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STANDARD MEASURES OF VISUAL ACUITY DO NOT PREDICT DRIVERS' RECOGNITION PERFORMANCE UNDER DAY OR NIGHT CONDITIONS

Joanne Wood[1] FAAO, PhD, D. Alfred Owens[2], PhD

[1]Centre for Health Research-Optometry, Queensland University of Technology, Kelvin Grove, Queensland, 4059, Australia**,**

[2]Whitely Psychology Laboratories, Franklin & Marshall College, Lancaster, Pennsylvania, USA 17604-3003

Author for correspondence
Joanne M Wood
Centre for Health Research - School of Optometry
Queensland University of Technology
Victoria Park Rd
Kelvin Grove Q4059
Australia
Telephone: +617-38645701
Fax: +617-38645665
e-mail: j.wood@qut.edu.au

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ABSTRACT

Purpose: This study investigated whether visual acuity or contrast sensitivity, measured under a range of luminance conditions could predict drivers' recognition performance under real-world day and night road conditions.

Methods: Twenty-four participants, comprising three age groups (younger, M=21.5 years; middle-aged, M=46.6 years; and older, M=71.9 years), drove around a 1.8 km closed road circuit under day and night-time conditions. At night, headlight intensity was varied over 1.5 log-units by ND filters mounted on the headlights. Participants drove around the circuit under five light conditions (daytime and four at night) and were asked to report relevant targets including road signs, large low contrast road obstacles, and pedestrians who wore retroreflective markings on either the torso or the limb-joints (creating "biological motion"). Real world recognition performance was measured as percent correct recognition and, in the case of low-contrast road obstacles, avoided. Clinical vision tests included high-contrast visual acuity and Pelli-Robson letter contrast sensitivity measured at four luminance levels.

Results: Real-world recognition performance of all age groups was significantly degraded under low light conditions, and this impairment was greater for the older participants. These changes in drivers' recognition performance were more strongly predicted by contrast sensitivity than visual acuity measured under standard photopic conditions. Interestingly, contrast sensitivity was highly correlated with visual acuity measured under low luminance conditions. Further analyses showed that recognition performance while driving is better predicted by combinations of two tests: either (1) photopic visual acuity and photopic contrast sensitivity, or (2) photopic and mesopic visual acuity.

Conclusions: These findings confirm that visibility is seriously degraded during night driving and that the problem is greater for older drivers. These changes in real-world recognition performance were better predicted by a standard test of contrast sensitivity than by visual acuity. Still better predictions can be obtained by the use of two vision tests. The implications of these findings for driver licensing standards are discussed.

Key words: night driving, recognition, visual acuity, contrast sensitivity, aging

Crash data from the US indicate that night-time fatality rates, adjusted for mileage, are 3-4 times higher than daytime rates.[1] A number of factors probably contribute to the higher death toll at night, including increased alcohol use and driver fatigue. Less obvious and potentially more pervasive are the vision changes experienced, but not necessarily appreciated, by drivers under reduced illumination. Leibowitz and colleagues have suggested that drivers are unaware of their visual limitations at night because their visual guidance abilities are relatively unimpaired, while their visual recognition abilities are selectively degraded.[2-5] According to the selective degradation hypothesis, drivers' sustained ability to steer their vehicle easily at night and to see well-illuminated signs and instruments masks their diminished ability to see low-contrast objects, resulting in unjustified confidence when driving at night. This theory draws some support from traffic studies, which report that traffic speeds are as high at night as under daytime conditions.[6]

The changes in visual function that occur under reduced illumination are well recognised and include reductions in visual acuity in central[7,8] and peripheral locations,[9] as well as reduced contrast sensitivity for all spatial frequencies.[10,11] The magnitude of these changes under night-time driving is moderated to some extent by headlighting, street lighting, dashboard instruments and a wide variety of retroreflective signs and markings. Recent evidence from a night driving simulator indicates, however, that vehicle guidance (steering) is unperturbed in low light, particularly for younger adults.[12] Moreover, these changes in night vision are more severe in older individuals,[8,12] due to age-related changes in both optical and neural processes.[13,14] Interestingly, while it is well documented that many older drivers minimize or avoid driving at night,[15,16] crash data show that drivers aged 65 and older have a greater rate of involvement in fatal crashes at night than other drivers, except those younger than 25 yrs.[17] Crash data also indicate that, although a small proportion of all night-time collisions involve older drivers, the proportion of drivers involved in pedestrian collisions at night increases with age.[18]

