The nighttime driving environment presents challenging visual conditions for drivers, including dim street lighting, oncoming headlight glare, and the need to quickly adapt across a wide range of lighting levels. These conditions make driving at night particularly difficult for older adults due to age-related deteriorations in vision, particularly under the mesopic and glare conditions of the nighttime driving environment. Visual function decreases at an earlier age and to a greater extent for low contrast targets and mesopic conditions compared to high contrast targets and photopic conditions. Thus we hypothesize that vision testing under conditions more representative of nighttime driving will better predict older adults’ nighttime driving ability than commonly used photopic high contrast testing conditions.

Visual factors significantly contribute to the elevated risk of fatal crashes at night, which are two to four times greater than in the daytime. Crash database analyses have demonstrated that poor visibility at night, rather than increased fatigue and alcohol, is the main reason for the elevated pedestrian fatality rate at night, which is seven times that in the daytime. In particular, older drivers are at greater risk of a fatal nighttime crash per distance driven compared to all drivers, with the exception of drivers aged younger than 25 years. Closed-road studies have demonstrated that headlight glare may also be an important contributing factor in pedestrian fatalities, where the presence of glare from headlights significantly impairs pedestrian detection performance and decreases recognition distances.

Nighttime driving difficulties are the most commonly reported age-related visual concern, with oncoming headlight glare being a particular problem, likely due to increased intraocular scatter from age-related lens and ocular media changes. Approximately one-third of all older drivers and an even greater proportion of drivers with eye disease report nighttime driving difficulties. In the absence of evidence-based advice from their eye care professionals, these patients are likely to self-select whether or not to drive at night. This is problematic, given that drivers are known to underestimate their visual limitations at night, and have limited insight into their own driving abilities, and regulate their driving based more on confidence than actual driving ability.

A clinical examination of vision typically involves assessment of high contrast visual acuity (HCVA) under photopic light levels, which does not fully capture the visual capacity required for safe driving, or for other lighting conditions such as the low luminance and glare conditions typically present when driving at night. Numerous studies have demonstrated the advantages and advocated the use of nonstandard vision tests for assessing older drivers’ visual capacity to drive at night.

Keywords: nighttime driving, visual function, mesopic, aging
nonstandard vision tests to represent visual function across a range of lighting conditions.\textsuperscript{2,3,38-44} While there is some evidence that driver safety and performance at night is associated with mesopic visual function and glare sensitivity, such as the Mesotest (mesopic CS in the presence and absence of glare)\textsuperscript{45,46} and mesopic visual acuity (VA),\textsuperscript{32} there has been very limited research into nighttime driving ability and the assessment of visual capacity to drive at night.

The primary purpose of this study was to examine the associations between photopic, mesopic, and glare-based tests of visual function and nighttime driving performance of older adults, as measured using standardized conditions on a closed-road circuit. A secondary aim was to investigate the effects of glare on nighttime driving performance for older adults self-reporting nighttime driving difficulties. We hypothesized that mesopic tests would be more strongly associated with nighttime driving performance than photopic tests for older drivers who report vision-related nighttime driving difficulties.

METHODS

Participants

We recruited 26 older drivers (mean age: 71.8 ± 6.3 years; range: 63–88 years) from a previous study that had been identified as having self-reported “night driving difficulties due to vision problems in dim light, with glare or with sudden changes in light levels.”\textsuperscript{47} Participants had no or minimal eye disease and were licensed drivers who 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. The study was conducted over two sessions including one session for visual function testing, followed by a nighttime driving assessment.

Assessment of Visual Function

Ocular health was assessed to determine the presence of any eye disease and to ensure participants met the minimum driving HCVA standard (binocular VA 20/40, 0.3 logMAR) with no visual field defects that could affect driving performance (monocular 40-point screening; Humphrey Visual Field Analyser; Carl Zeiss, Meditec, Inc., Dublin, CA, USA). A series of visual function assessments was conducted under photopic, mesopic, and glare conditions. To address the effects of fatigue and practice, the order of photopic and mesopic testing was counterbalanced, with the glare assessment always undertaken following the mesopic assessment. All measurements were performed binocularly using the participants’ habitual driving correction (if any), with the addition of an appropriate working distance lens if required.

