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Evaluation of the Driving Safety of Visually Impaired Bioptic Drivers Based on Critical Events in Naturalistic Driving

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Purpose: Visually impaired people may be allowed to drive if they wear bioptic telescopes. Bioptic driving safety is debatable, especially given that the telescopes are seldom used by most bioptic drivers. This preliminary study examined bioptic safety based on critical events that occurred in naturalistic daily driving.

Methods: Daily driving activities were recorded using in-car video recorders in 20 bioptic drivers (median age 55, visual acuity, 20/60–160) and 19 control subjects (median age 74) for two to eight weeks. In a secondary analysis, these subjects were compared with 44 cognitively impaired drivers with normal vision (median age 75).

Results: In 292 hours of driving by bioptic drivers and 169 hours by control drivers, seven bioptic drivers and three control drivers had eight and four near-collisions, respectively. Near-collision survival times were not significantly different between the two groups (hazard ratio [HR] = 1.93, $P = 0.591$) according to Cox hazards regression. Even without compensation for bioptic drivers' longer driving exposure, their odds ratio (OR) was not statistically significant (OR = 2.88, $P = 0.18$). When including cognitively impaired drivers with normal vision, cognition was a significant predictor of near collisions (HR = 3.86, $P = 0.036$), but vision loss was not (HR = 0.47, $P = 0.317$).

Conclusions: This preliminary study failed to find any evidence suggesting that bioptic drivers were more prone to near-collision than healthy drivers. Vision might be a less-significant factor than cognition.

Translational Relevance: Given that bioptic drivers use the telescope for less than 2% of the driving time, this study suggests that driving safety might not be substantially affected even when visual acuity is in the low vision range.

Introduction

Loss of driving privileges has devastating lifestyle consequences for many people in modern societies. One of the common causes of losing driving privileges is vision loss. The typical visual acuity requirement for an unrestricted driver's license ranges from 20/20 (Italy) to 20/25 (China), 20/28 (Japan), and 20/40 in the United States. However, in almost all the US states, as well as in the Netherlands, Quebec, people with visual acuity as low as 20/200 may be permitted to drive if they wear bioptic telescopes. These are small telescopes mounted on normal glasses that allow drivers to discriminate details at farther distances when needed (Fig. 1).

A simplified argument is that if one can wear eyeglasses to pass a vision test and drive legally, a visually impaired person should be allowed to use a telescope to do the same. However, a concern with bioptic driving is that the visual field may be restricted when looking through a telescope. The restriction occurs due to (1) the magnified image of the small field of view in the scene occupying a large retinal area, resulting in a ring-shaped blind area for the

Figure 1. Wearing bioptic telescope allows visually impaired people to drive legally in some countries. The telescope can help users to see details in distance when it is needed.

viewing eye[1] and (2) the body of some telescope designs obstructing the view.[2] To minimize the negative impact of the restricted visual field, the design of bioptic telescopes actually allows users to maintain unrestricted visual field through the carrier lens and also provides the capability to see smaller details in the distance when it is needed, by alternating gaze between the carrier lens and the telescope. This viewing strategy does not provide the same visual capacity of normally-sighted drivers, who simultaneously have high-resolution vision and wide visual fields. However, it should be noted that normally-sighted people have high visual acuity only in the central vision area and not in the entire visual field. Visual acuity drops to 20/75 at 5° eccentricity and 20/130 at 10° eccentricity and so on.[3] To see a wide scene with high-resolution vision, normally-sighted people constantly move their gaze position.[4,5] This gaze movement is fundamentally similar to the bioptic use pattern, except that it is more efficient. To help achieve efficient viewing for visually impaired drivers, bioptic driving professionals recommend they look through the telescope as briefly as possible. However, there is no consensus regarding how frequently they should look through the telescope. The general guideline is that they should use the telescope only when it is needed, such as reading roadway signs and examining traffic ahead. In our recent naturalistic driving study on a group of visually impaired drivers with bioptic telescope, we found that the median time spent looking through the telescope was only 1.4% of the total driving time.[6] In other words, the subjects were driving with a low level of visual acuity most of the time. This finding raises obvious questions about whether driving with impaired central vision and only occasional, brief use of the telescope is hazardous.

