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FEATURE ARTICLE ON LINE

Effect of Simulated Visual Impairment on Nighttime Driving Performance

Joanne Wood*, Alex Chaparro†, Trent Carberry‡, and Byoung Sun Chu§

ABSTRACT

Purpose. This study investigated the effects of simulated visual impairment on nighttime driving performance and pedestrian recognition under real-road conditions.
Methods. Closed road nighttime driving performance was measured for 20 young visually normal participants (M = 27.5 ± 6.1 years) under three visual conditions: normal vision, simulated cataracts, and refractive blur that were incorporated in modified goggles. The visual acuity levels for the cataract and blur conditions were matched for each participant. Driving measures included sign recognition, avoidance of low contrast road hazards, time to complete the course, and lane keeping. Pedestrian recognition was measured for pedestrians wearing either black clothing or black clothing with retroreflective markings on the moveable joints to create the perception of biological motion ("biomotion").
Results. Simulated visual impairment significantly reduced participants' ability to recognize road signs, avoid road hazards, and increased the time taken to complete the driving course (p < 0.05); the effect was greatest for the cataract condition, even though the cataract and blur conditions were matched for visual acuity. Although visual impairment also significantly reduced the ability to recognize the pedestrian wearing black clothing, the pedestrian wearing "biomotion" was seen 80% of the time.
Conclusions. Driving performance under nighttime conditions was significantly degraded by modest visual impairment; these effects were greatest for the cataract condition. Pedestrian recognition was greatly enhanced by marking limb joints in the pattern of "biomotion," which was relatively robust to the effects of visual impairment.
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Key Words: night driving, driving performance, simulated visual impairment, pedestrian recognition

Crash data provide evidence that driving at night can be more dangerous than driving during daytime hours. When adjusted for distance driven, the fatality rate at night is two to four times higher than that for daytime,[1] and the effects are even more pronounced for fatal crashes involving pedestrians, where the nighttime pedestrian fatality rates are up to seven times higher than those in the daytime.[2] Analyses of crash databases indicate that reduced lighting and poor visibility are associated with these relatively high fatal crash rates, rather than other factors that vary between day and nighttime, such as driver fatigue and alcohol consumption.[3,4]

The potential contribution of vision to the higher nighttime crash risk is supported by studies of self-reported nighttime driving difficulty and driving cessation. Older drivers commonly report difficulties with visibility at nighttime, and some report that they are reluctant to drive at night.[5–8] In large cohort studies of older adults, self-restriction of nighttime driving was significantly associated with reductions in contrast sensitivity (CS) in men and low contrast visual acuity (VA) in glare in women.[9] Similarly, those with a reduction in CS and visual fields were shown to have a higher likelihood of nighttime driving cessation.[10] Older adults with age-related maculopathy, glaucoma, or cataracts have also reported difficulties with night driving.[11–14] In age-related maculopathy, these difficulties were associated with measures of scotopic sensitivity,[11] whereas in glaucoma, those with greater visual field loss reported greater difficulty with nighttime driving.[14]

However, there have been few objective assessments of the impact of visual impairment or age on nighttime driving performance. Low-fidelity simulator studies have indicated that steering ability was disrupted by severe and sudden reductions in visual field extent but not by reductions in luminance and increased optical blur.[15,16] However, the older participants in one of these

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studies did show a decline in steering accuracy under low luminance conditions relative to the younger participants.[15] In a more recent study, wavefront-guided laser-assisted in situ keratomileusis (LASIK) was purported to improve nighttime driving performance assessed on a driving simulator compared with conventional LASIK.[17] However, the nighttime driving simulator task only required participants to detect and identify projected nighttime driving scenes, which even with the addition of a glare source does not replicate the environmental lighting conditions or the complexity of nighttime driving.

A recent study conducted under real-world driving conditions indicated that reduced luminance impaired the driving recognition ability of both young and older participants, and these impairments in performance were better predicted by CS and low luminance VA than high contrast VA.[18] This study also provided real-world evidence that nighttime pedestrian recognition could be increased by the use of retroreflective materials placed on the moveable joints to create the perception of biological motion[19] ("biomotion") even for older drivers, and this is in accord with other studies of nighttime pedestrian visibility.[20–24] Importantly, the participants in all these studies had normal vision, so it is unclear whether clothing incorporating "biomotion" is effective in the presence of commonly occurring visual impairments, including optical blur and cataracts.

This study investigated how simulated cataracts and optical blur affect driving performance under real-world nighttime driving conditions. A secondary aim was to determine whether "biomotion" clothing is beneficial in enhancing pedestrian visibility even in the presence of modest amounts of visual impairment.

METHODS

Participants

Twenty young participants (mean age 27.5 ± 6.1 years; range 18–36 years; 7 women and 13 men) were recruited through graduate students, research personnel, and their friends in the School of Optometry. None of the participants were familiar with the hypotheses under investigation. All participants were licensed drivers, reported that they drove regularly, passed the minimum drivers' licensing criteria for binocular VA of 6/12 (20/40), were free of ocular pathology, and in good general health.

A short confidential questionnaire was administered to obtain a general sense of the participants' driving experiences and habits. Only findings relevant to describing the general driving characteristics of the participants are reported here.

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.