Photopic Tests

The luminance level for photopic vision testing was 100 ± 6 cd/m\textsuperscript{2}, consistent with recommended photopic lighting requirements for each of the vision tests.\textsuperscript{18,49}

**Visual Acuity.** Photopic HCVA (90%) and low contrast visual acuity (LCVA; 10%) were measured using a Bailey-Lovie logMAR chart (Precision Vision, Woodstock, IL, USA) and letter by letter scoring method,\textsuperscript{50} where each letter represented 0.02 logMAR.

**Contrast Sensitivity (CS).** Photopic CS was measured using the Pelli-Robson chart (Clement Clarke International Ltd., Harlow, UK). Participants were encouraged to guess letters until a full triplet was answered incorrectly. Contrast sensitivity was scored as 0.05 log units for every correctly identified letter, with O and C being accepted interchangeably.\textsuperscript{51}

Mesopic Tests

The luminance level for mesopic vision testing was 0.38 ± 0.02 cd/m\textsuperscript{2} consistent with previous studies (0.1–1 cd/m\textsuperscript{2})\textsuperscript{5,37-44}; this level has been reported to provide reliable and repeatable results.\textsuperscript{42} Participants were given a 10-minute adaptation period to the mesopic light level based on previous study adaptation periods.\textsuperscript{35,38,40,42,52}

**Visual Acuity and Contrast Sensitivity.** Mesopic HCVA and Pelli-Robson CS were measured with the same method as the photopic assessments, using an alternative chart to avoid familiarity with the test letters.

**Motion Sensitivity.** A computer-based random dot kinematogram (dot density 0.43%, screen luminance 0.36 ± 0.02 cd/m\textsuperscript{2}) was used to measure motion sensitivity at a test distance of 3.2 meters.\textsuperscript{53,54} Participants identified the direction of movement of a central panel of dots that moved randomly in one of four directions and the minimum dot displacement threshold (D\textsubscript{min}; log deg arc) detected was determined using the mean of the last six reversals of a two-down one-up staircase algorithm.

Glare-Based Tests

The glare tests included in this study were selected to represent two different forms of glare testing: the Berkeley Glare Test uses a diffuse glare source, while the Aston Halometer uses a point glare source which could be considered to more closely represent headlight glare.

**Aston Halometer.** The halo size produced by glare from a bright white LED attached to the center of an LCD screen (iPad; Apple, Cupertino, CA, USA; see Ref. 55 for further detail) was measured at a 2 m working distance. The angular halo size was measured along eight meridians in a clockwise direction (0–360° at 45° intervals) using a high contrast letter (6/15, 0.4 logMAR) that was moved inward in 0.1° increments. The position closest to the LED where two out of three presentations of the target were correctly identified was recorded as the halo boundary. A seen-to-not-seen approach was used to minimize any photostress effect from the central LED source. The halo area was determined by calculating the angular area (in degrees) based on the eight meridian boundaries of the halo surrounding the LED glare source.\textsuperscript{55}

**Berkeley Glare Test.** The reduction in LCVA (18% Weber contrast), with the addition of a diffuse glare source, was measured using a set of Plexiglas opaque triangular letter charts mounted over a 30 × 27 cm light box.\textsuperscript{56} The disability glare index (DGI) was calculated by determining the difference between LCVA (logMAR) measured with and without the glare source on a medium setting of 750 cd/m\textsuperscript{2}.\textsuperscript{56}

