tvst

Article

Hazard Detection With Monocular Bioptic Telescopes in a Driving Simulator

Xiaolan Tang[1,2], P. Matthew Bronstad[2], Amy L. Doherty[2], Mojtaba Moharrer[2], Eli Peli[2], Gang Luo[2], and Alex R. Bowers[2]

[1] College of Information Engineering, Capital Normal University, Beijing, China
[2] Schepens Eye Research Institute of Massachusetts Eye and Ear, Department of Ophthalmology, Harvard Medical School, Boston, MA, USA

Correspondence: Alex Bowers, Schepens Eye Research Institute of Massachusetts Eye and Ear, Department of Ophthalmology, Harvard Medical School, 20 Staniford St., Boston, MA 02114, USA. e-mail: alex_bowers@meei.harvard.edu

Received: November 4, 2019
Accepted: December 18, 2019
Published: March 30, 2020

Keywords: bioptic telescope; scotoma; low vision; driving; central vision loss

Citation: Tang X, Bronstad PM, Doherty AL, Moharrer M, Peli E, Luo G, Bowers AR. Hazard detection with monocular bioptic telescopes in a driving simulator. Trans Vis Sci Tech. 2020;9(4):26, https://doi.org/10.1167/tvst.9.4.26

Purpose: In most states, people with reduced visual acuity may legally drive with the aid of a bioptic telescope. However, concerns have been raised that the ring scotoma may impair detection of peripheral hazards. Using a driving simulator, we tested the hypothesis that the fellow eye would be able to compensate for the ring scotoma when using a monocular telescope.

Methods: Sixteen bioptic users completed three drives with binocular viewing interleaved between three drives with monocular viewing. Forty pedestrians appeared and ran on the road for 1 second, including 26 within the ring scotoma, while participants were reading road signs through their own monocular telescopes. Head movements were analyzed to determine whether the pedestrian appeared before or only while using the telescope.

Results: For pedestrians that appeared only during bioptic use and were likely in the area of the ring scotoma, detection rates were significantly higher in binocular (fellow eye can compensate) than monocular (fellow eye patched) viewing (69% vs. 32%; $P < 0.001$); this was true for both current and noncurrent drivers. For pedestrians appearing before or after bioptic use, detection rates did not differ in binocular and monocular viewing. However, detection rates were even higher and reaction times shorter when the telescope was not being used.

Conclusions: Both current and noncurrent drivers' fellow eyes were able to compensate, at least in part, for the ring scotoma.

Translational Relevance: When using monocular telescopes, the fellow eye reduces the impact of the ring scotoma on hazard detection in binocular viewing.

Introduction

Bioptic telescopes are small, spectacle-mounted telescopes (Fig. 1) used by people with reduced visual acuity (VA) to see the details of distant objects. They can be used as driving aids[1,2] in 48 US states,[3] The Netherlands,[4,5] and the province of Quebec, Canada.[6] When people with reduced VA drive wearing bioptic telescopes, they spend most of the time looking through the carrier lens below the telescope. If they need to see the details of distant signs or traffic conditions, they tilt their head down to look through the telescope only briefly.[7] The time looking through the telescope typically occupies <1.5% of the total driving time.[7,8]

Bioptic telescopes can be either monocular (only one telescope for the left/right eye) or binocular (a telescope for each eye), though the majority of bioptic drivers use a monocular telescope.[9,10] The telescopes can be of Keplerian or Galilean design, with fixed or variable focus.[11] Different states have different requirements for the bioptic. For example, in Massachusetts, the bioptic must be monocular, fixed focus, no greater than 3 × magnification, and must be an integral part of the lens.[12]

tvst.arvojournals.org | ISSN: 2164-2591

translational vision science & technology

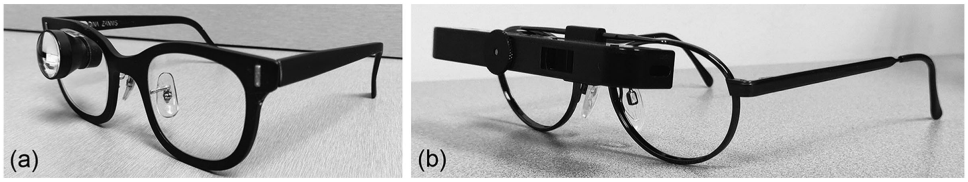


Figure 1. Monocular bioptic telescopes similar to those used by participants in the study: (**a**) A 3.0 × Designs for Vision Galilean bioptic telescope (Designs for Vision Inc., Ronkonkoma, NY, USA); (**b**) A 4.0 × Ocutech VES-K Keplerian bioptic telescope with the optics in a periscope arrangement in a rectangular housing across the width of the spectacle frame (Ocutech Inc., Chapel Hill, NC, USA).