Despite the legality of driving with a bioptic telescope, the safety of bioptic driving remains controversial. Previous retrospective studies comparing collision rates of bioptic drivers and normally-sighted drivers differ greatly in their conclusions. Studies have found that bioptic drivers had lower collision rates,[7] similar collision rates,[8,9] higher collision rates,[10,11] or mixed results.[12] A recent study[13] examining the relationship between visual functions of 237 bioptic drivers and their state motor vehicle collision history did not find visual acuity or contrast sensitivity to be significant predictors of safety outcomes. None of these retrospective studies could provide any precollision information about how or why the collisions happened. When examining the impact of bioptic use on driving safety, it is important to determine the cause of collisions. A collision may occur when the driver is looking through the telescope, which might cause blindness to traffic, or as a result of failure to look through the telescope, which might result in poor perception of important traffic situations. Other collisions may not be vision related. To understand the causal relationship between collision and use of the bioptic telescope, detailed driving behaviors at the time of collision must be closely monitored and analyzed.

In a standard on-road test, Wood et al.[14] investigated a group of bioptic drivers' telescope use behaviors and also evaluated their driving maneuver performance. Most of the bioptic drivers (22 of 23) in the study were rated safe. However, the relationship between bioptic use and driving performance could not be established. In this article, we present a naturalistic driving study in which near-collision frequency was compared between bioptic participants and normally-sighted control subjects. Motor vehicle collision rate can be considered the gold standard for safety evaluations. Considering the rare nature of collisions, however, a logical and more frequently used surrogate measure in research is the rate of near-collisions.[15] Near-collisions are not very frequent either, so extended naturalistic driving recording is necessary. Our ultimate goal is to investigate the effect of bioptic telescope use and the impacts of vision loss on driving safety, rather than driving maneuver performance. This article presents the first exploratory study toward this goal.

Method

Twenty bioptic drivers and 19 control group drivers were enrolled in this study. Bioptic driving participants were recruited from multiple sites:

15 participants from study sites in Boston and Ohio in the United States and five participants from Québec in Canada. Bioptic drivers' ages ranged from 22 to 90 years (median 55 years), bioptic driving experience ranged from less than a year to 44 years (median 11.5, interquartile range [IQR] 1–16.8), and their visual acuity ranged from 20/60 to 20/160 (0.47 and 0.92 LogMAR, median, 0.7, IQR 0.57–0.86). The ages of control group participants were between 60 and 83 years (median: 74 years). Their driving experience ranged from 40 to 66 years (median 53, IQR 46.5–60), and their visual acuity ranged from 20/15 to 20/50 (LogMAR −0.12 to 0.4, median 0.14, IQR 0–0.21). The control group came from our previous naturalistic driving study on cognitively impaired drivers.[16] Because the two studies shared the same control group, we also included the cognitively impaired drivers and conducted a secondary analysis to investigate the effect of visual impairment on driving safety compared with cognitive impairment. The control and cognitively impaired drivers were recruited from Rhode Island.

All participants had valid driving licenses and were active drivers during the study. Participants were instructed on procedures, risks, and benefits before the study, and written consent was obtained from them. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Institutional Review Boards at Schepens Eye Research Institute, Ohio State University, Nazareth, and Louis-Braille Institute, and Rhode Island Hospital.

The in-car recording system was comprised of two cameras, one recording the road ahead and one recording inside the vehicle, pointed toward the participant to capture driver behaviors. The entire recording system was packaged as a rear-view mirror, such that it could be mounted on top of the existing interior rear-view mirror. The recording system started automatically when the car was turned on and stopped recording when the car was turned off. After initial installation, the recording system did not require any adjustment or intervention by the participant. Driving data were recorded over a period of 2 to 8 weeks.

