Differential Effects of Refractive Blur on Day and Nighttime Driving Performance

Joanne M. Wood,[1] Michael J. Collins,[1] Alex Chaparro,[2] Ralph Marszalek,[1] Trent Carberry,[1] Philippe Lacherez,[1] and Byoung Sun Chu[1,3]

[1]School of Optometry and Vision Science and Institute of Health and Biomedical Innovation, Queensland University of Technology, Brisbane, Queensland, Australia
[2]Department of Psychology, Wichita State University, Wichita, Kansas, United States
[3]Department of Optometry and Vision Science, Catholic University of Daegu, Daegu, Korea

Correspondence: Joanne M. Wood, School of Optometry and Vision Science, Queensland University of Technology, Victoria Park Road, Kelvin Grove Q 4059, Australia; j.wood@qut.edu.au.

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Purpose. To investigate the effect of different levels of refractive blur on real-world driving performance measured under day and nighttime conditions.

Methods. Participants included 12 visually normal, young adults (mean age = 25.8 ± 5.2 years) who drove an instrumented research vehicle around a 4 km closed road circuit with three different levels of binocular spherical refractive blur (+0.50 diopter sphere [DS], +1.00 DS, +2.00 DS) compared with a baseline condition. The subjects wore optimal spherocylinder correction and the additional blur lenses were mounted in modified full-field goggles; the order of testing of the blur conditions was randomized. Driving performance was assessed in two different sessions under day and nighttime conditions and included measures of road signs recognized, hazard detection and avoidance, gap detection, lane-keeping, sign recognition distance, speed, and time to complete the course.

Results. Refractive blur and time of day had significant effects on driving performance ($P < 0.05$), where increasing blur and nighttime driving reduced performance on all driving tasks except gap judgment and lane keeping. There was also a significant interaction between blur and time of day ($P < 0.05$), such that the effects of blur were exacerbated under nighttime driving conditions; performance differences were evident even for +0.50 DS blur relative to baseline for some measures.

Conclusions. The effects of blur were greatest under nighttime conditions, even for levels of binocular refractive blur as low as +0.50 DS. These results emphasize the importance of accurate and up-to-date refractive correction of even low levels of refractive error when driving at night.

Keywords: refractive blur, driving, nighttime

Uncorrected refractive error (either undiagnosed or inadequately corrected) is the leading cause of visual impairment in adults aged over 40 years,[1] with the prevalence of refractive visual impairment increasing significantly with age.[2] The impact of blur on standard clinical measures of vision, such as visual acuity, is well known. The functional impairment resulting from uncorrected refractive errors on measures of reading,[3] falls risk,[4] and quality of life,[5] have also been investigated. However, the effect of uncorrected refractive errors on driving performance and safety are poorly understood. This is important, since many individuals drive with uncorrected refractive error; in one study, uncorrected refractive error accounted for 80% of drivers whose vision failed to meet the legal limit for driving.[6]

Previous studies have established that blurred vision can impair daytime driving in young normal subjects.[7,8] However, these studies did not systematically assess the effects of specific levels of refractive blur, but rather looked at the impact of blur as defined by the amount required to degrade visual acuity to three specific levels (20/40, 20/100, and 20/200). Driving simulator studies have indicated that large amounts of blur impair sign recognition, while other tasks such as steering and lane keeping are relatively unaffected, presumably because they can be performed using the lower-resolution capabilities of the peripheral visual field.[9,10]

Importantly, the impact of blurred vision on nighttime driving has received little attention, with the exception of two recent studies that examined one level of blur (selected to reduce visual acuity to ~20/40 to match that of a simulated cataract condition) and demonstrated that this had a significant impact on overall nighttime driving performance,[11] as well as pedestrian recognition distances.[12] The effect of blur at night is particularly relevant given that the road accident fatality rate at night is 2 to 4 times higher than that for daytime driving when adjusted for distances driven.[13] These effects are even more pronounced for fatal crashes involving pedestrians, where nighttime pedestrian fatality rates are up to 7 times higher than those in the day.[14] Analyses of crash statistics indicate that reduced lighting and poor visibility are the primary factors 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.[15,16]

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In this study, we systematically investigated the impact of a range of levels of refractive blur on day and nighttime driving performance using real-world tasks including road sign recognition, recognition and avoidance of road hazards, and judging gaps while maintaining lane control and an appropriate speed on a closed road circuit. We were particularly interested in better understanding how different levels of refractive blur, of the kind that may be commonly encountered in the driving population (including two levels that did not reduce visual acuity below driver licensing levels of 20/40 and one that did) would impact on driving performance and whether these effects were greater under day or nighttime conditions.