From the standpoint of road safety, this evidence raises the question of whether visual assessment for drivers' licensing can predict visual recognition abilities under real-world conditions, including night driving. Although most people drive under both day and night-conditions, vision standards for licensing are based upon photopic visual acuity in most countries. The only exception to this is Germany, which uses the Mesoptometer II test to assess low contrast acuity (using a Landolt C) under low mesopic luminance conditions (0.032 cdm^{-2}), in the presence and absence of glare (simulating low beam headlights). The legal standards for driving at night, set by the German Ophthalmological Society, require that a driver must be able to recognise a Landolt C (6/60) at a contrast level of 1:5 to be eligible to drive a private vehicle and a contrast level of 1:2.7 to drive a commercial vehicle.[19] The introduction of this standard was based upon the finding that visual acuity, measured under conditions similar to those encountered at twilight, was significantly reduced in older drivers, even though visual acuity measured under standard conditions was normal.[20] We are not aware, however, of any on-road studies which have provided external validation for this standard.

The present investigation was designed to determine whether visual acuity or contrast sensitivity, measured under a range of luminance levels, could predict visual recognition while driving under real-world conditions. This relationship was tested for licensed drivers of three different age groups. We hypothesised that the reduction in contrast sensitivity experienced under low light conditions might be more important than the changes in resolution, hence, contrast sensitivity would be more useful for predicting recognition performance when driving at night.

EXPERIMENTAL DESIGN

Participants

There were a total of 24 participants, including eight younger drivers (mean age: 21.5 ± 2.8 yrs), eight middle-aged drivers (mean age: 46.6 ± 4.2 yrs) and eight older drivers (mean age: 71.9 ± 2.6 yrs) with equal numbers of women and men in each group. Participants were recruited from the general driving population. They were licensed drivers with at least three years of driving experience, and all reported that they drove regularly. All participants passed the minimum drivers' licensing criterion for corrected binocular visual acuity of 6/12 (20/40). Participants wore their normal optical correction while driving.

The study was conducted in accordance with the requirements of the Queensland University of Technology Human Research Ethics Committee. All participants were given a full explanation of the experimental procedures and written informed consent was obtained, with the option to withdraw from the study at any time.

Vision Assessment

Visual acuity and contrast sensitivity were measured in the laboratory under four luminance conditions. All measures were taken binocularly. The room illumination resulted in a test chart luminance of 65 cd/m^2. Participants wore the same refractive correction used habitually for driving (and worn for all of the driving assessments described here), in conjunction with the appropriate correcting lens for the working distance of each test.

Following a dark-adaptation period of 30 minutes, visual acuity and contrast sensitivity were measured while the participants wore goggles that were fitted with ND filters of decreasing density: beginning with 3.0 ND (0.065 cd/m^2), followed by 2.0 ND (0.65 cd/m^2), 1.0 ND (6.5 cd/m^2), and finally no filter (65 cd/m^2). The order of luminance levels always proceeded from the dimmest to the brightest condition to minimise both the time required for dark adaptation and the potential for learning effects in successive tests.

Static Acuity. Static high contrast visual acuity was measured using two versions of a standard logMAR chart (Australian Vision Chart No. 5) at a working distance of 3.2 m, unless visual acuity was worse than the top line of the chart, in which case shorter viewing distances were employed and the results scored accordingly. Subjects were forced to guess letters even when they were unsure, until a full line of letters was incorrectly read. Each letter seen was scored as -0.02 log units.

Pelli-Robson Letter Contrast Sensitivity. Measures of contrast sensitivity were determined using two versions of the Pelli-Robson chart at the standard working distance of 1 m. Subjects were instructed to look at a line of letters and forced to guess the letter when they were not sure until a full line of letters was incorrectly read. Each letter was scored as 0.05 log units.

Driving Assessment

Real-world visual performance was assessed while participants drove under day and night conditions on the closed road circuit at the Mount Cotton Driver Training Centre, which has been used in previous studies of driving and vision.[21] The experiment was cancelled if it was raining or the road surface was wet. The circuit, which is representative of a rural road, consists of a two to three lane bitumen (asphalt) road surface and includes hills, curves, bends and straight sections as well as standard road signs and road markings. A 1.8 km (1.1 mile) section of the circuit was used for this study. The circuit does not include any street lighting. At night, realistic glare conditions, simulating an oncoming vehicle, were created by positioning automotive headlights mounted at the correct height and separation, at two locations along the circuit. These headlights were activated when the test vehicle drove through a series of remote sensors.