In total, 292 hours of driving for bioptic drivers and 169 hours of driving for control group drivers were included in this study. To review the recorded driving data, an automated data reduction system was developed to extract driving sections with potential safety concerns. The detected events were based on lane change events, rapid stops, going through major intersections, or instances of approaching with short estimated time-to-contact with the other vehicle ahead. The rapid stop and intersection driving events were extracted using GPS data, and short time-to-contact and lane change events were extracted by image processing.[17,18] The methods were developed in-house and used in our previous driving studies.[19–21] For control group drivers, 7264 events were detected, and for the bioptic driver group 18,425 events were detected. The extracted data were then visually reviewed to identify risky behaviors (not just near-collisions) using the Mocking Bird Scoring method which was developed by a commercial driving evaluation company, Lytx (San Diego, CA, USA), to identify risky behaviors in driving fleets. This method has been used in academic research to characterize and monitor driving in longitudinal studies of ambulance drivers[22] and cognitively impaired drivers.[21] The scoring system defines risky behaviors in eight major categories of concern: distractions, poor awareness, driver conduct, fundamentals, following too closely, driver condition, traffic violations, and other concerns. Each major category includes more detailed subcategories, which are assigned a severity scale score from 0 to 10 points.

None of the participants in either group had any collisions, but some of the participants had near-collision incidents. In this study, the near-collision incidents were defined according to the Mockingbird scoring method as "drivers failed to assess or react appropriately to a developing hazard and a collision was narrowly avoided either through late but effective input from the driver or by happenstance." Near-collisions have been used in the past for evaluating drivers' safety performance because such incidents can serve as one of "the most comprehensive" surrogate measures to identify important factors related to traffic safety.[23] Building on traffic conflict theory,[24] the near-collision rate is roughly proportional to the collision rate. The concept is the same as Heinrich's accident triangle model,[25] traditionally accepted in research on industrial accidents, which states that the minor accident rate is proportional to the rate of serious accidents.

Near-collisions can be compared using odds ratio (OR) analysis, which compares the number of "cases" (drivers in this study) with and without incidents (near-collisions in this study). The potential disadvantage of using total near-collisions in OR analysis is that it does not consider driving exposure. In this study, driving exposure was quantified as driving hours rather than enrollment period, because the former is more precise, but driving hours was very different across individuals. On average the bioptic drivers were recorded more than the control subjects. To normalize the driving exposure, we calculated the average near-collision rate in terms of driving hours per event and used that as the survival time in Cox hazard regression analysis. The reason why the analysis was conducted using average near-collision rate rather than the actual time to occurrence of near-collisions is that the actual occurrence time is arbitrary. A participant might have a very short survival time until the first near-collision during the study period, but that does not necessarily mean this person has a higher overall near-collision frequency compared with another driver who has multiple near-collisions but at a later time during the same duration. Rather, this may occur because our data collection happened by chance to start shortly before the near-collision event. Considering that control subjects were recorded for only two weeks and therefore had less chance to be involved in near collisions than the bioptic drivers (who were recorded for an average of eight weeks), a censored time window was determined for the purpose of Cox regression. According to an AAA survey,[26] American drivers drive for approximately 11.3 hours on average over two weeks. Therefore, in the Cox regression the censored (cut-off) driving exposure was set to 12 hours for all participants.