METHODS

Participants

Participants consisted of 12 younger, licensed drivers (mean age 25.8 ± 5.2 years; range, 17–33 years; 6 men and 6 women), who were visually normal and had binocular visual acuity of 20/20 or better. All participants reported that they drove regularly and had between 0.5 and 17 years of driving experience (mean = 6.6 ± 5.2 years). When questioned about their nighttime driving experiences over the previous year, participants reported an average of 30.4 ± 17.25% of their total driving was at nighttime. 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 Conditions

Driving performance was assessed in two sessions, one of which was conducted during daytime conditions and one at night after nautical twilight (approximately 52 minutes after sunset in Brisbane for the months when testing was conducted). Nautical twilight times were taken from the Astronomical Applications Department of the U.S. Naval Observatory (provided in the public domain by the U.S. Naval Observatory at http://aa.usno.navy.mil/data/docs/RS_OneYear.php). During each session, driving performance was assessed under four visual conditions: once with the participant wearing their optimal distance refractive correction (referred to as the baseline condition), and again under three different levels of blur, consisting of the baseline refractive correction plus either +0.50 DS, +1.00 DS, or +2.00 DS binocular spherical blur. For all conditions, participants drove while wearing goggles with standard wide-aperture trial lenses incorporating these lens powers, which provided a field of view equivalent to that of standard 38-mm trial lenses and therefore did not restrict the binocular field of view below that of driver licensing standards in Australia (which require an unobstructed field with a horizontal extent of 110°).

Visual acuity and letter contrast sensitivity were measured in each of the four visual blur conditions under photopic light levels. The order of the two vision tests was randomized for each condition. High contrast distance visual acuity was assessed at 6 m both binocularly and monocularly using a Bailey-Lovie logMAR chart with a chart luminance of 125 cd/m^2, which was scored on a letter-by-letter basis (–0.02 log units per letter correct). Letter contrast sensitivity was determined binocularly using the Pelli-Robson chart, with a chart luminance of 125 cd/m^2 and scored on a letter-by-letter basis (0.05 log units per each letter correct).

Driving Assessment

All testing was undertaken on the closed road circuit at the Mt. Cotton Driver Training Centre, which has been used by the researchers in previous studies of vision and driving.[17] The circuit (approximately 4 km) 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 artificial ambient lighting.[18–21] All experimental sessions were conducted during times when the road surface was dry and there was no rain.

The experimental vehicle was an instrumented right-hand drive car (1997 Nissan Maxima; Nissan, Nishi-ku, Yokohama, Japan) with automatic transmission and halogen headlights. A dual-camera parallax-based video measurement system was utilized to measure sign recognition distances,[21] and roof-mounted cameras were used to record lane-keeping performance.[11]

During each of the driving assessments, the participant completed five laps of the driving circuit: one practice lap and four data collection laps. The primary purpose of the practice lap was to familiarize the driver with the test vehicle, the driving circuit, and also the different tasks required of them. This practice run was identical to all of the four test runs except that it was performed in the opposite direction to the recorded runs, to reduce any practice effects. Each of the four data collection laps featured a different level of refractive blur, with the order of the refractive conditions randomized. Participants were instructed that they would be required to perform a number of concurrent tasks (driving performance measures) while they drove at what they felt was a comfortable speed, and also to drive in their own lane, except when avoiding hazards (strategically placed around the circuit). The trial runs were randomized both in terms of the order of blur conditions as well as whether the night or day condition was conducted first: day and night sessions were separated by at least 2 weeks in order to minimize practice effects.

Driving performance was assessed using real-world tasks such as reading road signs, recognizing and avoiding road hazards, and judging gaps while maintaining lane control and an appropriate speed on a closed road circuit. Measures included: (1) sign recognition; (2) hazard avoidance; (3) gap judgment; (4) lane keeping; and (5) driving time.