Visual Conditions

Driving performance was assessed under three visual conditions: normal best corrected VA and two visual impairment conditions, one replicating the effects of modest cataracts and the other using spherical plus lenses to create blurred vision. For all conditions,

participants drove while wearing the goggles incorporating their normal distance correction using standard wide aperture trial lenses, which provided a field of view equivalent to that of standard 38-mm trial lenses, which did not restrict the binocular field of view below that of driver licensing standards in Australia of a horizontal extent of 120°. The group mean normal corrected VA was −0.14 ± 0.11 logMAR. The cataract goggles have been described previously[25,26] and were used to simulate the increased glare and reduction in CS of cataracts and reduced distance VA to a mean level of 0.22 ± 0.08 logMAR (~20/32). Binocular plus lenses were used to reduce the distance VA of each participant individually to that of the cataract goggles. The mean blurring lens required to reduce VA to that of the simulated cataract was +1.33 D ± 0.29 D.

VA and CS were measured binocularly for each visual condition. Distance high contrast VA was assessed using a logMAR Bailey Lovie Chart, at a viewing distance of 3.0 m, with a chart luminance of 160 cd/m², and scored on a letter by letter basis. Pelli-Robson Letter CS (Letter CS) was measured at a working distance of 1.0 m, with a chart luminance of 170 cd/m², using a working distance lens of +0.75 DS. Participants were instructed to look at a line of letters and guess the letter when they were not sure; each letter reported correctly was scored as 0.05 log units.

Driving Assessment

The experiment was conducted under nighttime conditions on the closed road circuit at the Mount Cotton Driver Training Centre, which has been used in previous studies of driving and vision[18,25–28] and is represented schematically in Fig. 1. The experiment was only undertaken on nights when it was not raining, and the road surface was dry. The circuit, which is representative of a rural road, consists of a two- to three-lane bitumen road surface and includes hills, curves, intersections and straight sections, and standard road signs and markings; a 4-km section of the circuit was used. The circuit does not include any street lighting. Two sets of headlamps, consisting of pairs of stationary battery-powered car headlamps mounted at a height and width that duplicated a real car, were positioned at two locations along the road circuit to simulate the glare effects of an oncoming vehicle. The headlamps were triggered when the test vehicle drove through a pair of remote sensors.

The experimental vehicle was an instrumented 1997 Nissan Maxima with automatic transmission, which had been serviced (including headlamp alignment) immediately before the experiment; low-beam headlamps were used for all testing conditions. Lane keeping was assessed using two video cameras, mounted at a fixed position on the vehicle roof and aimed to record the position of the front corners of the vehicle relative to the edge and center lines of the road.

Each participant drove around the driving circuit four times (one practice lap and once for each of the three visual conditions), in both a clockwise and anticlockwise direction as indicated by the arrows in Fig. 1, with the order of the vision conditions randomized. The purpose of the practice run was to familiarize participants with the vehicle, the circuit, and the driving tasks, which were conducted under normal vision conditions in the opposite direction to the recorded run, to minimize any familiarity effects. For all laps, participants were instructed that they would be required to
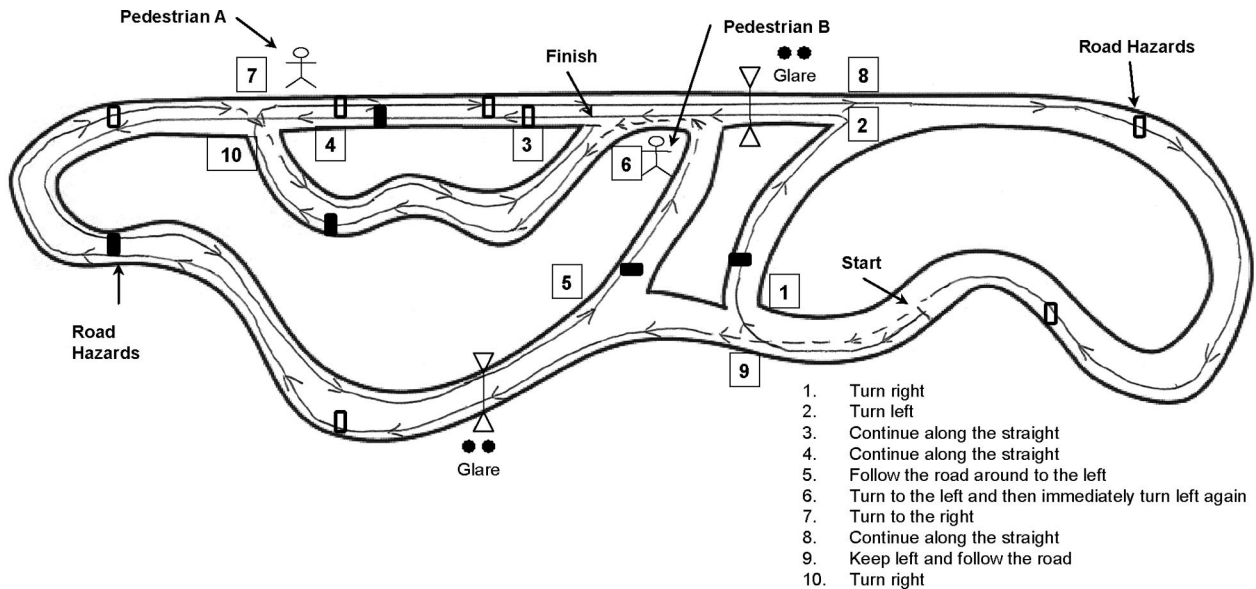
FIGURE 1.
Schematic map of the driving track for the assessment of nighttime driving.

perform a series of tasks while driving at what they felt was a safe speed for the conditions, to drive in their own lane except when avoiding road hazards, and to obey all regulatory signs. Performance measures consisted of the following.