Results

Driving Errors

In addition to near-collisions, events flagged by data reduction processing were manually reviewed to identify unsafe driving behaviors using the Modified Mocking Bird Scoring system. The driving error data for one of the bioptic group participants were not available, so there were 19 bioptic and 19 control group participants for this section's analysis. The bioptic and control groups were compared for all the behavior subcategories using Mann Whitney U analysis. Five types of behaviors were found to be significantly different: rolling stop ($U = 36$, $z = -4.3$, $P < 0.01$); traffic violation ($U = 35$, $z = -4.3$, $P < 0.01$); other distractions ($U = 78.5$, $z = -2$, $P < 0.01$); other unsafe/risky maneuvers ($U = 99$, $z = -2.7$, $P = 0.017$); lane positioning ($U = 110$, $z = -2.1$, $P = 0.04$). The control group was more likely to engage in risky behaviors than the bioptic group in all of the five behavior categories.

Near-Collision

Review of the detected events showed that three of 19 control group participants and seven of 20 bioptic driving participants had near-collision events, and one participant in each group had two near-collision events. Table 1 lists detailed annotations about those incidents along with screenshots associated with them. The mean driving exposure for the control and bioptic groups was 8.9 and 14.6 hours, respectively. There was no significant difference in the near-collision frequency (number of events per hour) between the two groups (Mann-Whitney U Test: $U = 224$, $z = 1.3$, $P = 0.351$). The near-collision OR of bioptic drivers was not significant either ($OR = 2.88$, $P = 0.18$, $z = 1.35$). Because the occurrences of near-collision events were not normalized by driving time, the near-collision OR for the bioptic drivers was overestimated because of their longer driving time compared with control group drivers. Nonetheless, the differences were not significant.

There was a significant age difference between control and bioptic drivers and (control = 72.5 years, bioptic = 53.1 years, $t[37] = 4.8$, $P < 0.01$). Studies suggest that there is a difference in the collision rates of different age groups. The collision rate per 100 million miles traveled for drivers of age group 50 to 59 is 315 and for drivers of age group 70 to 79 is lower, at 301.[27] However, as it is argued in the Discussion below, the difference between the two age groups is negligible.

Table 2 lists the vision, age, and sex information of all the 20 bioptic drivers. There was no significant difference in vision ($P = 0.777$, $t[18] = 0.288$) or age ($P = 0.726$, $t[18] = 0.356$) between those with ($n = 7$) and without ($n = 13$) near-collision incidents.

According to backward Cox proportional hazard regression analysis with age, sex, and vision status (visually impaired or not) as covariates, the survival time to near-collision was not significantly different between the bioptic and control groups. The hazard ratio ($HR = 1.93$) for vision impairment was not significant ($P = 0.591$).

In a secondary analysis, the control and bioptic groups were combined with 44 drivers with mild cognitive impairment (median age 75.1, median driving experience 55 years, IQR 50–63) enrolled in our previous study[16] to further evaluate the effect of vision loss in a larger mixed sample. All of the patients in the cognitive impairment group had normal vision. Data collection and near-collision event review methods were the same as described above in the Methods section. Backward Cox hazard regression was conducted, controlling for cognition (cognitively impaired or not), vision status (visually impaired or not), age, and sex. Cognition was found to be the only significant risk factor ($HR = 3.86$, $P = 0.036$), whereas vision ($HR = 0.47$, $P = 0.317$), sex, and age were not significant risk factors. Figure 2 shows the near-collision survival curves of the three groups based on the 12 hours of observed driving time censorship window.

