5-2012

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Scholarly Commons Citation

Wood, J. M., Tyrell, R. A., Chaparro, A., Marszalek, R. P., Carberry, T. P., & Chu, B. S. (2012). Even Moderate Visual Impairments Degrade Drivers' Ability to See Pedestrians at Night. *Investigative Ophthalmology & Visual Science*, 53(6). https://doi.org/10.1167/iovs.11-9083

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Low Vision

Even Moderate Visual Impairments Degrade Drivers' Ability to See Pedestrians at Night

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Purpose. To determine the effect of moderate levels of refractive blur and simulated cataracts on nighttime pedestrian conspicuity in the presence and absence of headlamp glare.

Methods. The ability to recognize pedestrians at night was measured in 28 young adults (M = 27.6 years) under three visual conditions: normal vision, refractive blur, and simulated cataracts; mean acuity was 20/40 or better in all conditions. Pedestrian recognition distances were recorded while participants drove an instrumented vehicle along a closed road course at night. Pedestrians wore one of three clothing conditions and oncoming headlamps were present for 16 participants and absent for 12 participants.

Results. Simulated visual impairment and glare significantly reduced the frequency with which drivers recognized pedestrians and the distance at which the drivers first recognized them. Simulated cataracts were significantly more disruptive than blur even though photopic visual acuity levels were matched. With normal vision, drivers responded to pedestrians at 3.6- and 5.5-fold longer distances on average than for the blur or cataract conditions, respectively. Even in the presence of visual impairment and glare, pedestrians were recognized more often and at longer distances when they wore a "biological motion" reflective clothing configuration than when they wore a reflective vest or black clothing.

Conclusions. Drivers' ability to recognize pedestrians at night is degraded by common visual impairments, even when the drivers' mean visual acuity meets licensing requirements. To maximize drivers' ability to see pedestrians, drivers should wear their optimum optical correction, and cataract surgery should be performed early enough to avoid potentially dangerous reductions in visual performance. (*Invest Ophthalmol Vis Sci.* 2012;53:2586–2592) DOI:10.1167/iovs.11-9083

Uncorrected refractive error and cataracts are the leading causes of visual impairment in adults over the age of 40 years[1] and their prevalence increases significantly with age.[2] One study reported that uncorrected refractive error (that was either undiagnosed or inadequately corrected optically) was the cause of visual impairment in 62% of visually impaired adults over 49 years of age.[1]

Although large numbers of individuals with uncorrected refractive error and cataract currently drive, the functional impact of these visual impairments on driving performance and safety is poorly understood. Uncorrected refractive error was the cause of reduced visual acuity in 80% of current drivers whose acuity levels were below the widely adopted legal limit of 20/40,[3] and many people live with cataracts for extended periods of time before having them removed and may continue driving even if their vision does not meet the visual standards for driving.[4] In an Australian study, 23% of patients about to undergo cataract extraction surgery were found to be driving illegally due to poor vision.[5]

Driving at night is likely to be particularly challenging for those with visual impairment given the associated reduction in contrast sensitivity and increased problems with glare. Problems with driving at night are a common complaint in patients with visual impairments resulting from cataracts, glaucoma, and age-related macular degeneration,[4,6,7] as well as in patients following refractive surgery and those wearing presbyopic corrections.[8,9]

Few studies have used objective assessments to determine the impact of visual impairment, particularly those arising from commonly occurring conditions such as uncorrected refractive error and cataract, on driving performance at night. Low-fidelity simulator studies and closed-road driving assessments have indicated that steering accuracy and lane-keeping are robust to relatively high levels of optical blur,[10–12] whereas recognition of road signs and pedestrians has been shown to be differentially affected by refractive surgery in studies using the Night Driving Simulator (Vision Sciences Research Corp., San Ramon, CA).[13,14] However, the night driving simulator task in the latter study required participants to simply detect and identify pedestrians in projected night driving scenes, which even with the addition of a glare source does not replicate the environmental lighting conditions nor the complex visuomotor demands faced by drivers at night. Still, the finding that subtle changes in visual performance might have an impact on drivers' ability to recognize pedestrians at night is of critical importance, given that pedestrian fatalities are up to seven times more common at night than in the day.[15]

Uncorrected refractive blur may reduce a driver's ability to resolve higher spatial frequencies in the environment that might represent pedestrians or other road hazards. Cataracts could have even more debilitating effects due to the increased scatter of light, which produces a veiling luminance that reduces retinal image contrast. Simulator and on-road driving studies have also shown that glare reduces the likelihood of detecting pedestrians,[16,17] with these detrimental effects of glare being observed at relatively low glare intensities typically

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Supported in part by an Australian Research Council linkage grant.