Driving Assessment

**Instrumented Vehicle.** All driving assessments were conducted in an automatic transmission sedan with the halogen headlights set to low-beam. The vehicle was instrumented with two roof-mounted cameras (HEROS; GoPro, San Mateo, CA, USA) which recorded lane position and on-road hazards. An audio recording device (MUVI HD; Veho, Southampton Hampshire, UK) was used to capture participants’ verbal responses to allow for post-testing verification and analysis. To provide the intermittent glare source, a dimmable 7.5 cm diameter diffuse LED light fixture (maximum 12 V, 10 W; 2700 K) was mounted on the driver side of the car bonnet at a visual angle of 10° (Fig. 1). The intensity of the glare source
Vision and Nighttime Driving Performance

Figure 1. Glare source appearance and location. Participants drove on the left side of the road.

was adjusted for each participant so that the illuminance at the eye was \(15 \pm 2\) lux, equivalent to \(650 \pm 10\) cd/m\(^2\) at the driver’s eyes if they looked directly into the glare source. The illuminance level was chosen based on pilot studies that matched the glare source to actual headlights based on intensity, subjective brightness and visual acuity reduction at a distance of 20 m.

Driving Circuit and Driving Performance Measures.

Nighttime driving performance was measured on a closed-road circuit at the Mt Cotton Driver Training Centre, as used in previous studies.\(^{26,32,57,58}\) Testing commenced at least 15 minutes after nautical twilight and when road surfaces were dry. The circuit was 4.6 km long, and included hills, curves, intersections, and straight sections. The circuit did not have any street lighting or any other ambient lighting.

Participants completed two runs of the circuit following a practice lap to familiarize the participant with the test vehicle and the required tasks. One run was undertaken in the absence of glare, and the other included the vehicle mounted glare source which was turned on intermittently (30% of the total run) at specific locations along the driving circuit. The glare sections were chosen to coincide with a variety of tasks, but still reflect natural nighttime driving conditions where headlight glare occurs intermittently. The practice lap was carried out in the reverse direction to the testing lap and the order of the intermittent-glare and no-glare runs was counter-balanced to minimize learning effects.

Participants were instructed to drive at a comfortable speed and attend and verbally report the following tasks while driving: speed signs (\(n = 21\)); triangular white or black road markings (\(n = 12\)); roadside wooden animals (\(n = 4\)); roadside pedestrians walking in place on the opposite side of the two-lane road (right side) wearing either a long-sleeved gray shirt (\(n = 2\)) or a reflective vest (\(n = 2\)) with black pants and shoes; and recognition and avoidance of low contrast gray foam hazards on the road (\(n = 12\)).\(^{32,58}\) Within the glare zone there were six speed signs, four road markings, three roadside animals, four roadside pedestrians, and six low-contrast hazards.

Two experimenters acted as pedestrians, while another two experimenters were seated in the instrumented vehicle to provide directions to the participants, record performance on the various driving tasks and control the onset and offset of the glare source at the required locations on the circuit. Recognition tasks were scored as the percent of total targets correctly recognized and hazard avoidance was scored based on the percent of total targets successfully recognized and avoided. Lane keeping was scored using video playback to calculate the percent of total runtime spent driving within the lane markings. The total time taken to complete each run was also determined from the video recordings.

Statistical Analysis

The driving performance measures (signs, road markings, roadside animals, roadside pedestrians, hazards), as a percent of the total possible score, and lane keeping were each converted to a \(z\)-score where a positive \(z\)-score represented better performance than the mean. Overall nighttime driving performance was calculated based on the mean \(z\)-scores of these six components, which captured participants’ performance relative to the group as a whole, as has been used in previous closed-road studies.\(^{57,59,60}\)