Table 1. Annotations and Screenshots of Near-Collision Incidents

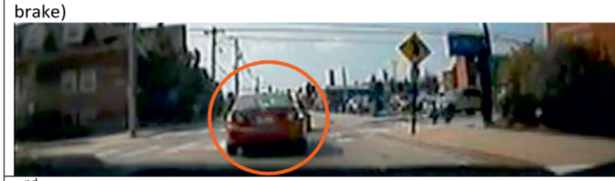
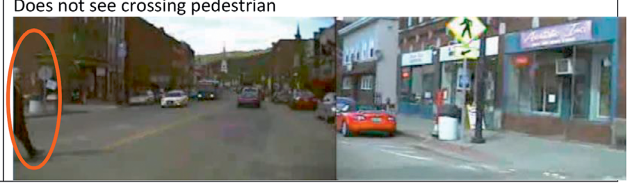
ID	Age	VA (20/x)	Group	Detail
3	81	30	Control Group	1st: Following too close to lead vehicle (late reaction to lead vehicle's brake)  2nd: Judgment error (turning with a small gap in oncoming traffic) 
7	81	40	Control Group	Not looking ahead (Looking at side lane during turn - missed pedestrian) 
18	70	25	Control Group	Distracted with mobile phone (Late reaction to lead vehicle's brake) 
1	66	160	Bioptic driving group	Not looking ahead - looking to the side (steers towards a stopped car) 
2	64	100	Bioptic driving group	Not looking ahead - looking at shops (misses a pedestrian in a parking lot) 
9	48	100	Bioptic driving group	Not giving way to a moving car on right side at a four-way stop 

Table 1. Continued

12	31	100	Bioptic driving group	Not looking ahead (looking at the other lane and brakes late) 
14	32	100	Bioptic driving group	Judgment error (Turns at intersection before oncoming traffic clears) 
15	55	125	Bioptic driving group	1st: Not looking ahead (misses a pedestrian stepping on the road)  2nd: Not looking ahead at a turn and misses a pedestrian crossing road  Pedestrian seen in the interior camera 
20	63	50	Bioptic driving group	Does not see crossing pedestrian 

VA, visual acuity.

Discussion

This study evaluated the safety performance of bioptic drivers based on near-collision incidents in naturalistic driving. This method was used previously to evaluate the driving safety of cognitively impaired drivers[16] who showed a higher probability of near-collision than the same control group. In this study we did not find a significant difference in the survival time to near-collision between bioptic drivers and the control group. The near-collision OR of bioptic drivers was not statistically significant either.

The OR analysis had one limitation—the visually impaired participants (bioptic group) and the control group participants were not matched for age and

Table 2. Vision, Age, and Sex Information of Bioptic Drivers

ID	VA 20/xx	Age	Sex
1*	159	66	M
2*	100	64	M
3	159	59	M
4	74.3	22	F
5	74.3	60	M
6	59	56	M
7	158.9	38	M
8	95.7	64	M
9*	100.2	48	F
10	74.3	67	F
11	126.2	90	M
12*	100.2	31	M
13	151.7	50	F
14*	100	32	M
15*	125	55	M
16	80	55	F
17	80	33	M
18	100	60	M
19	80	48	F
20*	50	63	M
Mean	99 ± 36	54 ± 17	—

The mean of visual acuity was calculated based on LogMAR and then converted to Snellen acuity. VA, visual acuity.
*Subjects who had near-collision incidents.

driving exposure. The driving exposure of visually impaired drivers was greater than for the control drivers, which would cause their odds of near-collision to be overestimated. They were also slightly younger than the control group. According to the US Department of Transportation (USDOT),[27] the collision rate is slightly higher for the age group represented by the bioptic drivers in our sample (50–59) than for the age group (70–79) represented by the control drivers, although the overall the USDOT data do show collision rates generally increase with age. We think that the slight difference in the collision rate (315 vs. 301) between the two age groups is negligible when considering the data from this study. The fact that the bioptic driver group had a point estimate for the OR of near-collision that was greater than one (although not statistically significant, OR = 2.88, $P = 0.18$) may be partially due to their greater driving exposure compared with the control group.

After controlling for age and driving exposure, the Cox hazard regression analysis of near-collisions did not show any significant difference between the two groups, although the point estimate of the hazard ratio was higher than 1 (HR = 1.93, $P = 0.591$). Future studies should include a larger sample size and longer follow-up to confirm the hazard ratio observed in this study. In other words, if there was indeed a real difference, it was not large enough to be confirmed by the 20 bioptic drivers and 19 control subjects in this study. Based on the preliminary data obtained in this study, we estimate that one would need about 49 bioptic drivers and 49 control subjects to be recorded for six months to confirm the HR = 2 of bioptic drivers to be statistically significant.

