Mesotest for assessing visual fitness to drive at night is potentially poor repeatability and greater variation in results than for other mesopic tests. Mesopic VA, mesopic Pelli-Robson CS and motion sensitivity demonstrated significant associations with vision-related night driving difficulty and driving performance in this program of research and therefore might be better options than the Mesotest for assessing visual fitness to drive at night.

6.3 OVERALL STRENGTHS, LIMITATIONS AND FUTURE RESEARCH

Older adults' primary mode of transport in developed countries like Australia is by private vehicle,[293,294] and the ageing of the population[11] suggests that there will be a steady increase in the number of older drivers on the road at night. Thus the results of this study are highly relevant and provide critical information to guide improvements of safety on the road at night as well as for the independence and quality of life for older drivers.

Given the widespread concerns reported by older drivers in the literature regarding vision and night driving, the development of a Rasch analysed instrument to quantify vision-related night driving difficulties provides a valuable addition to the existing vision-related PROMs. The VND-Q is novel because existing questionnaires about visual difficulties contain very few items relating to night driving (if any) and often target populations with moderate to severe levels of visual impairment. Many are specifically designed for individuals with eye disease who are likely to have much greater visual and driving difficulties than an individual who continues to regularly drive at night. This new night driving scale provides a validated and effective means of obtaining measures of self-reported vision-related night driving difficulty.

A primary strength of this research was the inclusion of a wide range of both standard and non-standard tests of visual function that were appropriate for clinical use. By including participants who had concerns about their vision for night driving, it was possible to investigate whether non-standard testing using mesopic or glare-based tests was useful for patients who might otherwise appear to have normal vision according to a standard assessment of photopic HCVA.

Notably, this study is the first to comprehensively investigate the relationship between visual function and actual night time driving performance, with a focus on the effects of glare. This was an important design feature given that Study 1 (Chapter 3) showed that one of the main night driving concerns of older drivers is with respect to glare from oncoming headlights. The use of a vehicle-mounted glare source that enabled control of the position and duration of the glare source enabled a comprehensive examination of the impact of glare on driving performance, including the ability of participants' visual function to recover after repeated intermittent exposure to glare.

There are only limited studies exploring the relationships between vision and actual night driving performance as very few research groups have access to closed-road conditions. Therefore, it was a major strength of the study to include unique measurements of driving performance captured on the closed-road. Furthermore, the inclusion of the Mesotest in the testing protocol was an important strength because no closed-road studies have previously been conducted to support the instrument's validity for discriminating between better and poorer night drivers. This is despite its current use in some countries, to assess visual fitness to drive at night.

There were however, some limitations of the study program. Open-road investigations (if feasible) and studies of night-time crash-risks are necessary to confirm the findings that were demonstrated on the closed-road. It also remains to be determined whether the current study participants had greater insight regarding their driving abilities and visual limitations than the general older population, because they all self-identified some level of difficulty with their vision for night driving. For Study 3, the participants also had prior exposure to a range of non-standard visual assessments conducted under low-luminance and glare conditions which may have improved their insight into their visual difficulties under night-time driving conditions. Future research should include drivers who do not report difficulties with night driving and also specifically include cohorts of drivers who already avoid driving at night or those who have a history of crashes at night. The development of a low-lighting performance questionnaire that is applicable to all older adults, not just those who drive at night, would also be a valuable area for future work.

Further study could also include samples with a wider age range, specific eye diseases known to affect mesopic vision (e.g. AMD, glaucoma, diabetic retinopathy) and investigations prior to and post cataract surgery. In addition, it would be interesting to investigate regional differences in vision-related night driving difficulties, in order to explore whether individuals who are exposed to more challenging night driving conditions more often have greater or less difficulty driving at night, as assessed by the VND-Q. For example, studies could include drivers who frequently travel on rural roads and from countries that experience a greater proportion of low-luminance hours per day, particularly in the winter months. An investigation of risk factors for discordance between driving performance and self-reported difficulty on the VND-Q would also be valuable to help identify individuals that may have poor insight into their driving ability. If future work firmly establishes the associations between mesopic vision tests and night driving safety, these drivers could then undergo mesopic vision testing to determine whether they should self-restrict their driving or not.