The test vehicle was a 1997 Holden Commodore station wagon, equipped with automatic transmission and a digital video system to measure lane position. The driver's view of the speedometer was occluded by translucent film. High beam headlights were active during all night tests to maintain a consistent beam pattern. In addition to the normal high beam, lower headlight intensities were obtained by mounting ND filters on the headlights, thus attenuating the luminous intensity of the beam by 0.6 (-75%), 0.9 (-87.5%), and 1.5 (-97%) log units. One should note that none of these conditions duplicates the illumination of a low-beam system because low and high beams differ in both the luminous intensity and optical distribution of the light. Low-beams aim the maximum illumination downward and toward the shoulder, whereas high beams aim the maximum illumination either toward the horizon straight ahead (European designs) or toward the horizon but slightly (1°) toward the shoulder (US designs).[22,23] We avoided confounding variations of intensity with those of beam pattern by using only the high beam setting. If one compares the luminous intensity of the road and shoulder at long distances (i.e., 0° elevation, and 0° to 0.5° toward the shoulder), US low-beams are most closely approximated by the ND 0.9 condition, and European low-beams are comparable to the ND 1.5 condition.

Participants drove around the circuit five times, once in daylight and four times at night with the headlight beams set at each of the four intensity levels. Participants were instructed to drive at a comfortable speed, to be alert for unpredictable hazards (like wild animals) as they ordinarily would on rural roads, and to report relevant targets including: road signs, low contrast road hazards and pedestrians. Between laps the headlight filters were changed surreptitiously in preparation for the next test-run, while the driver was distracted by the administration of a questionnaire. Participants also drove around the same test circuit under daytime conditions and were required to complete the same driving tasks. The order of day and night test conditions and the order of headlight intensities at night were counterbalanced across participants within all age groups.

There were 21 standard road signs located around the circuit, and participants were instructed to report all road signs and other important targets (e.g., animals or pedestrians) as they drove around the circuit. Large, low contrast road hazards were placed at four locations along the circuit. These road hazards consisted of ~15 cm x 80 cm x 220 cm (reflectance of ~10%) thick gray foam rubber, so that although participants could feel the hazards when hit, they had a minimal effect on vehicle control. Participants were asked to report when they saw a road hazard and to avoid it by steering around it. Performance was measured as the number of road hazards reported as seen and the number hit. Two pedestrians, who were wearing retroreflective markings of *equal area* but in different spatial configurations, walked along the shoulder of the opposite lane in a direction facing the oncoming test vehicle. To minimize learning effects, the pedestrians were positioned at variable locations, including both straight and curved segments of the circuit. Both pedestrians wore a black tracksuit and either a sash consisting of a single retroreflective stripe (2.5 cm wide) that extended diagonally from the right shoulder to the left hip; or the same quantity of retroreflective material in narrower (0.75 cm) stripes attached to the sweatsuit at the waist, shoulders, elbows, wrists, knees, and ankles known as “biomotion”. The biomotion condition was based upon research by Johansson[24] which established that luminous markings on the limb joints create a unique perceptual phenomenon called “biological motion”. Later work using video projections of the night road environment indicated that “biomotion markings” may be superior to other marking configurations,[25] and this finding has been replicated in the US[26] and Finnish[27] road environments using passengers as subjects. But to our knowledge, it had not yet been investigated for drivers of different ages under real world conditions. Hence, the biomotion condition was included to determine the extent to which biomotion markings could improve pedestrian visibility, relative to more conventional markings of the torso, for drivers of various ages.

Several additional dependent measures were collected, including measures of driving behaviour and responses to an extensive questionnaire. The present report will focus on the clinical vision tests and their relationship to the drivers’ ability to recognise relevant road objects (road signs, road hazards and pedestrians) while driving. This latter measure was calculated as the percentage recognition of signs, road hazards and pedestrians correctly recognised.