Sign Recognition. Participants were instructed to verbally report the identity of 49 standard road signs containing 72 items of information as they drove around the circuit. These included a mixture of speed advisory and speed limit signs, stop/give way signs, road condition signs (e.g., floodway), street name signs, and general advisory signs (e.g., exit, keep left) as would be encountered under normal driving conditions. With the exception of street name signs, these signs are important for maintaining driving safety. We also measured the recognition distance for one specific road sign while the participant was driving. This measurement was conducted on a straight section of the circuit after the completion of each lap, on the way back to the starting position. It was not possible to measure recognition distances for all signs given the other driving tasks that participants had to complete.

Hazard Avoidance. Participants were required to report and avoid hitting any of nine large, low-contrast grey foam "hazards" (220 × 80 × 15 cm) positioned orthogonally in the driving lane along the roadway, the locations of which were randomized between trials.

Gap Judgment. Nine pairs of 350-mm traffic cones of variable lateral separation were positioned throughout the

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TABLE. The Results of the Two-Way Repeated Measures ANOVA Conducted to Examine the Effects of Blur and Time of Day on the Measures of Driving Performance

Effect	Measure	F	P
Blur	Performance Z score	36.33	<0.001
	Signs recognized	38.03	<0.001
	Hazards hit	34.43	<0.001
	Gap judgments	1.27	0.301
	Lane crossings	1.99	0.135
	Lap time	13.55	<0.001
	Sign recognition distance	84.41	<0.001
Time	Performance Z score	44.90	<0.001
	Signs recognized	4.30	0.062
	Hazards hit	38.83	<0.001
	Gap judgments	4.10	0.068
	Lane crossings	0.03	0.876
	Lap time	24.88	<0.001
	Sign recognition distance	21.37	<0.001
Time × blur	Performance Z score	8.59	<0.001
	Signs recognized	18.37	<0.001
	Hazards hit	11.61	<0.001
	Gap judgments	0.46	0.716
	Lane crossings	2.43	0.083
	Lap time	2.48	0.078
	Sign recognition distance	1.78	0.169

course, with equal numbers being set to be wide enough, not wide enough, and just wide enough for the car to pass through; the separation of cone pairs varied between trials. Participants drove at a "comfortable speed" and were required to report whether the approaching cone gap was wide enough to drive through and if so, to do so; while if the gap was judged to be too narrow they were instructed to drive around the cones. Performance was scored in terms of whether the judgments were correct.

Lane Keeping. This was recorded by two video cameras mounted on the vehicle roof (GoPro Hero 3; Woodman Labs, San Mateo, CA, USA) and scored posttesting as the number of lane crossings. Lane crossings where the participant was responding to a hazard on the road were not included.

Driving Time. Time to complete the road course was also recorded for each refractive condition.

Analysis

A composite score (*Z*), as used in our previous studies, was also derived to capture the overall driving performance of the individual participants compared with the whole group, and this included road sign recognition, cone gap perception, course time, and the number of road hazards hit.[17,22,23] *Z* scores for each of these four component driving measures were determined and the mean *Z* score for each participant calculated to give an overall score with an equal weighting assigned for all tasks. The data were transformed where necessary to ensure that better performance was always represented by a more positive *Z* score. A series of two-way repeated measures ANOVA were conducted examining the effects of blur and time of day on the measures of driving performance, with Greenhouse-Geisser adjustment to account for departures from sphericity where necessary.

Results

Refractive blur had a significant effect on both visual acuity, $F(3,33) = 125.92$; $P < 0.001$, and letter contrast sensitivity, $F(3,33) = 9.35$; $P < 0.001$. The levels of blur included in the study reduced visual acuity from a baseline group mean average of –0.12 ± 0.06 logMAR to –0.05 ± 0.09 logMAR for +0.50 DS blur, +0.10 logMAR ± 0.11 for +1.00 DS blur, and +0.51 logMAR ± 0.15 for +2.00 DS blur. All pairwise differences were significant. Thus, for all but the +2.00 DS blur conditions, the participants would have been driving with better than the Australian driver licensing standards of visual acuity of 20/40 (+0.30 logMAR) or better. Contrast sensitivity was also significantly reduced from the baseline group mean average of 1.90 log units ± 0.06 compared with all of the blur conditions: 1.86 log units ± 0.10 for +0.50 DS blur, 1.85 log units ± 0.08 for +1.00 DS blur, and 1.83 log units ± 0.10 for +2.00 DS blur. The blur conditions did not differ significantly from one another, and the magnitude of the reduction in contrast sensitivity was only small (of the order of one letter).