Further study using the Mesotest is also necessary, not only because it is currently the only instrument used in licencing for night driving, but also because the results of this study show that it may have the capacity to determine ability to drive safely at night. The new standard implemented by the German Ophthalmological Society should be investigated using crash analyses and open-road studies to confirm the results of this closed-road investigation. However, it should be noted that the current studies also show there may be other mesopic tests that are more valuable for assessing visual fitness to drive at night. In addition to tests used in these studies, visual field examinations conducted under mesopic conditions, the measurement of dark adaptation curves and photostress recovery times may also be beneficial to explore with respect to predicting night driving difficulties.

6.4 PRACTICAL IMPLICATIONS

6.4.1 Should the assessment of non-standard tests of visual function become standard in ophthalmic examinations? – if so, which ones?

The findings of this program of PhD research have demonstrated that the assessment of visual function under mesopic conditions can provide valuable information about patients' night driving abilities. The use of non-standard tests of visual function such as mesopic CS and the Mesotest II were shown to be particularly useful for verifying the visual difficulties of patients who report having substantial difficulty seeing under night driving conditions yet appear to have unimpaired vision based on a standard assessment of photopic VA.

Motion sensitivity and mesopic HCVA were the most strongly associated with actual measures of driving performance. This association supports previous findings from closed-road studies[26,27] and other studies that have discussed the importance of mesopic-related aspects of vision[14,29,119,122,262,295–297] and motion sensitivity[149,222,281–283] for night driving. The introduction of a standard measurement of mesopic VA under a low luminance of 0.38cd/m^2 could feasibly be introduced as a test for assessing fitness to drive safely at night. An advantage of using mesopic VA is that it is it is familiar to both clinicians and patients and would not require additional equipment to implement, other than the ability to adjust lighting levels in examination rooms. A measurement of mesopic CS is also recommended, given the current study findings, in conjunction with previous research outcomes, that have found CS to be particularly valuable for assessing visual deficits not revealed by photopic HCVA. When mesopic conditions are not an option, either due to time or lighting constraints, a measurement of photopic LCVA would also be of benefit to provide insight into patients' night driving capacity. Although the test of motion sensitivity and the Mesotest (pass/fail criteria) have demonstrated value for assessing night driving difficulties and performance, their feasibility needs to be further explored as they require specialised software or equipment that would need to become more widely available to be implemented in clinical settings.

The advantage of introducing standardised testing of visual function under mesopic conditions for the purposes of assessing driving would be in the ability to monitor changes to these visual functions over time. This may provide earlier diagnosis of eye diseases such as AMD[41] and more timely referral for interventions such as cataract surgery. Furthermore, the standardised assessment of mesopic-related vision could help to educate patients about how limited their vision is under night driving conditions, particularly as they become older and their eyes undergo age-related deteriorations. Educating older patients regarding their visual limitations has previously been shown to be beneficial in promoting safe driving practices and the self-regulation of driving in visually challenging situations.[22] This study also demonstrated that older drivers may have improved insight about their vision-related night driving difficulties after an assessment of visual function under mesopic conditions.

Advice to the European Driving Licencing Committee regarding a revision of vision standards for driving, recommends that “the future introduction of requirements regarding twilight vision should be made possible and anticipated, after proper research has been performed”.[298] The document states that both assessment techniques, and determination of detrimental levels of impairment for contrast and glare sensitivity, are required before screening practices for twilight vision are justified. The findings of this research support this position but the precise level at which vision becomes unsafe for night driving remains to be determined for tests of visual function that can be easily implemented in clinical settings.

The specific importance of night driving and the impact of restriction or cessation of night driving for older adults’ quality of life is an area requiring further exploration, together with ways to minimise the impact of night-time driving restrictions that may be necessary for some older drivers. The decision of whether to drive at night or not potentially has significant consequences for older drivers’ quality of life and health trajectories therefore, it is critical that advice about night driving is supported by a strong evidence base.