Road Sign Recognition

A total of 40 road signs were located along the route and contained a total of 65 pieces of information. These signs included warning signs, regulatory signs, and street signs.

Road Hazard Recognition

Nine, large low contrast foam road hazards ($\sim$50 cm $\times$ 250 cm and 15 cm thickness; reflectance, $\sim$10%) were positioned on the circuit at different positions for any given run. An experimenter changed the position of the road hazards between runs in a predetermined order to minimize familiarity effects (there were a total of 12 potential positions (Fig. 1)—those represented in solid black remained the same between laps, whereas those represented as black outlines were varied in position between laps). Participants were asked to report whenever they saw a road hazard and avoid it if it was safe to do so.

Time to Complete the Circuit

The time to complete the circuit was recorded.

Lane Keeping

Lane keeping was recorded by the two roof-mounted video cameras. The videotapes were analyzed by recording the time spent out of the lane for the left and right line markings calculated separately; lane crossings made when participants were avoiding a hazard were excluded from the lane-keeping score.

Pedestrian Recognition

Two pedestrians were positioned at two different locations along the circuit. Both pedestrians walked in place facing the driver; the test vehicle was driven in the left-hand lane toward the pedestrians who were positioned in the far right-hand lane (Fig. 1). One pedestrian was positioned at the end of a straight section of three-lane roadway (A: Fig. 1), which the drivers encountered first; the pedestrian moved away from view after the vehicle had passed. The second pedestrian was positioned at the other end of the straight section of the circuit and on the opposite side of the three-lane roadway (B: Fig. 1). This pedestrian did not take their place on the roadway until the vehicle had passed them going in the opposite direction. Each pedestrian had a two-way radio, as did the experimenter who was seated in the vehicle. All communication was conducted between laps with the experimenter outside of the vehicle, so the participant could not hear the conversation.

For each lap, the pedestrians wore one of two clothing conditions, black or biomotion:

- Black: A black cotton sweatshirt (2% reflectance), a pair of black cotton sweatpants, black gloves, and black shoe covers.
- Biomotion: The clothing from the black condition with the addition of white retroreflective (diamond grade) straps (2.5 cm; 1 inch) around the wrists, elbows, shoulders, waist, knees, and ankles (total area = 525 cm^2).

The pedestrian clothing was randomized between laps, with the driver encountering one pedestrian wearing black and one wearing biomotion on each lap.

Dependent Measures

The outcome measures included road signs recognized, hazards hit, time to complete the course, number of pedestrians recognized, and lane keeping. A composite Driving Recognition and
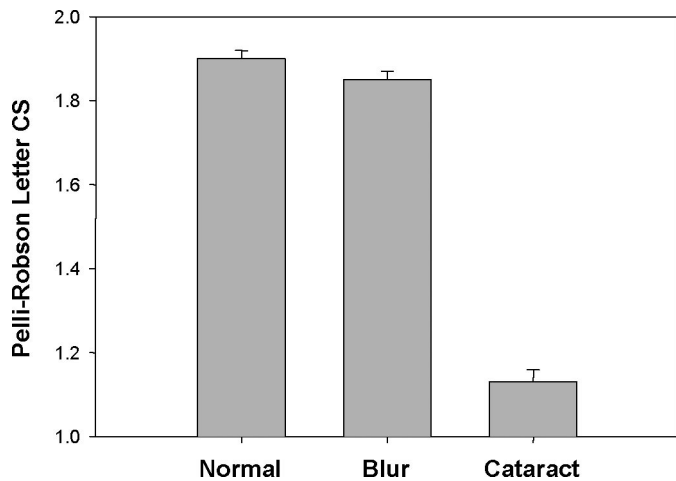
FIGURE 2.

Group mean and standard error (SE). Pelli-Robson Letter CS scores as a function of visual condition.

FIGURE 3.

Group mean and SE for the overall Driving Recognition and Speed score as a function of visual condition.

Speed score was derived to capture the driving performance of the individual participants compared with the whole group as has been used in previous studies[26–28] and included sign recognition, course time, and the number of hazards hit. Z scores for each of these three driving measures were determined and the mean Z score for each participant calculated to provide the composite Driving Recognition and Speed score (data were transformed where necessary to ensure that better performance was always represented by a more positive Z score).

RESULTS

The questionnaire data demonstrated that participants had a mean of 8.7 ± 4.3 years driving experience and reported that $28.2\% \pm 10.7$ of their driving was at night. All participants reported that they felt either "comfortable" or "very comfortable" driving at night in good weather, and all participants reported that the headlamps of oncoming traffic were only "rarely" or "occasionally" troublesome.