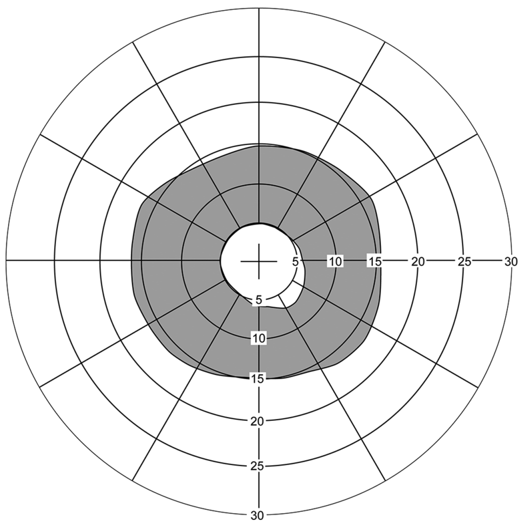


Figure 2. Ring scotoma plotted when looking into a 3.0 × monocular Galilean bioptic telescope. The central white area represents the magnified field of view, which the participant saw through the telescope, whereas the outer white area is the field of view outside the telescope (without magnification). The grey shaded area is the ring scotoma, located in this case from about 5° to 15°.

When a bioptic user looks through a monocular telescope, the magnified field of view causes an annular blind area in the telescope eye, often called a ring scotoma (Fig. 2). Some have maintained that the scotoma will obscure hazards relevant to the driver and that driving with a bioptic is, therefore, unsafe.[13,14] Others have argued that the non-telescope eye, the fellow eye, may be able to compensate for the ring scotoma in binocular viewing conditions.[15–17] For example, in the simple visual conditions of traditional perimetry, the only blind area in the binocular view is the overlap of the physiological blind spot of the fellow eye with the ring scotoma of the telescope eye.[18] However, in visually complex environments, such as encountered when driving, the magnification difference between the two eyes may cause binocular rivalry or suppression.[19–21] The increase in motion velocity in the magnified view, compared with the unmagnified fellow eye view, may increase the predominance of the telescope eye,[19] which might reduce the likelihood of the fellow eye being able to compensate for the ring scotoma.

In prior studies of monocular bioptic telescopes, the fellow eye compensated fully for the ring scotoma when static stimuli were presented over a stationary patterned background.[18,22] However, when viewing real-world driving videos, only about 50% of hazards within the ring scotoma were recognized by the fellow eye.[23] We developed a driving simulator paradigm to investigate hazard detection when using a bioptic telescope,[24] which addressed some of the limitations of the earlier studies (such as prolonged viewing through the bioptic and lack of engagement in a driving task). Results of an initial study[24] using the new paradigm suggested that the fellow eye of normally sighted observers with simulated VA loss was largely able to compensate for the ring scotoma. We now extend our investigation to visually impaired bioptic users.

In this study, bioptic users with a wide range of driving experience were recruited representing the range of bioptic users who might be encountered in a clinical setting. While driving in the simulator, pedestrian hazards were programmed to run on the road in the area of the ring scotoma when the participant was using a monocular bioptic to read information on a road sign. Some of the pedestrians were in the scene only while participants were looking through their bioptic (called All-during-Telescope events, abbreviated to All-during-Tx throughout this paper). Other pedestrians appeared before the head tilt down into the bioptic and/or remained in the scene until after the end of the upward head movement (called Part-during-Telescope events, abbreviated to Part-during-Tx throughout this paper). We tested the hypothesis that participants would be able to use the fellow eye to compensate for the ring scotoma in binocular viewing. For events where the pedestrian was in the scene only while participants were looking through their bioptic (All-during-Tx events), we expected that detection rates would be higher in binocular viewing when the fellow eye could compensate than in monocular viewing when the fellow eye was patched and could not compensate. For events where participants had a

translational vision science & technology

brief glimpse of the pedestrian either before or after the telescope use (Part-during-Tx events), we expected that detection rates would not differ in binocular and monocular viewing conditions.