6.5 CONCLUSIONS

In conclusion, this program of PhD research adds to evidence that the commonly used measurement of photopic HCVA is not optimal for assessing visual fitness to drive at night. A well validated instrument for assessing vision-related night driving difficulties was developed (VND-Q) based on 283 older drivers' questionnaire responses. Self-reported VND-Q scores were associated with poorer measures of visual function, including photopic HCVA, for 72 participants. Importantly, for a subgroup of 29 participants who had good photopic HCVA for their age yet reported substantial night driving difficulties, the assessment of mesopic CS and the Mesotest II varied according to their level of self-reported difficulties. Furthermore, closed-road night driving performance in 26 participants was more strongly associated with mesopic tests of visual function such as motion sensitivity, mesopic HCVA and mesopic CS, than photopic measures of visual function or glare based tests. This study was also the first to provide closed-road driving evidence that the Mesotest II DOG pass/fail criteria for night driving discriminates between better and poorer night drivers.

The specific investigation of the effect of glare on driving performance revealed that intermittent glare caused an overall decrease in night driving performance and had significant effects on the visibility of pedestrians wearing retro-reflective vests. Drivers slowed down significantly in the presence of the intermittent glare and this appeared to improve their avoidance of low contrast hazards, although the change in driving speed and improvement in performance was only slight.

This study provides a unique and comprehensive report on the interrelationships between self-reported vision-related night driving difficulties, standard and non-standard tests of visual function, and closed-road night driving performance in the presence and absence of intermittent glare. The maintenance of safety on the road at night is vital and given that one third of the population of older drivers report vision-related night driving difficulties, the results of this study are highly relevant and applicable particularly in view of the currently ageing population. Night driving is hazardous so the decision on whether to drive at night must be considered carefully by balancing safety implications against impacts on older drivers' independence and quality of life. The results of the present study will help to guide future research regarding the standardised assessment of visual fitness to drive at night and advice that clinicians can provide patients to help ensure their safety and comfort on the road at night.

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APPENDICES

Appendix A Illuminance levels at the eye during night driving

In order to assess visual functioning and performance under low-light conditions that replicate night roads, it is important to know the illuminance that is present at the eye during actual night driving. This pilot study determined the illuminance at the eye during six runs of a 25 minute night drive on two separate evenings during conditions of light rain and dry, clear weather. The aim was to measure the range of mesopic illuminance that the eye is exposed to on well-lit roads, freeways and in zones of poorly lit streets.

Methods

Ambient white light illuminance (lux) was measured using an Actiwatch 2 (Philips Respironics, USA) which contains a silicone photodiode light sensor to measure visible light illuminance ranging between 400 to 900 nm with a peak sensitivity of 570 nm.[299] The sensor was set to capture instantaneous illuminance at 15 second intervals. The Actiwatch was mounted at eye level on the centre of a spectacle frame facing directly forward as shown in Figure A-1. The night driving scene was simultaneously video recorded using a goPro camera (HERO4 GoPro; San Meteo, USA) attached to the windscreen of the car. Synchronisation of the video and illuminance levels occurred via accurate time-stamps recorded by the instrumentation and was assessed for time points within the drive to enable exploration of night road scenes and their corresponding light levels at the eye.

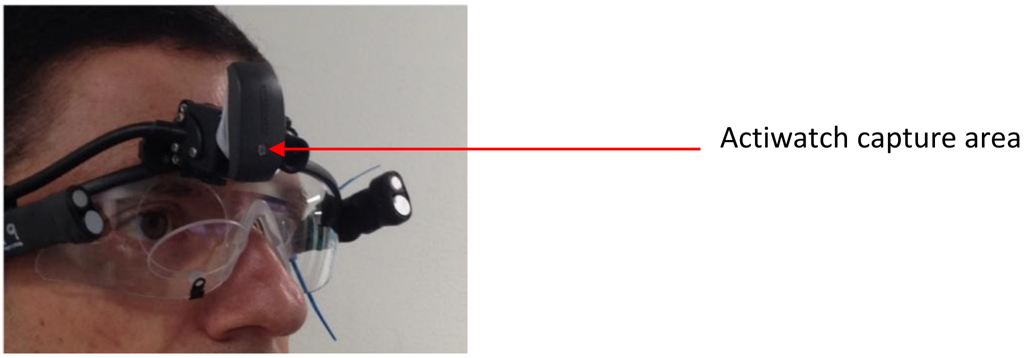


Figure A-1: Actiwatch sensor position

The Actiwatch 2 is specified for use between 5-10,000 lux[299] therefore accuracy of the Actiwatch for measuring low illuminance levels was assessed before investigations. Illuminance measurements with the Actiwatch were compared to the Topcon 1M-2D illuminance meter (Topcon, Tokyo, Japan) which is specified as having accuracy of ±5% for measurements between 0.1-19,990 lux.[284] Static readings on both instruments were taken for 30 different room lighting conditions.