Vision Measures

The effect of simulated visual impairment on Letter CS is shown in Fig. 2 and demonstrates that blur had a relatively small impact on Letter CS compared with that of cataracts. A one-way repeated measures analysis of variance with visual condition as the within subjects variable indicated that Letter CS was significantly affected by visual condition ($F_{2,38} = 592.8$, $p < 0.001$, partial $\eta^2 = 0.98$); post hoc testing indicated that there were significant differences between the cataract condition and both the normal ($F_{1,19} = 912.2$, $p < 0.001$, partial $\eta^2 = 0.98$) and blur ($F_{1,19} = 529.6$, $p < 0.001$, partial $\eta^2 = 0.965$) conditions, and between the normal and blur conditions ($F_{1,19} = 10.0$, $p = 0.005$, partial $\eta^2 = 0.345$).

Driving Measures

The group mean data for the overall Driving Recognition and Speed score and component driving measures were analyzed using a series of one-way repeated meas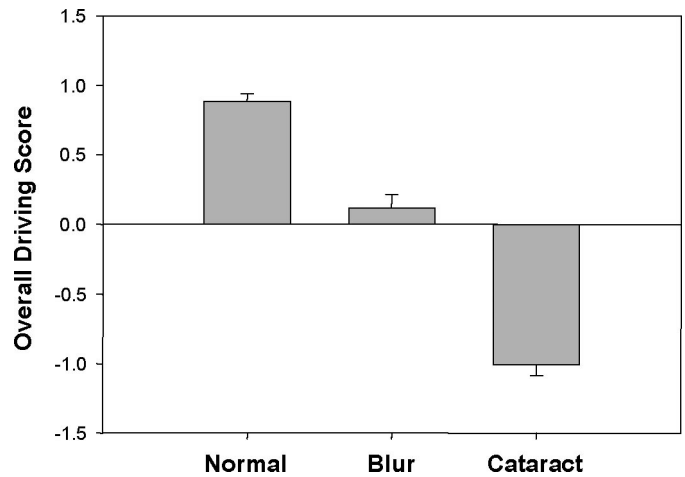ures analysis of variances with visual condition as the within subjects variable. There was a significant main effect of visual condition for the overall Driving Recognition and Speed score ($F_{2,38} = 221.7$, $p < 0.001$, partial $\eta^2 = 0.92$), which was significantly better when driving under normal vision conditions compared with either the blur ($F_{1,19} = 58.9$, $p < 0.001$, partial $\eta^2 = 0.756$) or cataract ($F_{1,19} = 661.6$, $p < 0.001$, partial $\eta^2 = 0.972$) conditions; driving with blurred vision was significantly better than driving with simulated cataracts ($F_{1,19} = 138.8$, $p < 0.001$, partial $\eta^2 = 0.88$) (Fig. 3).

There was a significant main effect of visual condition for sign recognition ($F_{2,38} = 64.8$, $p < 0.001$, partial $\eta^2 = 0.773$) (Fig. 4A). Sign recognition was significantly better when driving with normal vision compared with the blur ($F_{1,19} = 46.8$, $p < 0.001$, partial $\eta^2 = 0.711$) and cataract conditions ($F_{1,19} = 181.5$, $p < 0.001$, partial $\eta^2 = 0.905$) and was also significantly better when driving with blurred vision compared with the cataract condition ($F_{1,19} = 12.5$, $p = 0.002$, partial $\eta^2 = 0.98$, partial $\eta^2 = 0.397$).

Similarly, there was a significant main effect of visual condition for hazards hit ($F_{2,38} = 99.6$, $p < 0.001$, partial $\eta^2 = 0.84$) (Fig. 4B). Participants hit significantly more hazards for the cataract condition compared with either the normal ($F_{1,19} = 184.8$, $p < 0.001$, partial $\eta^2 = 0.907$) or blur ($F_{1,19} = 58.8$, $p < 0.001$, partial $\eta^2 = 0.756$) conditions and for the blurred condition compared with normal vision ($F_{1,19} = 42.2$, $p < 0.001$, partial $\eta^2 = 0.689$).

There was a significant main effect of visual condition for time to complete the course ($F_{2,38} = 131.8$, $p < 0.001$, partial $\eta^2 = 0.874$), with participants driving more slowly under the visual impairment conditions (Fig. 4C). Participants drove more slowly for the cataract condition compared with both the normal ($F_{1,19} = 281.9$, $p < 0.001$, partial $\eta^2 = 0.937$) and blurred vision conditions ($F_{1,19} = 101.9$, $p < 0.001$, partial $\eta^2 = 0.843$) and for the blurred vision condition compared with normal ($F_{1,19} = 13.6$, $p = 0.002$, partial $\eta^2 = 0.417$).

The lane-keeping data demonstrated that there was no significant effect of visual condition for either the percentage of time driven across the center ($F_{2,38} = 1.7$, $p = 0.19$) or the edge ($F_{2,38} = 1.8$, $p = 0.18$) lane lines.