Submitted for publication November 15, 2011; revised February 23, 2012; accepted February 28, 2012.

Disclosure: **J.M. Wood**, None; **R.A. Tyrrell**, None; **A. Chaparro**, None; **R.P. Marszalek**, None; **T.P. Carberry**, None; **B.S. Chu**, None

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associated with visual discomfort, with older adults being disproportionally affected.[17]

It is common for licensing agencies to allow unlimited access to driving for those with a corrected acuity of 6/12 (20/40). Yet the extent to which drivers with this suboptimal acuity level can be expected to respond in visually challenging conditions (e.g., encountering an unexpected pedestrian at night) is unclear. The aims of this research were to better understand how drivers' ability to recognize pedestrians at night is affected by moderate visual impairments (refractive blur and simulated cataracts) that maintain mean acuity within levels that are typically permitted by licensing standards. Headlamp glare was manipulated to determine the extent to which it exacerbates the effects of these visual impairments.

Methods

Participants

Participants included 28 young adults (mean age = 27.6 ± 4.7 years, range = 20 to 36 years; 14 males and 14 females). All participants were licensed drivers and satisfied the minimum Australian drivers' licensing criteria for binocular visual acuity of 20/40 (logMAR +0.30) or better when wearing their presenting optical correction (if any).

The study followed the tenets of the Declaration of Helsinki and was approved by the Queensland University of Technology Human Research Ethics Committee. All participants were given a full explanation of the nature and possible consequences of the study, and written informed consent was obtained with the option to withdraw from the study at any time.

Visual Impairments

Pedestrian recognition at night was measured under a baseline best-corrected vision condition and two simulated visual impairment conditions. One visual impairment condition used frosted lenses that were designed to simulate the visual effects of cataracts, incorporated into full aperture lenses and mounted in modified goggles, together with each participant's distance refractive correction normally worn while driving. These cataract filters have been used in previous studies of vision and driving[12,18–20] and, like real cataracts, have a greater effect on contrast sensitivity and disability glare than on visual acuity. The filters result in moderate reductions in photopic visual acuity, to an average level of approximately 20/40 (logMAR +0.30), with associated reductions in contrast sensitivity at both high and low spatial frequencies,[20] and increased glare disability, where the glare is of a magnitude similar to that shown by commercial filters (Vistech), which have also been used previously to simulate the visual effects of cataracts.[21] The cataract goggles reduce light transmission by 75% with a negligible effect on color (<0.01 on both x and y CIE 1931 chromaticity coordinates), which again is similar to the effects of the filters (Vistech) reported previously.[22] The goggles preserve the binocular field to a horizontal extent of 120° or greater, which satisfies driver licensing standards in Australia. The second visual impairment condition was optical blur, where positive lenses induced binocular optical blur that reduced the photopic visual acuity of each participant to match as closely as possible the acuity that he or she achieved when wearing the cataract simulation goggles. For each condition, visual acuity, contrast sensitivity, and disability glare were measured binocularly. Distance high-contrast visual acuity was assessed under standard illumination conditions using a logMAR Bailey Lovie Chart at a viewing distance of 3 m and scored on a letter-by-letter basis. Letter contrast sensitivity (CS) was measured using a Pelli-Robson chart under the recommended viewing conditions. Disability glare was measured using the Berkeley Glare Test (BGT), which has been used to measure disability glare in previous studies investigating the functional effects of cataract surgery.[23] The BGT can assess glare sensitivity monocularly or binocularly, and measures the ability to recognize low-contrast letters (10% contrast) in the presence and absence of a glare source at the medium setting of 750 cd/m^2.[24] The glare score is the difference in visual acuity for glare and no-glare conditions (expressed in letters).