Results

The accuracy of the Actiwatch for measuring ambient illuminance at low light levels has not previously been published. Static measurements for 30 different room lighting conditions were within 4.5 lux of measurements taken by the Topcon Illuminance meter (IM-2D Japan). The average difference between the two instruments was 1.8 lux with the Actiwatch tending to produce consistently higher values than the Illuminance meter. The correlation between the Illuminance meter and Actiwatch was high (r=0.99) (Figures A-2 & A-3).

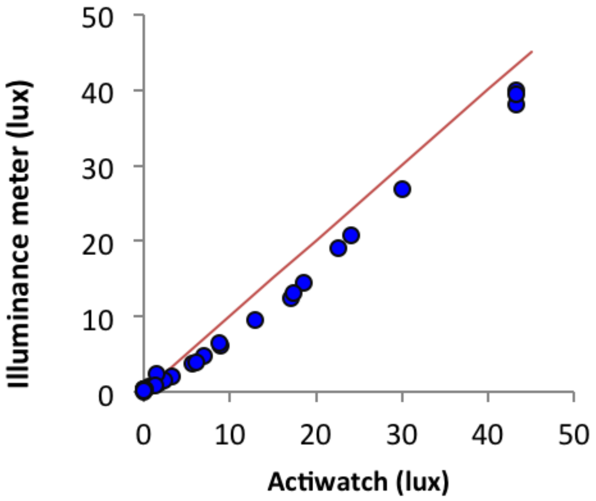


Figure A-2: Correlation between the Actiwatch and Illuminance meter outputs is high. The Actiwatch appears to consistently report higher illuminance values than the Illuminance meter. The red line represents perfect correlation between the two instruments.

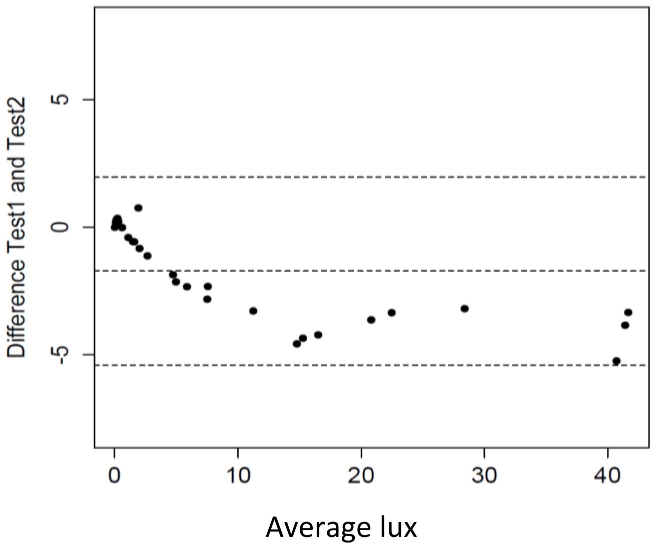


Figure A-3: Bland-Altman Plot of agreement between the Topcon Illuminance Meter and the Actiwatch.

Average illuminance values for each of the driving runs are shown in Table A-1 and averages for different roadway condition are shown in Table A-2.