Statistical analyses were performed using statistical software (IBM SPSS, version 21; IBM Corporation, Armonk, NY, USA) and \(P\) values <0.05 were used to indicate statistical significance. Paired \(t\)-tests were used to assess differences between the driving performance scores for the no-glare and intermittent-glare conditions for each of the individual driving performance components, as well as for overall driving performance \(z\)-scores. Linear mixed models with glare as a repeated factor and random intercept for participants were used to determine the difference between no-glare and intermittent-glare overall driving scores when taking runtime into account. Generalized linear regression was used to assess whether there was a learning effect across participants’ first and second run. Generalized linear regression models were also used to investigate the relationship between visual function measures and nighttime driving performance summed across the no-glare and intermittent-glare runs. All models included runtime as a covariate to account for differences in participants’ driving speed. For tests showing a significant association with driving performance, residuals were used to calculate the additional percent of the variation explained in driving performance with the inclusion of each visual function test in separate models.\(^{61}\)

Results

Table 1 provides a summary of the participant demographics, eye conditions, and driving habits. Seven participants had previous cataract surgery and intraocular monofocal lenses (six bilateral and one unilateral). Participants reported around 25% of their driving was at night and almost half avoided nighttime driving at least “a little” of the time due to their visual difficulties.

Driving Performance and Effects of Glare

Table 2 shows the mean overall driving performance \(z\)-scores and component driving outcome measures for the no-glare and intermittent-glare runs. Some driving tasks were performed well by participants, such as recognition of roadside animals and lane keeping, while others showed poorer performance, such as recognition of pedestrians and road markings. Overall driving performance \(z\)-scores was significantly worse in the presence of intermittent glare, compared to the no-glare condition (\(P = 0.002\)). There was no evidence of a significant learning effect across the two driving runs (\(P = 0.09\)).

Of the individual driving components, pedestrian recognition was most affected by the presence of the intermittent glare, where pedestrian recognition was reduced by 38% on average compared to the no-glare condition (\(P < 0.001\)). Low contrast hazard avoidance was also significantly affected by glare (\(P = 0.035\)). The time to complete the drive for the intermittent-glare run was also significantly longer compared to the no-glare run (\(P = 0.001\)), although the magnitude of the mean difference was small (20 seconds).

It should be noted that participants drove at varying speeds around the circuit, which reflects the circuit design, where...
TABLE 2. Summary of Participants’ Driving Performance Across the Two Driving Runs (No-Glare and Intermittent-Glare)

<table>
<thead>
<tr>
<th>Driving Variable</th>
<th>No-Glare Run</th>
<th>Intermittent-Glare Run</th>
<th>t-Statistic</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall driving z-score</td>
<td>0.15 ± 0.09</td>
<td>-0.98 to 1.40</td>
<td>-0.15 ± 0.22</td>
<td>-1.02 to 0.80</td>
</tr>
<tr>
<td>Component driving tasks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low contrast hazards, % seen and avoided</td>
<td>81.9 ± 15.6</td>
<td>42 to 100</td>
<td>78.2 ± 16.1</td>
<td>29 to 100</td>
</tr>
<tr>
<td>Triangular road-markings, % seen</td>
<td>60.8 ± 25.5</td>
<td>0 to 100</td>
<td>63.5 ± 23.5</td>
<td>8 to 100</td>
</tr>
<tr>
<td>Roadside animals, % seen</td>
<td>97.1 ± 8.1</td>
<td>75 to 100</td>
<td>93.9 ± 11.4</td>
<td>67 to 100</td>
</tr>
<tr>
<td>Signs, % seen</td>
<td>70.1 ± 20.1</td>
<td>5 to 95</td>
<td>67.4 ± 20.2</td>
<td>14 to 100</td>
</tr>
<tr>
<td>Pedestrians, % seen</td>
<td>48.1 ± 30.8</td>
<td>0 to 100</td>
<td>9.6 ± 15.9</td>
<td>0 to 50</td>
</tr>
<tr>
<td>Lane keeping, % of runtime keeping in lane</td>
<td>82.4 ± 4.4</td>
<td>72 to 92</td>
<td>82.4 ± 5.2</td>
<td>69 to 93</td>
</tr>
</tbody>
</table>

* P < 0.05.
** P < 0.01.