Procedures

All testing was conducted at night on a closed-road circuit that has been used in previous studies. The circuit is representative of a rural road, and includes hills, bends, curves, intersections, lengthy straight sections, and standard road signs and lane markings but does not include ambient lighting.[18,25–27]

The experimental vehicle was an instrumented right-hand drive vehicle (1997 Nissan Maxima) with automatic transmission and halogen headlights. Consistent with the fact that drivers have repeatedly been shown to be heavily reliant on their low beams,[28] the headlamps of the test vehicle were kept on their low-beam setting during testing. A dual-camera parallax-based video measurement system was used to determine the distance at which the participant (as a driver) first recognized the presence of a pedestrian.[27]

Three sets of headlamps (glare lights), consisting of pairs of stationary battery-powered halogen headlamps mounted at a height and width that is typical for sedans, were positioned at three locations along the road circuit to simulate stationary vehicles that faced toward the experimental vehicle. The illumination provided by these headlamps was measured at a series of distances from the pedestrian at the approximate eye height and lane position that was representative of an approaching driver. We compared these data to those of the research vehicle at the same position. The comparison revealed that the illumination at the driver's eye was not significantly different from that of the low-beam setting of the research vehicle [$t(18) = -0.47$; $P = 0.641$]. To provide a degree of visual complexity, and to act as distracters, "clutter" zones (arrays of retroreflective objects such as cones and bollards) were positioned at three locations along the circuit.

Two pedestrians walked in place on the right shoulder of the roadway. One was located at the end of a 400 m straight section of roadway. This straight section of roadway started and finished at approximately the same elevation but featured a dip halfway along its length. This pedestrian was not near a clutter zone but walked in place near headlamp glare lights for 16 of the participants. When viewed from the experimental vehicle, the glare lights were positioned directly in line with and 2.5 m to the left of the pedestrian. To reduce the drivers' expectation that the pedestrian would always be in a single location, another pedestrian was located at a corner at the opposite side of the circuit; data for this pedestrian are not reported due to the limited sight distance available.

For each lap the pedestrians wore one of three clothing conditions. To represent a range of pedestrians differing in conspicuity, clothing configurations that have been shown to provide enhanced pedestrian recognition (incorporating retroreflective materials) were included along with more typical, low-reflectance pedestrian clothing.[29] The *black condition* was a black sweatshirt, sweatpants, and shoe covers (2% reflectance). The *vest condition* was the clothing from the black condition plus a large, silver retroreflective (Scotchlite, 3M, 8910 silver fabric, initial average $R_A = 500$, reflected color was white) rectangular panel measuring 28.5 × 46.5 cm (1325 cm^2) worn on the chest. The *biomotion condition* was the clothing from the black condition with the same silver retroreflective (Scotchlite) fabric used for the vest condition but configured in strips (50 mm wide) around the wrist, elbows, ankles, knees, shoulders, and waist. The total area of retroreflective material was matched to the vest condition. Each pedestrian wore each of the three clothing conditions three times, once for each of the three different visual conditions (normal, cataract, and blur), resulting in a total of nine data collection laps and one lap where the pedestrian was absent to reduce expectancy effects. In

Table 1. Group Mean Visual Function for Each of the Three Visual Conditions

	Visual Conditions		
	Normal	**Blur**	**Cataract**
Visual acuity (logMAR)	−0.12 (0.02)	+0.27 (0.03)	+0.28 (0.03)
Letter contrast Sensitivity (log CS)	1.88 (0.02)	1.79 (0.02)	1.10 (0.01)
Disability glare Sensitivity score (letter difference)	0.96 (0.69)	0.25 (0.55)	23.75 (1.55)

addition, an initial (practice) lap familiarized the driver with both the vehicle and the circuit.

Participants were instructed to follow the specified route, to drive at a comfortable speed, and to press a large (12 × 6 cm) luminous dash-mounted touch pad (and announce "pedestrian!") as soon as they recognized that a pedestrian was present ahead. In an effort to increase driver workload, we also instructed participants to read aloud all road signs that were encountered around the circuit; performance on this task was neither recorded nor analyzed.