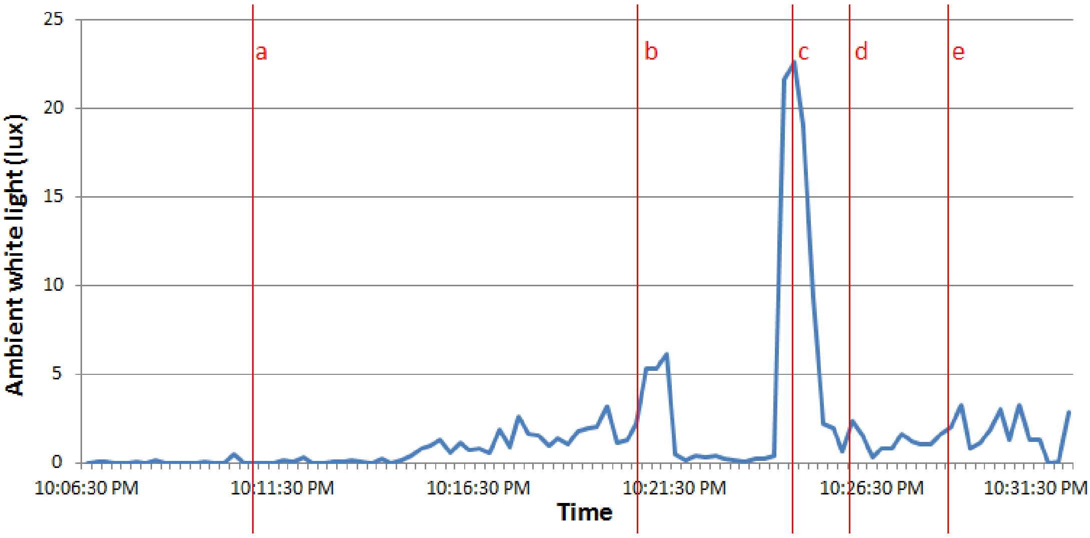
Table A-1: Mean illuminance at the eye for 25 minute night driving runs

Weather	Run	Mean lux ± SD
Dry clear	1	2.1 ± 1.9
	2	1.5 ± 1.4
	3	1.7 ± 1.6
Light rain	4	1.7 ± 1.5
	5	1.7 ± 1.7
	6	2.3 ± 2.9

Table A-2: Mean illuminance at the eye for different roadway conditions. Data based on driving run 1 in dry, clear weather.

	Mean lux ± SD
Well-lit Road	3.79 ± 1.08
Freeway	2.12 ± 0.14
Low-lit Road	0.37 ± 0.28

The range of illuminance measured at the eye, using an Actiwatch 2, was 0-23 lux. A series of selected night scenes and illuminance values from run 1 in dry, clear weather are depicted in Figure A-4. Peak illuminance levels tended to occur when driving on well-lit urban roads, given the brighter road lighting, more oncoming traffic and headlights. There were many zones of low illuminance (<5 lux) measured during sections of the drive corresponding to rural and minor roadways. By definition, the mesopic illuminance range extends approximately from 0.05-50 lux,176 therefore this pilot study shows that night driving illuminance levels at the eye require a low mesopic state of retinal adaptation.




b


c


d

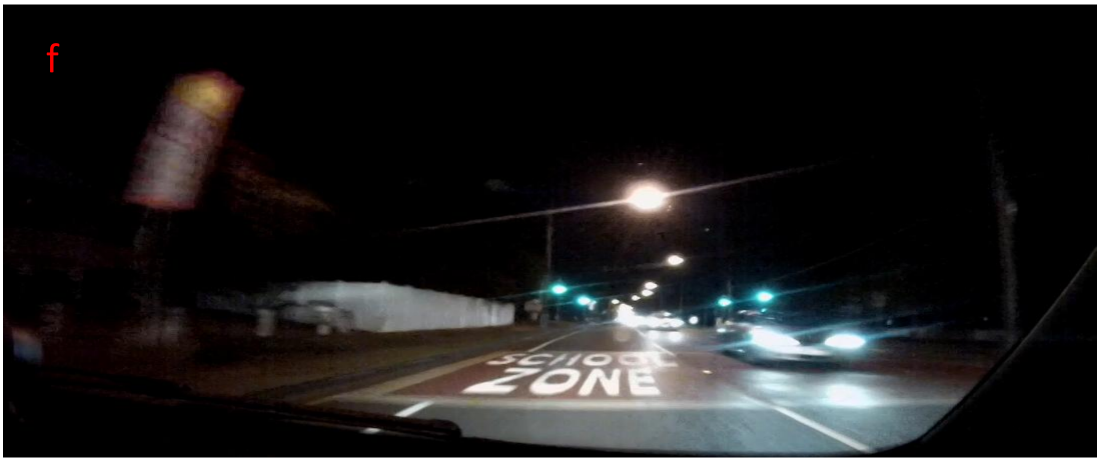


Figure A-4: Illuminance levels measured at the eye during a 25 minute drive. Red vertical lines on the chart represent time points illustrated by the night road scenes shown in images a-e. Lower illuminance values correspond to rural, minor roads whereas higher illuminance values correspond to night scenes on trafficked and well-lit major roads.