When the pedestrians were wearing black clothing they were seen 35% of the time under the normal vision condition, 5% of the
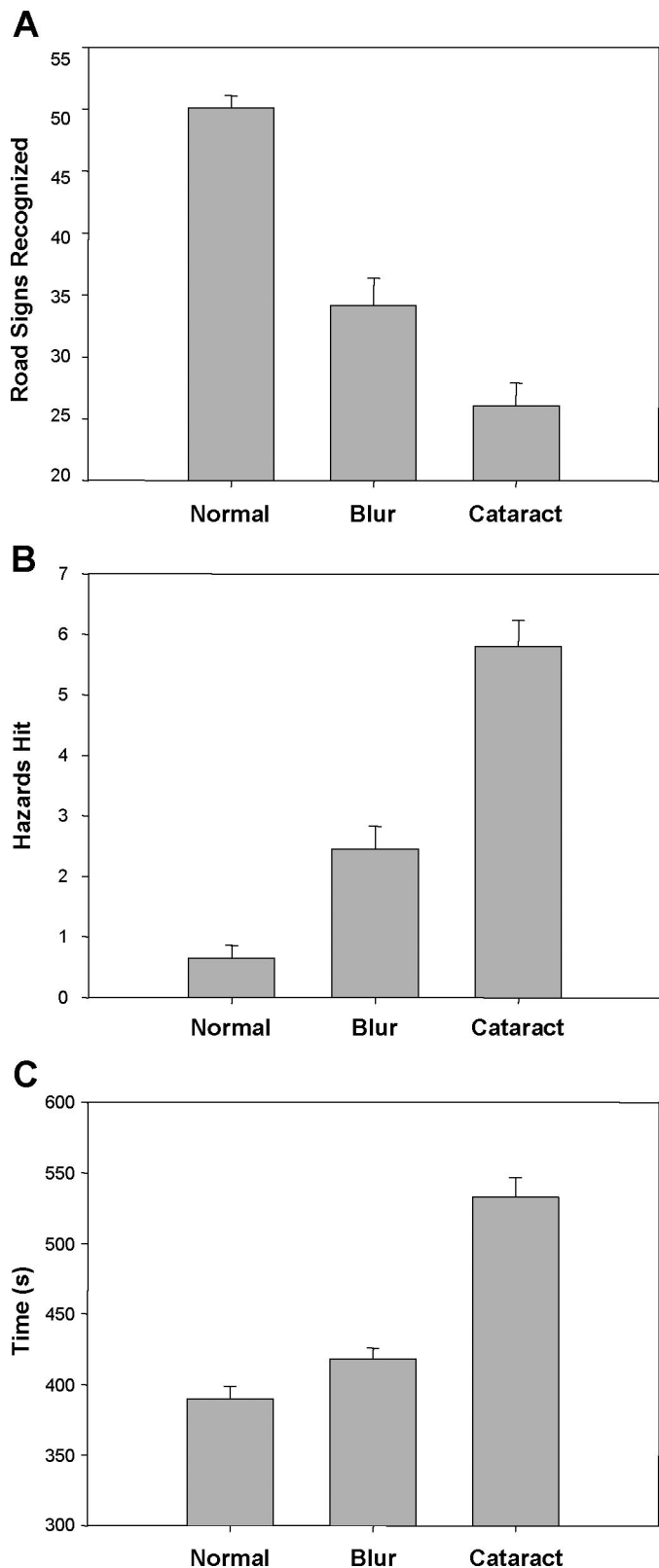
A

B

C

FIGURE 4.

Group mean and SE for the individual driving performance measures as a function of visual condition. A: road sign recognition, B: road hazard avoidance, and C: time to complete the driving circuit.
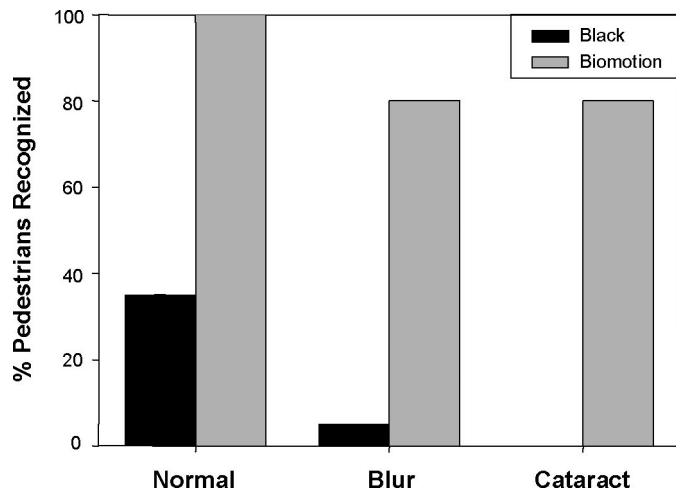

FIGURE 5.

Percentage of pedestrians recognized as a function of visual condition and pedestrian clothing.

time for the blurred vision condition, and were never seen for the simulated cataract condition (Fig. 5). Conversely, 100% of the pedestrians wearing "biomotion" clothing were seen when the participants were driving with normal vision and 80% of the time for both the blur or cataract conditions. The likelihood that a pedestrian would be recognized was modeled as a function of pedestrian clothing and driver vision condition using a generalized estimating equation model with pedestrians correctly recognized as a binomial criterion. Both pedestrian clothing [$\chi^2(1) = 362.8$] and the drivers' vision condition [$\chi^2(2) = 615.7$] significantly ($p < 0.001$) explained the ability to recognize pedestrians. The models were compared using an independent or autocorrelation error structure and were the same.