Two primary dependent variables are reported. The first is the percentage of trials in which the participant correctly identified the presence of the pedestrians and the second is the distance (from the pedestrian) at which the driver responded to the pedestrian. Response distances were coded as zero for all trials in which the driver did not respond to the test pedestrian or had passed the pedestrian before pressing the touchpad. Recognition distances are not presented for the secondary pedestrian due to the limited sight distance that was available. The frequency with which participants correctly identified pedestrians was analyzed using repeated-measures logistic regressions (Generalized Estimating Equations [GEEs]) with participant identity as a random factor, visual condition (Normal, Blur, and Cataract), and clothing (Black, Vest, and Biomotion) as repeated-measures factors, and glare as a between-subjects factor with response (correct identification vs. no correct identification) as a binomial criterion. GEEs were compared using independence, autoregressive (AR1), and exchangeable correlation structures using the QICC index; the exchangeable structure was selected because it provided the best fit to the residuals. The distance measures were analyzed using repeated-measures ANOVA with two within-subject factors (visual status and clothing) and one between-subjects factor (the presence or absence of glare).

Results

Table 1 presents the mean visual function data for each of the three visual conditions. Relative to the baseline normal vision condition, binocular visual acuity was significantly reduced in both the blur and cataract conditions ($F_{2,26} = 187.8$; $P < 0.001$). Although the visual acuity of six of the participants was reduced below 20/40 for the cataract simulation condition, the group mean visual acuity while wearing the simulated cataract goggles was slightly better than 20/40 (6/12). For each participant, the positive (blurring) lenses in the blur condition were individually chosen to match the same participant's acuity from the simulated cataract condition. The blur and cataract conditions significantly impaired contrast sensitivity ($F_{2,26} = 1276.1$; $P < 0.001$). Although the blurring lenses matched the visual acuity degradation of the simulated cataracts, they resulted in only a modest reduction in contrast sensitivity, with a mean reduction in contrast sensitivity of −0.09 (from 1.88 to 1.79). Conversely, the cataract simulation markedly impaired contrast sensitivity with a mean difference of −0.78 (from 1.88 to 1.10 log units). Disability glare was significantly increased for the cataract condition compared to the blur and normal conditions, which were not different to one another ($F_{2,26} = 101.3$; $P < 0.001$).

Figure 1 shows the percentage of pedestrians recognized on average for each of the visual impairment and glare combinations. The visual manipulations significantly affected pedestrian conspicuity: drivers responded to the pedestrian 56.9%, 52.1%, and 29.9% of the laps in the normal vision, blur, and cataract conditions, respectively [$\chi^2(2) = 46.52$, $P < 0.001$].

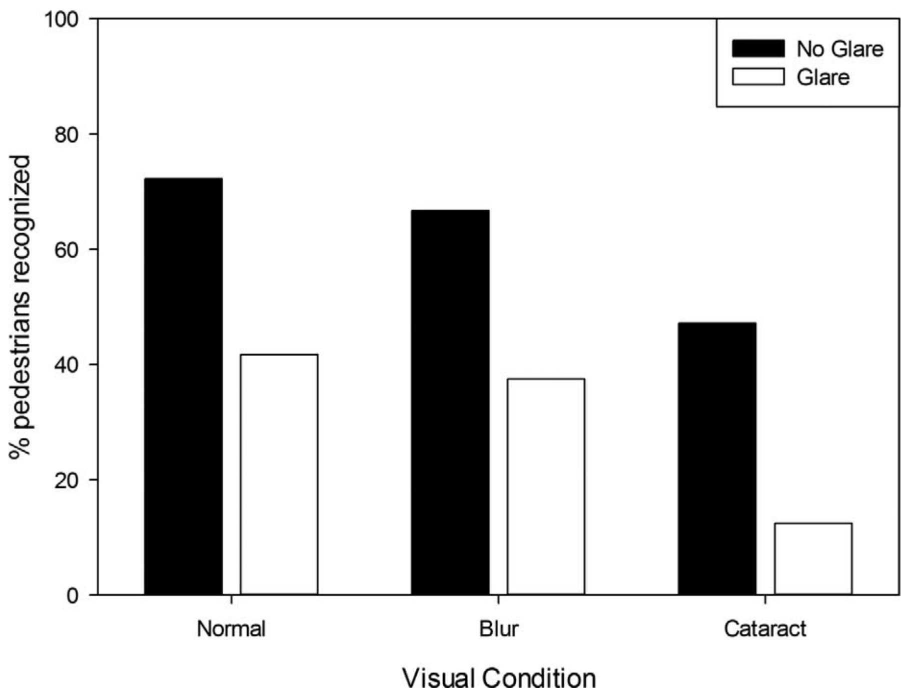

Figure 1. Percentage of pedestrians recognized as a function of driver visual status and glare condition.