RESULTS

Vision Tests

The group mean data for visual acuity and contrast sensitivity are plotted as a function of luminance and age in Figure 1. This shows similar performance levels for the young and middle-aged participants, while the older participants had lower performance levels across all of the luminance conditions. A repeated measures ANOVA of the visual acuity data with one within subject factor (chart luminance) and one between subjects factor (driver age) showed significant main effects of luminance, [$F(3, 63) = 598.9$; $p<0.001$] and age [$F(2,21) = 11.2$; $p<0.001$], and a significant interaction between luminance and age [$F(6, 63) = 4.6$; $p=0.008$]. Because the data did not meet assumptions of sphericity, the Greenhouse-Geisser correction was used in computing alpha levels.

The contrast sensitivity data showed similar trends to those for visual acuity, with an ANOVA showing significant main effects for luminance, [$F(3,63) = 540.6$; $p<0.001$] and age [$F(2,21) = 12.03$; $p<0.001$)], but no significant interaction between luminance and age [$F(6, 63) = 0.64$; NS].

Intercorrelations between vision tests

The relationship between visual acuity and contrast sensitivity was also examined under the four different luminance levels; Table 1 gives the Pearson r values for the full correlation matrix. When a Bonferroni correction factor was applied, all but one of the correlations were significant at the $p<0.05$ level, with the exception being the correlation between visual acuity measured under the brightest condition and contrast sensitivity measured under the lowest luminance condition.

Under standard photopic test conditions, contrast sensitivity and visual acuity were modestly correlated ($r=-0.61$, $p<0.05$). The correlation between contrast sensitivity and visual acuity was much higher for visual acuity measured under lower luminance levels, as indicated by higher correlations ($r=-0.84$, $p<0.01$).

Effect of luminance and age on recognition while driving

Figure 2 illustrates the change in recognition performance on the road, defined as the mean percentage recognition of all targets, as a function of luminance and the age of the driver. A repeated measures ANOVA with one within subject factor (light condition) and one between subjects factor (driver age) showed significant main effects for light condition [$F(4,84) = 23.1$, $p < 0.001$] and driver age [$F(2,21) = 3.48$, $p = .05$], with older drivers performing worse than either middle-aged or younger subjects. The interaction between age and light condition was not significant [$F(8,84) = 1.31$, $p = .25$].

Relationship between vision tests and recognition while driving

The relationship between the vision tests and drivers' ability to recognise road objects, including signs, pedestrians and road hazards, was examined through a series of correlational and multiple regression analyses. As contrast sensitivity under standard photopic conditions was highly correlated with visual acuity measured under low luminance conditions (r=0.77-0.89) (Table 1), we first examined the correlations between standard (photopic) measures of visual acuity and contrast sensitivity and real-world recognition ability under the five different illumination conditions. Table 2 represents the portion of variance in real-world recognition that could be explained by either photopic visual acuity or contrast sensitivity (r^2 values).

Table 2 clearly shows that photopic visual acuity measures did not predict variations of recognition while driving, for either day or night-time conditions. A stronger relationship was found for photopic contrast sensitivity, which showed increasing predictive power as the lighting condition was reduced, ranging from a non-significant 14% of the variance in daylight to 40% in the darkest condition (Figure 3). The same pattern of correlations was obtained when analyses were restricted to data for sign recognition, excluding pedestrians and low contrast hazards.

Multiple regression analyses were used to determine whether prediction of real-world performance could be improved through the use of multiple vision tests. The first analysis used a stepwise regression model to determine an optimal combination of tests by entering all measures of acuity and contrast sensitivity (for all four luminance levels) as possible predictors of driving recognition for each of the five light conditions. As shown in Table 3, there was no consistent pattern of 'optimal' predictor variables for all five driving conditions. The addition of age as a predictor produced a small improvement in only one of the five road conditions. Two practical test combinations were suggested, however, by the fact that three vision tests appeared among the 'optimal' predictors for multiple conditions: namely, photopic contrast sensitivity (PR65), mesopic visual acuity (VA6.5), and photopic visual acuity (VA65). In view of the fact that photopic visual acuity is already established as the standard test, two additional "practical models" were examined to determine if adding one more test to the existing standard would offer a substantial improvement. The practical models were:

1. Practical Model #1: Photopic Visual Acuity and Photopic Contrast Sensitivity (i.e., VA65 and PR65)
2. Practical Model #2: Photopic Visual Acuity and Mesopic Visual Acuity (i.e., VA65 and VA6.5)

Table 3 presents the resulting r^2 values for both of the Practical Models in comparison with the predictive power of the stepwise regression for all vision tests combined. These analyses showed that both "practical models" have greater merit than any single test, and both are only marginally inferior to the more complex (and impractical) combinations of all possible tests. A similar pattern of results was also found when the predictive power of photopic visual acuity and contrast sensitivity were compared with that of the two "practical models" for predicting driving recognition when all of the conditions were combined (average performance for day and the four night conditions) and that of the difference in performance between day and the darkest night condition (Table 4); although Practical Model #2 did offer improved predictive power when considering all conditions combined.