Relationship Between Vision and Driving

Because the simulating goggles affected VA and CS to differing extents, it was of interest to examine whether the changes in driving performance were primarily driven by the changes in VA, CS, or both. For this analysis, a series of linear mixed effects models were constructed with Letter CS and VA as covariates, measures of driving performance as criteria, and with a participant identifier entered as a random variate to account for repeated observations. Variables were standardized before analysis to enable comparison of the regression coefficients. Coefficients of determination for each model were calculated using the procedure recommended by Xu.[29]

The results show that the experimentally induced changes in CS and VA were strong predictors of overall Driving Recognition and Speed score ($F_{1,46.14} = 77.6$, $p < 0.001$, $\beta = 0.59$ for CS and $F_{1,43.36} = 44.7$, $p < 0.001$, $\beta = -0.43$ for VA, respectively, overall $R^2 = 0.84$), signs recognized ($F_{1,49.82} = 10.5$, $p = 0.002$, $\beta = -0.57$ for CS and $F_{1,44.7} = 37.9$, $p < 0.001$, $\beta = 0.31$ for VA, respectively, overall $R^2 = 0.65$), and road hazards hit ($F_{1,44.09} = 28.9$, $p < 0.001$, $\beta = -0.55$ for CS and $F_{1,40.04} = 19.9$, $p < 0.001$, $\beta = 0.34$ for VA, respectively, overall $R^2 = 0.66$), whereas only Letter CS was a significant predictor of time taken to complete the course ($F_{1,35.23} = 35.1$, $p < 0.001$, $\beta = 0.63$ for CS, $F_{1,37.93} = 3.73$, $p = 0.06$, $\beta = 0.16$ for VA, overall

$R^2 = 0.59$). The regression coefficients indicate that Letter CS contributed substantially more to all of the driving scores than did VA.

DISCUSSION

The results of this study demonstrate that when driving at night under real-world driving conditions, simulated cataracts, which substantially reduce CS but have only a modest effect on VA, significantly degrade driving performance. Relatively small amounts of optical blur that were selected to reduce VA to the same levels as that of the cataract condition also had a detrimental effect on measures of nighttime driving performance but to a lesser extent than that of the simulated cataracts.

Both of the simulated visual impairment conditions significantly reduced the number of signs recognized, with the simulated cataract condition almost halving the mean number of signs recognized, even though the majority of the signs were retroreflective. This is consistent with previous studies that have shown that the ability to read road signs at night was the most difficult activity reported by patients with cataracts[30] and that nighttime sign recognition was significantly reduced when VA was degraded by refractive blur to levels similar to those in our study.[31]

Similarly, the ability to detect road hazards and avoid them was significantly worse when participants were driving with visual impairment, particularly for the cataract condition where the mean number of road hazards hit was six. This finding is not unexpected given that the hazards were selected to be of low contrast and further reinforces the concept that it is contrast and not size that is important for visibility under nighttime driving conditions.

All participants drove more slowly with simulated visual impairment, with participants taking 36% longer for the cataract condition but only 7% longer for the blurred vision condition relative to normal. Importantly, despite the fact that all participants drove more slowly for the visual impairment conditions, it was not sufficient to compensate for the decrease in their recognition abilities, as evidenced by the reduction in ability to detect the road signs, road hazards, and pedestrians. These results are in agreement with our previous findings for day[26,32] and nighttime driving,[33] which demonstrate that while choosing to drive more slowly is one potential compensatory action adopted by drivers with impairment (through visual problems and/or normal aging), it is rarely sufficient to offset the degradation in driving abilities.

Interestingly, lane-keeping ability was not significantly affected when driving with simulated visual impairment, which is in accord with our previous findings on a closed road circuit for daytime driving conditions.[25,26,32] Similarly, nighttime driving simulator studies have shown that lane-keeping ability is relatively unaffected by refractive blur, even when the amounts of blur were extreme (up to amounts of 8 to 10 D of blur).[15,16] Collectively, these findings are consistent with the "selective degradation" theory,[34] which suggests that "focal" visual tasks that rely on foveal vision, such as the detection and identification of hazards and signs, are degraded by optical blur and reduced illumination, whereas those that rely on "ambient" (i.e., peripheral) vision, including lane keeping, heading, and speed, are relatively immune to the effects of optical blur and reductions in illumination.

The results of this study suggest that the purported advantages of "biomotion" for enhancing nighttime pedestrian visibility reported for drivers with normal vision[18,20–22] are maintained even in the presence of visual impairment. This finding is supported by previous laboratory-based studies of biological motion that have demonstrated that the perception of biological motion is remarkably robust. Observers show no decrease in sensitivity to biological motion defined by luminance, texture or random contrast polarity,[35] or under dim lighting conditions.[36] Importantly, the conspicuity advantage conferred by the placement of reflective markers creating biological motion has been shown to be greater than that derived from wearing a reflective vest (that included an equal amount of reflective material to that of the biomotion condition) or a stripe of reflective material.[18,22,24]

In terms of determining how well-standard vision tests can predict night driving performance, our findings suggest that although both VA and CS predicted nighttime driving performance (with the exception of driving time which was only significantly associated with CS), CS contributed more substantially to the driving scores than did VA. Similar findings were reported in a related nighttime study,[18] where CS or low-luminance VA were better predictors of nighttime recognition than were standard measures of VA. In a study of daytime driving,[25,32] some, but not all, measures of driving performance were linearly related to VA degradation produced by optical blur; however, the greatest decrement in driving performance resulted when the VA degradation resulted from simulated cataracts, as was also the case in the study reported here. Collectively, these findings suggest that although VA remains the most commonly administered measure of vision for driving across the world, its ability to predict both day and nighttime driving performance is not as strong as that of measures of CS. However, it is also important to recognize that day and nighttime driving performance potentially involves other aspects of visual performance, including visual attention,[26] detection of motion,[27,37] peripheral vision[38,39] and patterns of optical flow[40]; it would be useful to incorporate these measures into future studies of vision and driving performance.