There were significant main effects of blur on the overall performance *Z* score, hazards hit, lap time, signs recognized, and the distance at which the selected sign was first recognized (Table). For the measures of number of signs recognized, the distance at which signs were recognized and the overall performance *Z* score, all differences between blur conditions were significant. The number of signs recognized decreased with increasing blur (48.83 ± 7.80 for plano, 46.08 ± 7.92 for +0.50 DS blur, 42.92 ± 5.32 for +1.00 DS blur, and 32.5 ± 6.38 for +2.00 DS blur), with sign recognition distance also significantly decreased with increasing blur (124.93 m ± 13.59 for plano; 107.12 m ± 21.73 m for +0.50 DS; 78.17 m ± 31.07 for +1.00 DS; and 18.41 m ± 14.40 for +2.00 DS). The performance *Z* score also decreased significantly with increasing blur (0.35 ± 0.29 for plano, 0.28 ± 0.52 for +0.50 DS blur, 0.01 ± 0.36 for +1.00 DS blur, and –0.64 ± 0.42 for +2.00 DS blur). For hazards hit, while the +0.50 DS and +1.00 DS level conditions and the +0.50 DS and plano conditions did not differ significantly from one another, all other differences were significant (0.17 ± 0.33 for plano, 0.33 ± 0.49 for +0.50 DS blur, 0.79 ± 0.69 for +1.00 DS blur, and 2.33 ± 0.96 for +2.00 DS blur). Lap times increased significantly with increasing blur (6 minutes, 26 seconds ± 46 seconds for plano; 6 minutes, 42 seconds ± 56 seconds for +0.50 DS blur; 6 minutes, 41 seconds ± 48 seconds for +1.00 DS blur, and 6 minutes, 59 seconds, ± 55 seconds for +2.00 DS blur); all differences were significant with the exception of the difference between +0.50 DS and +1.00 DS blur conditions. There were no significant effects of blur on either gap judgments or lane crossings.

There was a significant main effect of time of day, such that performance was worse at night than in the day, for the measures of overall performance *Z* score (–0.262 ± 0.35 vs. 0.262 ± 0.38); hazards hit (1.27 ± 0.47 vs. 0.54 ± 0.47); lap time (7 minutes 7 seconds ± 55 seconds vs. 6 minutes 17 seconds ± 51 seconds), and distance to recognize signs (70.83 m ± 18.83 vs. 93.48 m ± 15.48), as well as marginally significant main effects for sign recognition (40.56 ± 6.23 vs. 44.6 ± 7.43) and gap judgments (7.81 ± 0.58 vs. 8.13 ± 0.39); see the Table. There was no significant effect of time of day on lane crossings.

There were also significant interactions between refractive blur and time of day for sign recognition, hazards hit, and the overall performance *Z* score, with the magnitude of the effect of refractive blur on driving performance being greater at night than in the day. Specifically, for the overall performance *Z* score (Fig. 1), the +2.00 DS blur condition was significantly different to the other blur levels both at night and during the day. The +1.00 DS blur condition was also significantly different from the plano condition at night but not during the day. For signs recognized (Fig. 2), all differences between blur conditions were significant during the night, but the difference between the +1.00 DS and +0.50 DS blur conditions

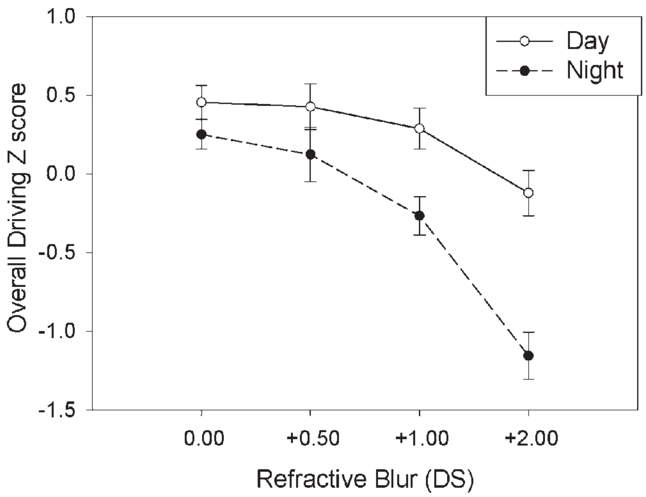

Figure 1. Group mean and standard errors for the overall driving *Z* score as a function of refractive blur under day and nighttime driving conditions. A higher *Z* score indicates better driving performance.