DISCUSSION

Our findings confirm that reduced luminance and increasing age have a detrimental affect on drivers' recognition ability measured while travelling on a closed road circuit, as well as on clinical measures of visual acuity and contrast sensitivity. Importantly, our results demonstrate that, contrary to commonly accepted licensing standards, visual acuity measured under standard photopic testing conditions did not predict drivers' recognition ability under either day or night-time road conditions. Rather, photopic contrast sensitivity provided better predictions of recognition while driving, especially under the dimmest night-time condition. Multiple regression analyses, which evaluated the combined predictive power of both visual acuity and contrast sensitivity measured under a wide range of luminance levels, did not reveal a consistent optimal combination. Further evaluation of two practical models indicated, however, that adding either photopic contrast sensitivity or mesopic visual acuity to the standard acuity test can provide a much more useful alternative to current drivers' licensing vision standards.

The results for the clinical tests of visual function are in accord with previous studies which have also demonstrated that under reduced luminance levels both visual acuity[7] and contrast sensitivity measured with the Pelli-Robson chart[28,29] are decreased, and these effects are exacerbated for older participants. The present study extends these findings in a potentially useful way to the prediction of performance in real-world conditions. The correlation between visual acuity and contrast sensitivity measured under standard luminance conditions was relatively modest, which is in accord with previous findings.[30] Contrast sensitivity measured under standard photopic test conditions was significantly correlated with visual acuity measured at lower luminance levels, however, and appears to tap into similar mechanisms, assessing sensitivity at intermediate spatial frequencies.

The finding that the visual function of older participants is degraded to a greater extent under low luminance compared to standard photopic conditions has prompted many to suggest that older drivers should pass a low luminance visual acuity examination to be eligible to drive at night.[8,20,31] Similar conclusions were drawn by Anderson and Holliday,[32] who showed that photopic measures of visual acuity did not predict visual acuity measured under night-time driving conditions in a roadside vehicle, which is consistent with the results of the study reported here. The present findings provide new evidence based on target recognition in the road environment that (a) photopic visual acuity is of limited value in predicting performance of the current population of drivers and (b) prediction of real-world performance can be enhanced by use of a photopic test of contrast sensitivity. Still better predictions of drivers' performance were obtained by the use of two vision tests, which supplement the current standard with either photopic contrast sensitivity or mesopic visual acuity. Selection of the best practical combination will require further research to establish appropriate criteria for combining the two scores and to examine logistical aspects of the second test. Photopic contrast sensitivity has the advantage of a standardized procedure under normal lighting conditions, whereas mesopic visual acuity has the advantage of seeming familiar to non-professional examiners and those to be tested. On the other hand, measurements of acuity under mesopic conditions can vary widely as a result of small uncontrolled variations in luminance,[31,33] which may be problematic in light of the fact that (a) it may be impractical to control luminance precisely, and (b) there are no standardized procedures for assessing mesopic acuity.

Our data collected while participants were driving under real world conditions, demonstrate that recognition ability under night-time conditions is reduced compared to daytime ability and that these effects are more severe for older drivers. These data are in accord with previous studies, which have shown that older drivers have poorer sign recognition at night-time compared to younger drivers,[34] and have greater difficulty in recognising roadside pedestrians.[35-37]

We should note that the correlations between contrast sensitivity and real-world recognition performance reported here may be an under-estimate of the strength of the relationship because of individual differences in the speed travelled on the closed road circuit. Our results, reported elsewhere, showed that the older participants drove more slowly than the younger participants.[38] It is likely that these differences in speed tended to reduce the recognition scores of the younger drivers and to enhance those of older drivers. If so, the correlations reported in Tables 2-4 would have been higher if all participants had travelled at the same speed. As it is, however, the present data provide a more valid estimate of the predictive strength of clinical vision tests for ‘normal’ (unconstrained) driving behaviour.