Although these and other research findings clearly highlight the important relationship between reduced contrast and driving performance, what is less well understood is which specific visual cues are degraded or lost when viewing the driving environment through cataracts. Cataracts may reduce the availability of those formal and informal driving cues that are of relatively low contrast, such as weathered lane markings and signs, changes in roadway texture, potholes, and real-world speed bumps, which are significant because they require the driver to take some kind of evasive action to avoid an incident. Alternatively, cataracts might also impede or slow the recognition and processing of important environmental cues[41,42] and have concomitant effects on higher levels of cognitive processes including the perception of risk and allocation of attentional resources.[43] Better understanding of how reduced contrast impacts on the acquisition and processing of driving-related information is essential to the development of interventions to improve the safety of older drivers.

The finding that simulated blur reduced many aspects of nighttime driving performance could be considered relevant to the issue of night myopia, a condition observed under low illumination, where normal observers become myopic (short sighted) in the ab-

sence of a strong visual stimulus to drive the accommodative response.[44] However, although there have been some reports of increased nighttime crashes for those with night myopia,[45] the evidence is limited and as highlighted by Arumi et al.,[46] night myopia only becomes significant at light levels below 0.03 cd/m^2, which is much lower than that normally encountered under nighttime driving conditions. To fully understand the potential role of night myopia in nighttime driving, it would be necessary to continuously monitor the accommodative status of participants while undertaking night driving under real-world conditions.

In summary, our results demonstrate that modest amounts of visual impairment have the ability to reduce components of nighttime driving ability, including recognition and speed and the effects are greater for simulated cataracts than refractive blur, despite the fact that the VA levels were matched between conditions. This implies that both the correction of refractive errors and extraction of cataracts have the potential to improve nighttime driving performance. Our data also support the more widespread adoption of "biomotion" clothing for pedestrians with high levels of exposure at nighttime, such as road workers and emergency service personnel, given that the positive benefits for improved visibility are robust even in the presence of visual impairments that can be reasonably expected to be encountered in the driving population (including small amounts of uncorrected refractive error and cataracts).