The number of pedestrians seen in the cataract condition differed significantly from both the blur and normal conditions ($P < 0.001$), but the blur and normal conditions did not differ from one another. Drivers responded to pedestrians twice as often in the absence of headlamp glare compared to when the headlamps were present (62% vs. 30.6%) [$\chi^2(1) = 12.2$, $P < 0.001$].

Pedestrians were recognized on average on only 13.5% of laps when wearing black clothing; recognition increased by a factor of more than three on average when the pedestrian wore the retroreflective vest (43.1% of laps), and by a factor of greater than six when the pedestrian was wearing the biomotion clothing (82.3% of laps) [$\chi^2(2) = 73.38$]. All pairwise differences were significant ($P < 0.001$).

A repeated-measures ANOVA was conducted examining the distances at which participants recognized the pedestrian, with two within-subject factors (visual status and clothing) and one between-subjects factor (the presence or absence of glare). The mean distances at which the drivers responded to the pedestrian are shown in Figure 2, demonstrating that in the normal condition, the drivers responded at distances that were on average 3.6- and 5.5-fold longer than that in the blur or cataract conditions, respectively. This main effect of visual status was significant ($F_{2,25} = 22.12$, $P < 0.001$, partial $\eta^2 = 0.64$), and the three means were all significantly different from one another ($P < 0.05$). When collapsed across visual status and glare, drivers responded to the pedestrian at a mean distance of only 0.57 m (SE = 0.2) when the pedestrian was wearing black clothing, at 27.7 m (SE = 7.21) for the vest condition and 110.9 m (SE = 10.93) when wearing the biomotion clothing. This main effect of clothing was significant ($F_{2,25} = 49.51$, $P < 0.001$, partial $\eta^2 = 0.79$) and all pairwise differences were significant. When averaged across visual status and clothing, the mean distance at which drivers responded was 57.5 m (SE = 7.55) when the glare headlamps were off and 35.3 m (SE = 6.54) when the glare headlamps were on. This main effect of glare was significant ($F_{1,26} = 4.95$, $P = 0.035$).

There was a significant interaction between visual status and clothes ($F_{4,23} = 11.12$, $P < 0.001$), such that visual status had no effect on the black clothing condition (since the three mean distances were all near-zero) but had a substantial effect when the pedestrian wore the vest or biomotion configurations. For all visual conditions, the pedestrian wearing biomotion was seen at longer distances than pedestrians wearing either the vest or black clothing, but this effect was greater in the visually normal condition than that in the two visual impairment conditions. The pedestrian wearing the vest was seen at longer distances than the pedestrian wearing black in all visual conditions, but the differences did not reach significance for the cataract condition. The interactions between visual status and glare ($F_{2,25} = 0.41$, $P = 0.67$), between pedestrian clothing and glare ($F_{2,25} = 2.74$, $P = 0.08$), and between visual status, glare, and clothing ($F_{4,23} = 0.40$, $P = 0.81$) were not significant.

Discussion

This study demonstrated that drivers' ability to see and respond to pedestrians at night is degraded by modest but common visual impairments, even when drivers' visual acuity meets commonly adopted levels of visual acuity required for driver licensure. Blurred vision (typically encountered when a driver fails to wear optimal corrective lenses) and simulated cataracts both reduced the ability of the drivers to recognize pedestrians, with the cataract condition having a greater impact. Although both the blur and simulated cataracts reduced visual acuity to the same extent, cataracts reduced contrast sensitivity to a greater extent than did blur, and it is likely that this is the reason for the larger reduction in pedestrian recognition. Irrespective of whether glare was present, none of the drivers with simulated cataracts responded to the pedestrians wearing black, yet drivers wearing blurring lenses responded to 42% (no glare) and 6% (glare) of the pedestrians wearing black.