Besides the statistical significance of an effect, effect size is an important consideration. To interpret the data from a geriatrics perspective, we compared the data with our previous study in which we found cognition to be a significant factor for driving safety. In that study, the hazard ratio of predicted collision for older adult drivers with normal vision but mild

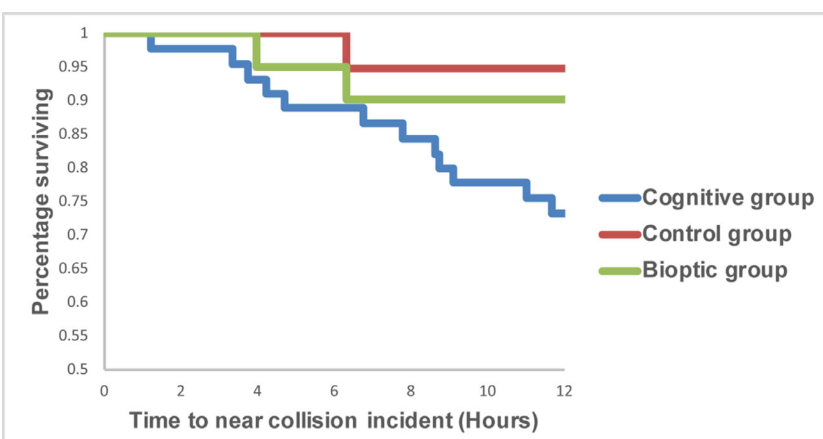


Figure 2. Survival probabilities for the control group (n = 19), visually impaired subjects (n = 20), and cognitively impaired subjects (n = 44) based on near-collision in a 12-hour time window censored.

cognitive impairment was about 6, using the same control group as in this study.[16] An HR around 6 is considered to be a large effect size in epidemiologic studies.[28] When all three groups of drivers (control, bioptic, and cognitively impaired) were pooled together, cognitive impairment was the only significant risk factor predicting collision, with an HR of 3.86 ($P = 0.036$). On the contrary, visually impaired bioptic drivers were not at a higher risk compared with normally sighted drivers that included cognitively impaired people (HR = 0.47, $P = 0.317$). Therefore we speculate that poor visual acuity may be a relatively small risk factor compared with cognitive impairment.

Additionally, reviewing the videos of the near-collision incidents (See the screenshots in Table 1), we could not identify any incidents clearly due to an inability to discern hazardous obstacles. The bioptic driver with the worst visual acuity, 20/160, should be able to resolve an object which contains high contrast detail subtending eight minutes of arc. However, according to our observations, all of the obstacles (2.7 degrees, or 162 minutes of arc, and above) that played significant roles in the incidents were much larger than the bioptic drivers' resolution limits when they became hazardous. Although the contrast of those obstacles was not as high as letters on a visual acuity chart (see Table 1), the bioptic drivers should not have needed to use their telescopes to spot these obstacles if they used their best retinal locus to look at them. It appeared to us that the perception and judgment errors of bioptic drivers were similar in nature to those of control subjects—they all failed to see obstacles because of inattention.

Another possible explanation for bioptic drivers' performance is that visually impaired drivers might compensate for their low visual acuity through self-control of driving behaviors. The driving error analysis showed that bioptic drivers were more cautious than normally sighted drivers, including stopping fully at stop signs and not engaging in distracting activities.

As in some of the previous studies,[7–9] our naturalistic study did not find that the likelihood of visually impaired bioptic drivers being involved in collisions was considerably greater than that of normally sighted drivers. These results, taken together with the fact that the bioptic drivers spend an overwhelming majority of their driving time under low visual acuity conditions (i.e., not looking through the telescope),[6] raise an important question about the role of vision in driving—Isn't visual acuity crucial for driving? More than four decades ago, Feinbloom[29] recruited 12 normally-sighted drivers, fitted them with fogging lens to reduce their visual acuity to about 20/225, and then let them drive for a week. Those subjects reported no difficulty in driving in city traffic or avoiding obstacles such as small animals. Despite the lack of a control group, this study seemed to suggest that visual acuity was not as crucial as many people think.