ACKNOWLEDGMENTS

REFERENCES

1. National Highway Traffic Safety Administration (NHTSA). 2004 Annual Assessment. Motor Vehicle Traffic Crash Fatality Counts and Injury Estimates for 2004, updated August 2005: DOT HS 809923. Available at: http://www-nrd.nhtsa.dot.gov/Pubs/809923.PDF. Accessed February 10, 2010.
2. Sullivan JM, Flannagan MJ. Determining the potential safety benefit of improved lighting in three pedestrian crash scenarios. Accid Anal Prev 2007;39:638–47.
3. Owens DA, Sivak M. Differentiation of visibility and alcohol as contributors to twilight road fatalities. Hum Factors 1996;38:680–9.
4. Sullivan JM, Flannagan MJ. The role of ambient light level in fatal crashes: inferences from daylight saving time transitions. Accid Anal Prev 2002;34:487–98.
5. Molnar LJ, Eby DW. The relationship between self-regulation and driving-related abilities in older drivers: an exploratory study. Traffic Inj Prev 2008;9:314–9.
6. Kosnik WD, Sekuler R, Kline DW. Self-reported visual problems of older drivers. Hum Factors 1990;32:597–608.
7. Shinar D, Schieber F. Visual requirements for safety and mobility of older drivers. Hum Factors 1991;33:507–19.
8. Charlton JL, Oxley J, Fildes BN, Oxley P, Newstead S, Koppel S, O'Hare M. Characteristics of older drivers who adopt self-regulatory driving behaviours. Transp Res F Traffic Psychol Behav 2006;9: 363–73.
9. Brabyn JA, Schneck ME, Lott LA, Haegerstrom-Portnoy G. Night driving self-restriction: vision function and gender differences. Optom Vis Sci 2005;82:755–64.
10. Freeman EE, Munoz B, Turano KA, West SK. Measures of visual function and their association with driving modification in older adults. Invest Ophthalmol Vis Sci 2006;47:514–20.
11. Scilley K, Jackson GR, Cideciyan AV, Maguire MG, Jacobson SG, Owsley C. Early age-related maculopathy and self-reported visual difficulty in daily life. Ophthalmology 2002;109:1235–42.
12. Owsley C, Stalvey B, Wells J, Sloane ME. Older drivers and cataract: driving habits and crash risk. J Gerontol A Biol Sci Med Sci 1999;54: M203–11.
13. McGwin G Jr, Scilley K, Brown J, Owsley C. Impact of cataract surgery on self-reported visual difficulties: comparison with a no-surgery reference group. J Cataract Refract Surg 2003;29:941–8.
14. Janz NK, Musch DC, Gillespie BW, Wren PA, Niziol LM. Evaluating clinical change and visual function concerns in drivers and non-drivers with glaucoma. Invest Ophthalmol Vis Sci 2009;50:1718–25.
15. Owens DA, Tyrrell RA. Effects of luminance, blur, and age on nighttime visual guidance: A test of the selective degradation hypothesis. J Exp Psychol Appl 1999;5:115–28.
16. Brooks JO, Tyrrell RA, Frank TA. The effects of severe visual challenges on steering performance in visually healthy young drivers. Optom Vis Sci 2005;82:689–97.
17. Schallhorn SC, Tanzer DJ, Kaupp SE, Brown M, Malady SE. Comparison of night driving performance after wavefront-guided and conventional LASIK for moderate myopia. Ophthalmology 2009; 116:702–9.
18. Wood JM, Owens DA. Standard measures of visual acuity do not predict drivers' recognition performance under day or night conditions. Optom Vis Sci 2005;82:698–705.
19. Johansson G. Visual perception of biological motion and a model for its analysis. Percept Psychophys 1973;14:201–11.
20. Blomberg RD, Hale A, Preusser DF. Experimental evaluation of alternative conspicuity-enhancement techniques for pedestrians and bicyclists. J Safety Res 1986;17:1–12.
21. Luoma J, Schumann J, Traube EC. Effects of retroreflector positioning on nighttime recognition of pedestrians. Accid Anal Prev 1996; 28:377–83.
22. Wood JM, Tyrrell RA, Carberry TP. Limitations in drivers' ability to recognize pedestrians at night. Hum Factors 2005;47:644–53.
23. Owens DA, Antonoff RJ, Francis EL. Biological motion and nighttime pedestrian conspicuity. Hum Factors 1994;36:718–32.
24. Tyrrell RA, Wood JM, Chaparro A, Carberry TP, Chu BS, Marszalek RP. Seeing pedestrians at night: visual clutter does not mask biological motion. Accid Anal Prev 2009;41:506–12.
25. Higgins KE, Wood JM. Predicting components of closed road driving performance from vision tests. Optom Vis Sci 2005;82:647–56.
26. Wood J, Chaparro A, Hickson L. Interaction between visual status, driver age and distracters on daytime driving performance. Vision Res 2009;49:2225–31.
27. Wood JM. Age and visual impairment decrease driving performance as measured on a closed-road circuit. Hum Factors 2002;44:482–94.
28. Chaparro A, Wood JM, Carberry T. Effects of age and auditory and visual dual tasks on closed-road driving performance. Optom Vis Sci 2005;82:747–54.
29. Xu R. Measuring explained variation in linear mixed effects models. Stat Med 2003;22:3527–41.
30. Pesudovs K, Garamendi E, Keeves JP, Elliott DB. The Activities of Daily Vision Scale for cataract surgery outcomes: re-evaluating validity with Rasch analysis. Invest Ophthalmol Vis Sci 2003;44:2892–9.
31. Kline DW, Buck K, Sell Y, Bolan TL, Dewar RE. Older observers'

tolerance of optical blur: age differences in the identification of defocused text signs. Hum Factors 1999;41:356–64.

32. Higgins KE, Wood J, Tait A. Vision and driving: selective effect of optical blur on different driving tasks. Hum Factors 1998;40:224–32.

33. Owens DA, Wood JM, Owens JM. Effects of age and illumination on night driving: a road test. Hum Factors 2007;49:1115–31.

34. Leibowitz HW, Rodemer CS, Dichgans J. The independence of dynamic spatial orientation from luminance and refractive error. Percept Psychophys 1979;25:75–9.

35. Ahlstrom V, Blake R, Ahlstrom U. Perception of biological motion. Perception 1997;26:1539–48.

36. Grossman ED, Blake R. Perception of coherent motion, biological motion and form-from-motion under dim-light conditions. Vision Res 1999;39:3721–7.

37. Gegenfurtner KR, Mayser H, Sharpe LT. Seeing movement in the dark. Nature 1999;398:475–6.

38. Wood JM, Troutbeck R. Effect of restriction of the binocular visual field on driving performance. Ophthal Physiol Opt 1992;12:291–8.

39. Owsley C, McGwin G Jr. Vision impairment and driving. Surv Ophthalmol 1999;43:535–50.

40. Kandil FI, Rotter A, Lappe M. Driving is smoother and more stable when using the tangent point. J Vis 2009;9:11.1–11.

41. Harley EM, Dillon AM, Loftus GR. Why is it difficult to see in the fog? How stimulus contrast affects visual perception and visual memory. Psychon Bull Rev 2004;11:197–231.

42. Pashler H. Evidence against late selection: stimulus quality effects in previewed displays. J Exp Psychol Hum Percept Perform 1984;10:429–48.

43. Wingfield A, Tun PA, McCoy SL. Hearing loss in older adulthood: what it is and how it interacts with cognitive performance. Cur Dir Psychol Sci 2005;14:144–8.

44. Leibowitz HW, Owens DA. Night myopia and the intermediate dark focus of accommodation. J Opt Soc Am 1975;65:1121–8.

45. Cohen Y, Zadok D, Barkana Y, Shochat Z, Ashkenazi I, Avni I, Morad Y. Relationship between night myopia and night-time motor vehicle accidents. Acta Ophthalmol Scand 2007;85:367–70.

46. Arumi P, Chauhan K, Charman WN. Accommodation and acuity under night-driving illumination levels. Ophthal Physiol Opt 1997;17:291–9.

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