Although no previous studies have systematically investigated the effects of blur and cataracts on the distances at which drivers respond to pedestrians at night, our previous closed-road study demonstrated that the frequency that pedestrians were seen at night was reduced by similar levels of refractive blur and cataracts.[12] There is evidence that drivers with cataracts have increased crash risk and impaired driving performance compared with age-matched control drivers,[4,30,31] and refractive blur has been shown to significantly impair other aspects of driving performance.[12,32,33] Nonetheless, the present study is the first to quantify how these impairments reduce the distances at which drivers respond to the presence of pedestrians at night, a critical safety variable.[34]

Importantly, both the refractive blur and cataract simulation conditions resulted in a substantial impact on pedestrian conspicuity at night, even though the reduction in visual acuity was only moderate. This suggests that even relatively small reductions in acuity can represent threats to safety. Further, this finding indicates that not all causes of acuity reduction are equal, since the cataract-induced acuity loss was far more debilitating than the blur-induced acuity loss. In addition, these data support other studies that have suggested that licensing standards might benefit from including measures such as contrast sensitivity that may provide additional information that can be used to predict safety outcomes.[35] The strong impact of visual impairment on pedestrian conspicuity in this study stands in contrast to the finding that the ability to steer and maintain proper lane position is more robust to blur.[10,32,36] This pattern of optical blur being more disruptive for some abilities (e.g., seeing pedestrians) than for others (e.g., steering) is consistent with the selective degradation hypothesis suggested by Leibowitz and Owens. This hypothesis asserts that drivers' robust steering abilities, combined with the relatively low frequency with which hazards such as pedestrians are encountered at night, can prevent drivers from appreciating the extent to which their visual abilities are impaired by low illumination and/or optical blur.[37]

The effects of headlamp glare effectively halved the likelihood that drivers detected the presence of a pedestrian on average, regardless of clothing condition, and also significantly decreased the distances at which pedestrians were recognized. This finding that the presence of glare at night reduces pedestrian conspicuity is in general accord with that of Theeuwes et al.,[17] who found that the ability of drivers to detect simulated pedestrians at the roadside at night was significantly decreased, even when the illumination levels of the simulated glare sources mounted on the vehicle's hood were relatively low. Similarly, Ranney et al.,[16] using a night driving simulator, reported that the presence of glare slowed the detection of pedestrians.

Clothing that included retroreflective tape in a biological motion configuration was shown to be relatively robust to the effects of both visual impairment and glare, whereas pedestrians wearing either a reflective vest or black clothing were rarely recognized in time for drivers to stop at a safe distance. This finding confirms and extends previous work on pedestrian clothing.[25,26,38,39] The conspicuity benefits of biomotion were evident in this study for all conditions. Pedestrians wearing the biomotion clothing configuration were recognized significantly more often and at significantly longer distances than pedestri-