The potential use of the Pelli-Robson chart in driver licensing is also supported by other researchers who have found that contrast sensitivity is a significant factor contributing to the prediction of crash rates in older drivers,[39] and closed road driving performance under daytime conditions.[40] Interestingly, the Pelli-Robson chart has also been cited in the debate in the medical literature regarding the use of night vision testing for licensing. Jory[41] in a letter to the editor proposed the Pelli-Robson chart for night vision testing, while Leung[42] argued that there are a number of other equally important factors contributing to night driving ability including dark adaptation rate, glare sensitivity and scotopic retinal sensitivity. These letters typify much of the debate on vision and driving, in being opinion-based, rather than evidence-based. The study reported here is the first to provide evidence-based data to support the proposal that specific combinations of two tests of visual function can predict visibility during night-time driving.

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FIGURE LEGENDS

FIGURE 1.

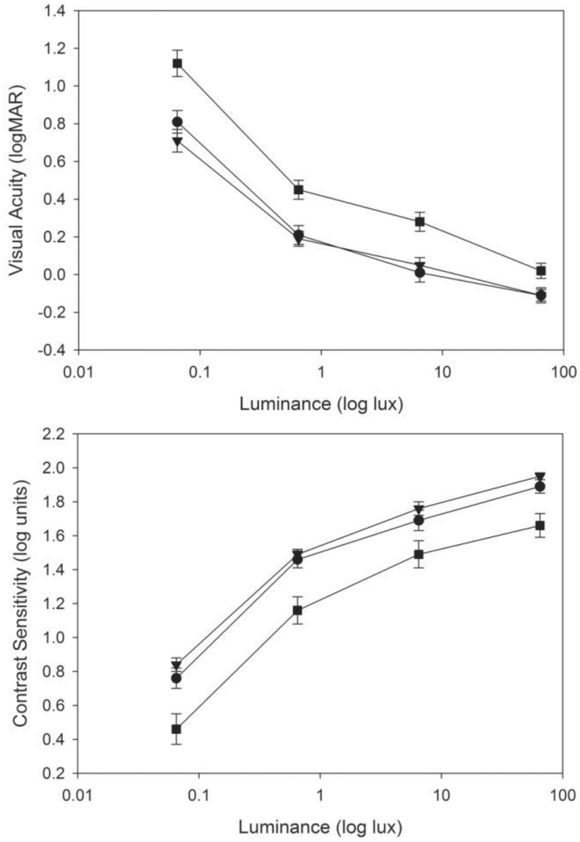
Group mean) visual acuity (top) and contrast sensitivity (bottom) as a function of chart luminance and driver age (young participants (circles), middle-aged participants (inverted triangles), older participants (squares)). Error bars indicate two standard errors of the mean.

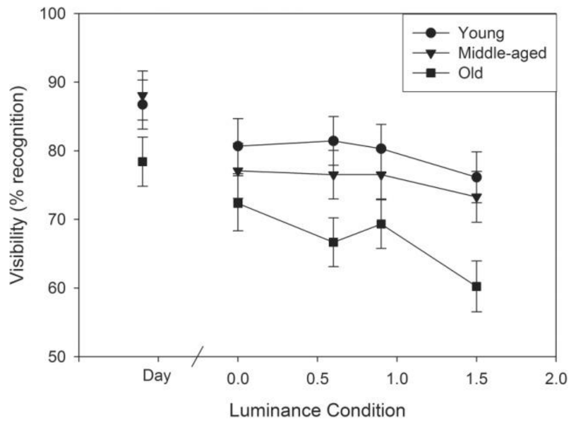
FIGURE 2.

Group mean driver recognition ability (%) (as a function of headlamp lighting and driver age (young participants (circles), middle-aged participants (inverted triangles), older participants (squares)). Error bars indicate two standard errors of the mean.

FIGURE 3.

Relationship between contrast sensitivity and night-time driver recognition ability for the 1.5 ND filter condition.


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
Visual Acuity (logMAR)
0.01
0.1
1
10
100
Luminance (log lux)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
Contrast Sensitivity (log units)
0.01
0.1
1
10
100
Luminance (log lux)


Young
Middle-aged
Old
Visibility (% recognition)
100
90
80
70
60
50
Day
0.0
0.5
1.0
1.5
2.0
Luminance Condition