DISCUSSION

This study demonstrated that nonstandard tests of visual function, which reflect the environmental conditions when driving at night, were more strongly associated with nighttime driving performance than a standard test of photopic HCVA. The results suggest that photopic HCVA provides limited information for eye care practitioners and patients to inform visual capacity to drive at night. Mesopic measures of motion sensitivity and HCVA accounted for around twice the variation in overall driving performance scores (29% and 24%, respectively) compared to photopic HCVA (14%). Therefore, measures such as these should be incorporated into the clinical assessment of visual capacity to drive at night for patients who self-report vision-related nighttime driving difficulties.

This study is the first to explore the capacity of a range of different visual function tests, including different target contrasts and light levels as well as glare, for predicting nighttime driving performance measured under closed-road conditions. Notably, the novel use of a vehicle-mounted glare source enabled repeated intermittent and more sustained exposure to glare than previous studies, which used stationary roadside headlights from real or simulated vehicles.8,17,26,27,32,62 Therefore, the current experimental design may better reflect natural nighttime driving conditions, such as multiple oncoming headlights, albeit without the changes in headlight intensity and angle of incidence that occur under real-world conditions. The focus on the effects of glare on nighttime driving performance was an important feature of this study, given that one of the main nighttime driving concerns of older drivers is the glare from oncoming headlights.47

Performance on some of the driving tasks, such as pedestrian recognition, was relatively poor, particularly in the presence of intermittent glare, which may have directly impaired vision or interfered with recognition due to compensatory behaviors such as squinting, light aversion, or distraction. Older drivers, in particular, have been shown to look away from a glare source while driving to minimize their discomfort.15 The pedestrians in the present study were positioned on the same side of the road as the glare source, which could have contributed to the finding that pedestrian...
recognition was more affected by the intermittent glare than the other driving tasks, which were positioned on the road surface or on the opposite side of the road to the glare source. The glare light was intermittent (to represent oncoming headlights within traffic) rather than constant, thus it was not possible, given the nature of the driving circuit, to position equal proportions of each of the driving tasks within the glare zones. Thus, the differential effects of exposure to a constant glare source on specific aspects of nighttime driving performance could not be determined. However, our findings of pedestrian recognition difficulties at nighttime are supported by crash statistics that suggest that nighttime roads are dangerous, particularly for pedestrians. The significant decline in pedestrian recognition due to intermittent glare was comparable to that previously demonstrated on the closed-road for young participants with simulated cataracts, suggesting that the effects of glare on pedestrian recognition for older drivers with normal vision may be even greater than previously reported.

Importantly, mesopic HCVA and motion sensitivity, which have been previously identified as significant predictors of aspects of nighttime driving performance, remained the strongest predictors of nighttime driving performance in the current study, which had a more realistic glare design and a more comprehensive battery of visual function tests. While halo area was significantly associated with driving performance, the glare tests did not prove to be better predictors than mesopic HCVA or motion sensitivity. Indeed, daytime driving studies of older adults with cataract have also found that glare tests are not useful predictors of driving performance, despite the fact that intuitively they might be expected to be better than tests that less closely simulate challenging visual conditions.

The findings from the current study support existing evidence which shows that photopic HCVA is not optimal for predicting day or nighttime driving performance. Furthermore, our findings support those of a previous crash analysis study showing that drivers with reduced mesopic contrast sensitivity and increased sensitivity to glare (based on performance on the Mesotest) were more likely to be involved in a nighttime crash. Together, the current and previous study findings suggest that it is likely that there are functional