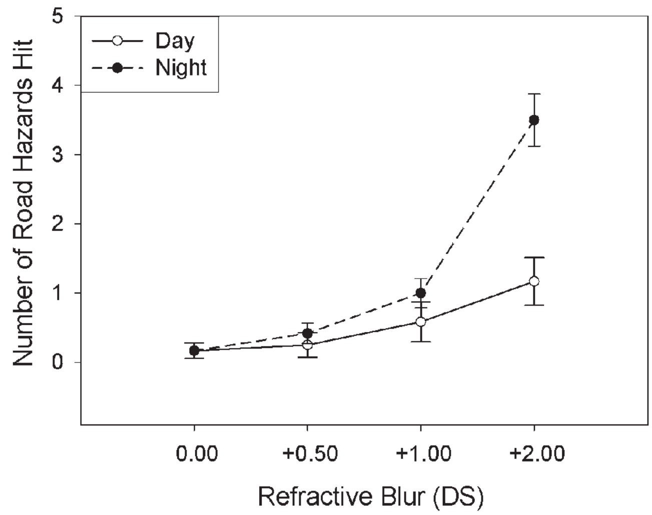

Figure 3. Group mean and standard errors for number of road hazards hit as a function of refractive blur under day and nighttime driving conditions.

was not significant during the day, nor was the difference between the +0.50 DS and baseline conditions. In the daytime, the +2.00 DS blur condition differed from both the baseline and the +0.50 DS blur conditions in terms of the number of hazards hit (Fig. 3), but no other differences were significant; while at nighttime, all differences were significant except between the plano and +0.50 DS blur level.

Discussion

In this study, we compared the effect of different levels of binocular refractive blur on driving performance for day and nighttime driving for a group of young visually normal drivers. Our findings indicate that increasing blur had an increasingly detrimental effect on all of the components of driving performance measured (road sign recognition, road sign visibility distance, hazard recognition and avoidance, driving speeds) except for gap judgment and lane keeping. This differential effect of blur on specific aspects of driving performance is in accord with our previous findings for daytime driving performance.[7] Most aspects of driving performance were worse at night than in the day and importantly, there were also significant interactions between refractive blur and time of day, where the effects of blur were exacerbated under nighttime driving conditions.

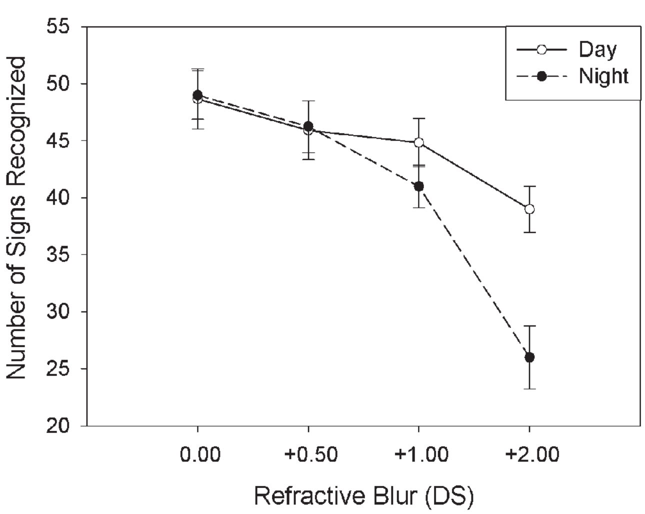

Figure 2. Group mean and standard errors for the number of road signs correctly recognized as a function of refractive blur under day and nighttime driving conditions.

Our findings demonstrate that even low levels of binocular refractive blur have a detrimental effect on detection and avoidance of low contrast hazards, the number of road signs recognized as well as the distance at which the selected road sign was first recognized, particularly at night. This is of particular interest, since the drivers in this study also drove significantly more slowly when driving with blur. But this strategy was not sufficient to compensate for the decrement in visual performance. In open road traffic conditions, the opportunity to slow down to this extent is unlikely to be available in normal traffic flow. Thus, the effects of refractive blur are likely to be greater under open road conditions. Importantly, while the binocular +2.00 DS level of blur did reduce visual acuity below the licensing requirement of 20/40 binocularly, with blur levels of +0.50 DS and +1.00 DS all participants would have passed the acuity requirements for licensing, but based on our results would still experience significant decrements in sign and hazard recognition. For example, under nighttime conditions for the highest blur condition, over 30% of the large low contrast hazards would not have been seen, and around 11% would not have be seen for the +1.00 DS blur level. The low contrast targets we employed are similar to real-world objects that require some form of evasive action by the driver that might include potholes, debris on the highway, or speed bumps; failure to recognize even one of these hazards could have important safety implications. Similarly, for the highest level of blur at night, the participants recognized just over a third of the road sign information, with just over half being recognized for the lower levels of blur at night. While some signs include street names that are of less consequence for driving safety, others like stop and give way signs may be critical.