We believe that, if one studies visual acuity across a wide range, from normal to blind, it is likely that there is a strong correlation between visual acuity and motor vehicle collision. However, if we study driving safety within a smaller range, for instance, within the normal vision range, or from normal (e.g., 20/20) to moderate vision loss (e.g., slightly worse than 20/40) as typically allowed by most states, the effect size of vision (often quantified as visual acuity) may be too small to detect. The study by Rubin et al.[30] enrolled 1801 older drivers, among which 97% had vision better than 20/40, and visual acuity was not found to be associated with motor vehicle collision according their survival analysis. The study by Cross et al.[31] enrolled 3158 older drivers, which included the participants in the study by Rubin et al.,[30] and 96% of the drivers had vision better than 20/40. Visual acuity was still not found to be a factor predicting motor vehicle collision. In a comprehensive review, Owsley and McGwin[32] concluded that "visual acuity is, at best, very weakly linked to driver safety (i.e., collision involvement)." This conclusion should be interpreted as referring to a certain range of visual acuity. Dougherty et al.[13] specifically studied the driving records of 237 bioptic drivers in Ohio, whose vision ranged from 20/50 to 20/250 (median 20/120), and did not find visual acuity to be related to annual motor vehicle collision rate. These seemingly unexpected findings motivated us to investigate whether, by enrolling subjects with a large range of visual acuity (from normal to legally blind by U.S. standards) and adjusting for driving exposure, we could find a significant effect of visual acuity on collisions.

Although the finding from the small sample in this study still needs to be confirmed by future studies, it raises questions regarding the validity of existing visual acuity requirements for driver licensure at 20/40 in the United States or 20/20 in Italy. The findings suggest that it is necessary to look beyond vision when considering driving fitness. Statistics showed that the crash rate of drivers under age 18 in the United States is at least four times higher than for drivers between ages 30 to 79,[27] and our findings that the HR of older drivers with mild cognitive impairment may be as high as six compared with age-matched normal control subjects.[16] Considering the large impacts of age and cognition on driving safety, it might not be a groundless consideration from an ethical perspective to relax the visual acuity requirement for licensure. If the visual acuity requirement could be relaxed to a certain degree based on scientific evidence, many people with visual impairment would benefit from the change.

In reality, there is an ethical barrier preventing researchers from studying driving safety in naturalistic settings in drivers with visual acuity far below the licensure thresholds. Considering the very low rate of use of bioptic telescopes in their driving,[6] investigating this unique population of drivers can help us to better understand the role of vision in driving in general, that is, bioptic drivers can serve as a cohort for researchers to ethically and legally study the role of vision in driving in natural real-world environments.

Some studies have suggested other visual functions to be correlated with collisions. For instance, Rubin et al.[30] and Cross et al.[31] reported that visual field loss and useful field of view were associated with collisions. Owsley et al.[33] found that contrast sensitivity in patients with cataract was associated collisions. Previous studies have also suggested that motion perception may also play an important role in driving hazard perception.[34–36] These visual functions should be evaluated in future naturalistic driving studies.

Conclusion

We did not find any evidence indicating that bioptic drivers were more prone to motor vehicle collision than normally sighted controls. Considering our earlier findings on the low rates of actual usage of the bioptic telescope among these drivers, we postulate that, even without using the telescope, people with moderately low visual acuity might be able to drive with collision rates somewhat comparable to normally sighted drivers. Further studies using longer duration on-road assessments and collision history in larger samples are needed to confirm this hypothesis and identify visual function measures that may be more predictive for collision risk than visual acuity.

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