| TABLE 3. Associations Between the Separate Visual Function Tests and Overall Driving Performance (Summed Across No-Glare and Intermittent-Glare Runs) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Mean ± SD | Range | Wald Chi-Square Values | P Value | R2† | |
| Photopic | | | | |
| High contrast VA (logMAR) | −0.05 ± 0.09 | −0.26 to 0.10 | 4.74 | 0.029* | 14 |
| Low contrast VA (logMAR) | 0.15 ± 0.10 | −0.04 to 0.36 | 6.83 | 0.009** | 19 |
| Contrast sensitivity (logCS) | 1.93 ± 0.06 | 1.65 to 1.95 | 1.10 | 0.29 | |
| Mesopic | | | | |
| High contrast VA (logMAR) | 0.33 ± 0.12 | 0.08 to 0.56 | 9.29 | 0.002** | 24 |
| Contrast sensitivity (logCS) | 1.45 ± 0.25 | 0.95 to 1.95 | 6.03 | 0.014* | 17 |
| Motion sensitivity (Dmin, log deg arc) | −1.72 ± 0.15 | −2.00 to −1.45 | 11.90 | 0.001** | 29 |
| Glare | | | | |
| Halometer area (deg) | 12.88 ± 5.16 | 3.48 to 18.47 | 5.38 | 0.020* | 16 |
| DGI Berkeley Glare Test (logMAR) | 0.13 ± 0.07 | 0.00 to 0.30 | 2.19 | 0.14 | |

All generalized linear regression models included runtime as a covariate.

* P < 0.05.

** P < 0.01.

† Percent of total variance explained by the vision measure in the generalized linear regression model.

FIGURE 2. Association between mesopic HCVA (logMAR) and overall nighttime driving performance across the two runs.

FIGURE 3. Association between motion sensitivity (log deg arc) and overall nighttime driving performance across the two runs.
driving performance losses for older drivers with impaired mesopic vision and that these may have real impacts on the safety of older drivers when driving at night. There is a greater and earlier age-related decline of vision when tested with low contrast targets and under low luminance conditions,5–8 which may explain why low contrast and low luminance tests better represent older adults’ functional vision for nighttime driving.

Testing of visual function under nonstandard conditions may be beneficial in monitoring changes in visual functions relevant to nighttime driving over time. This information could assist eye care practitioners with timely referral for interventions such as cataract surgery, given that patients' self-reported dependence on driving and glare sensitivity are already considered as a reason for referral.65 Furthermore, the assessment of mesopic vision could help practitioners to advise patients about their vision under nighttime driving conditions, since 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.66 In addition, some drivers self-regulate their driving by restricting or ceasing nighttime driving too early67,68; the assessment of mesopic vision could help to reduce unnecessary avoidance of nighttime driving (due to perceived visual difficulties), thereby helping to maintain quality of life, mobility, and independence.69–70

A strength of our study was the measurement of driving performance captured on a closed-road circuit, which allows standardization of traffic conditions in a controlled safe environment (without other vehicles) under lighting conditions encountered at night. Low-beam headlights were used as they are the most commonly used headlight beam setting,71 and added visual complexity to the tasks. A limitation of the study was the relatively small sample size with participants having minimal or no eye disease. Importantly, this is the first study demonstrating the value of nonstandard assessments of visual function for predicting closed-road nighttime driving capacity, and provides a basis for further research with older drivers with greater levels of vision loss, as well as for the exploration of associations with naturalistic on-road nighttime driving performance. Establishing a minimum level of vision that is necessary for safe nighttime driving should be the aim of larger scale studies and determining whether it is possible that nonstandard tests can help to advise patients about their self-regulation of nighttime driving for real-world nighttime driving conditions.

Given that driving is the primary mode of transport for older adults in developed countries,72–73 and the population is aging,74 the number of older drivers on the road at night is likely to increase. Thus the findings of this study are highly relevant and provide a valuable basis on which to inform improvements of safety on the road at night, as well as for the independence and quality of life for older drivers. While photopic HCVA is the most common visual test for driver licensing, tests of mesopic vision are stronger predictors of nighttime driving capacity for older adults who report vision-related nighttime driving difficulties. It is therefore important that further research is conducted to inform the advice that clinicians can provide older patients to help ensure their safety, confidence, and comfort when driving at night.

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