All of the driving outcome measures, with the exception of lane keeping, were worse at night compared with daytime conditions, both with and without additional blur. This is likely to be primarily due to the lower ambient light levels causing reduced visibility of both spatial and contrast details. This finding of diminished performance for nighttime compared with daytime driving in the presence of blur is similar to the reports of increased problems with night driving expressed by patients with cataracts, glaucoma, and AMD,[24–26] as well as in patients following refractive surgery and those wearing presbyopic corrections.[27,28] However, the mechanisms leading to the increased difficulty with night compared to daytime driving may differ between these various conditions. The robust lane-keeping behavior is consistent with earlier findings that show that lane-keeping behavior is largely unaffected by reduced acuity resulting from optical manipulations (i.e., spherical refractive blur)[17] or environmental conditions such as low illumination.[9]

An important finding of this study is the increased impact of binocular refractive blur at night compared with daytime conditions. A contributing factor to this difference is likely to be the increased pupil size in low illumination levels leading to a larger blur circle at the retinal plane. Atchison et al.[29] reported that the effect of uncorrected refractive errors on visual acuity was significantly greater with larger pupil diameters under photopic conditions. However, pupil size appears to have relatively little impact on the overall contrast sensitivity function in the presence of refractive blur in photopic conditions.[30] Other factors associated with reduced ambient illumination, such as the shift from predominantly cone (photopic) to a combination of rod- and cone- (mesopic) based vision, may play a role in the relationship between blur and driving performance at night. It is well known that visual acuity is reduced when the level of illumination is decreased.[31,32] But the interrelationships between refractive blur, visual acuity, and luminance are less clear. Some authors have found visual acuity to be affected similarly by refractive blur across a range of luminance levels,[31] whereas other authors have reported that the effect of blur is less under low luminance compared with high luminance levels.[32] The interactive effect of refractive blur and luminance for other visual functions that might be related to driving performance, such as contrast sensitivity and motion sensitivity, are unknown.

An advantage of the approach taken in this study is that the only factor that varied between tests was the refractive status of the participants, and that this factor was manipulated by the use of blurring lenses. By manipulating visual function rather than simply observing individual differences in function, we reduced the potential for confounding with other individual differences, such as variations in experience or personality type. It was also possible to minimize the effects of practice on the tests by randomizing the order in which the blurring lenses were worn. There are, however, inherent limitations in simulating the effects of blur, in that while the use of simulated blur allowed us to isolate the effects of vision, it is recognized that the effects observed may not exactly reflect those of drivers who have longer-term experience of living with refractive blur. There is evidence that individuals can partly adapt to the presence of blur,[33,34] and that the time course of this adaptation is approximately 6 minutes with any improvement levelling off after this period.[35] Since the participants in our study were exposed to each of the blur conditions for at least 6 minutes before testing began, their responses are likely to represent those of a person who is adapted to their refractive blur. However, we cannot rule out the possibility that adaptation over much longer periods of time may further reduce the impact of blur on performance. Another factor to consider in this discussion of adaptation to blur is the relatively young age of the participants (mean age: 26 years). Older persons are reported to show slightly better visual performance than younger persons when exposed to defocus blur[36,37] and this could translate to better relative performance of older drivers under blurred conditions. The prior visual experiences of individuals, both short and longer term, are therefore likely to be of importance when driving in the presence of blur.

Our finding that even low levels of refractive blur have a negative impact on driving performance under day and particularly nighttime conditions has implications for the correction of refractive errors for driving. These differences in performance are likely to have a tangible impact on driving safety in situations where timely recognition of hazardous situations is critical. In particular, our findings emphasize the importance of accurate and up-to-date refractive correction and for the correction of even low levels of refractive error when driving at night.

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