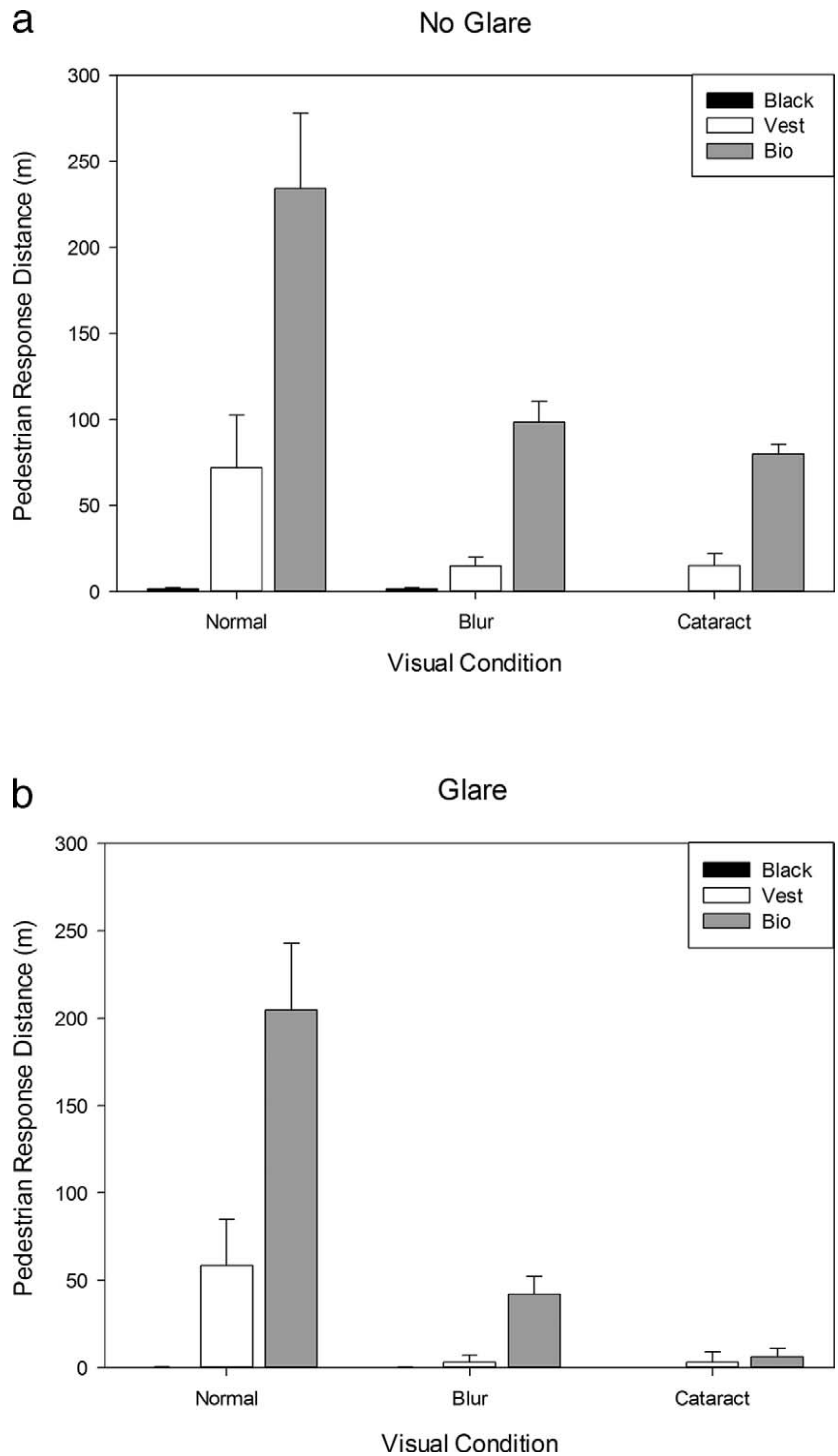

FIGURE 2. Mean distances (+ 1 SEM) at which drivers responded to the presence of a pedestrian as a function of the visual status of the drivers and pedestrian clothing in the absence (*top*) and presence (*bottom*) of glare.

ans wearing either the retroreflective vest (that incorporated the same amount of retroreflective tape) or black clothing. Importantly, the relative benefit of the biomotion was consistent; even when vision was impaired, response distances for biomotion were 5–8 times greater than for vest in the blur and cataract conditions.

An advantage of the approach taken in this study is that the only factor that varied between tests was the visual status of the participants as manipulated by the filters. In studies that have compared driving performance between participants with and without cataracts, many other variables may have differed between groups apart from their visual status. In studies that compare performance before and after cataract surgery, performance may also be influenced by the length of time between tests and by practice effects. In the approach adopted here it was possible to minimize the effects of practice on the tests by randomizing the order in which the filters were applied. There are, however, inherent limitations in simulating the effects of cataracts or any other type of visual impairment, in that although the use of simulated visual impairments allowed us to isolate the effects of vision, it is recognized that the effects observed may not perfectly reflect those from people who have gained substantial experience in living with their visual impairment.

Collectively these results provide strong evidence that pedestrian conspicuity at night is decreased by moderate visual impairments and in the presence of the glare from oncoming headlamps. Clothing that incorporates retroreflective tape in a biomotion configuration can significantly improve the conspicuity of pedestrians, especially for drivers with common types of visual impairment. The implications of these results are that particularly at night, drivers should be encouraged to wear their optimum optical correction to maximize their ability to see pedestrians from distances that allow them to respond safely. These findings, together with those of Keeffe et al.,[3] who showed that 80% of drivers who failed to meet the visual requirements for driving had uncorrected refractive error, suggest the need for greater emphasis by licensing and health care authorities of the need to wear appropriate optical corrections when driving, particularly at night. Further, cataract surgery should be encouraged early enough that potentially dangerous reductions in visual performance are avoided. Future studies are required to further explore the impact of uncorrected refractive error, cataracts, and other forms of visual impairment on driving performance and safety and to determine the value of visual measures, such as straylight testing and contrast sensitivity, on predicting driver performance and safety, particularly at night.

Acknowledgments

The authors thank Queensland Transport for allowing use of the facilities at the Mt Cotton Driver Training Centre and the staff of the Mt Cotton Centre for their generous cooperation and support.

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