Methods

Participants

People with reduced VA were recruited from a database of subjects who had participated in prior studies at Schepens Eye Research Institute, from referrals from vision rehabilitation clinics, and through social media advertisements. Inclusion criteria were VA of 20/40 to 20/200 in the telescope eye (without the telescope), current bioptic telescope user, and no manifest strabismus. In total, 16 participants were recruited, including 10 current bioptic drivers, 4 former drivers who currently used bioptic telescopes for nondriving tasks, and 2 other current bioptic users with no driving experience. Thus, participants covered the entire range of bioptic users from those with no driving experience to those with a lot of driving experience, as might be encountered in clinical practice. A short questionnaire was administered to all participants to quantify the frequency of bioptic telescope use and the tasks for which it was used.[9,10] A majority (88%) of the participants used their own monocular bioptic telescopes when driving in the simulator. Two (12%) who only owned binocular bioptic telescopes used a 3 × monocular bioptic telescope provided for the purposes of the study. Telescopes were focused at the distance of the driving simulator screen either using adjustable focus (when available), or a lens placed over the end of the telescope (a lens cap).

The study followed the tenets of the Declaration of Helsinki and was approved by the institutional review board of Massachusetts Eye and Ear. Written informed consent was obtained from all participants.

Vision Measures

VA was measured monocularly and binocularly without the bioptic, and with the telescope eye through the bioptic, at a distance of 20 feet (Test Chart 2000 Pro; Thomson Software Solutions, Herts, England). A custom, computerized device[25] was used to carry out tangent-screen-like kinetic perimetry to map the area of the ring scotoma with white stimuli presented against a darker background. The participant, sitting at 1 meter from a rear-projection screen (1.65 × 1.25 meters), was asked to focus on a cross (0.2° × 1.2°) in the center through the bioptic telescope, and then to press a button as soon as a square stimulus (1.9°) was seen. During the test, the square was moved inward or outward from unseen to seen in order to plot the inner or outer boundary of the ring scotoma. For all the participants the monocular ring scotoma (Fig. 2) was measured with the fellow eye patched. In addition, the binocular visual field with the telescope eye viewing through the bioptic was also measured when the subject had central visual field loss in the fellow eye that might overlap with the ring scotoma in the telescope eye to create a scotoma in the binocular visual field, or when the telescope might cause a scotoma in the binocular visual field (such as the Ocutech VES Keplerian telescope, Fig. 1b) (see field plots in the Appendix).

Driving Simulator Task

Apparatus

A DE-1500 (FAAC Corp., Ann Arbor, MI, USA) driving simulator with five LCD screens (42” diagonal, 1366 × 768 pixels, 60 Hz) providing 225° field of view was used. The simulator included all the controls found in an automatic transmission vehicle, and had a three degrees-of-freedom motion seat. Driving scenarios were developed using the Scenario Toolbox software (FAAC Corp.). The location and status of the driver’s car in the virtual world, as well as the data of all programmed objects, such as the pedestrians, the road signs, and other cars, were continuously recorded at 30 Hz.

A Smart Eye remote six-camera IR system (Smart Eye Pro 6.1, Gothenburg, Sweden) was used to track the participant’s head and eye movements at 60 Hz. The timing of the bioptic telescope use was determined from the head movement data based on tracking of facial features, which could be tracked reliably even when using the bioptic. Although eye movements were recorded, the data were often noisy with a lot of data drop outs due to difficulties in tracking eyes of people with nystagmus, tracking through high prescription glasses, and loss of tracking when looking into the bioptic. Thus, the eye data were not analyzed. Custom software was used to synchronize the 60-Hz Smart Eye data stream with the 30-Hz simulator data stream and the virtual world coordinate system.

Driving Simulator Procedure

All participants completed 6 test drives, each about 10 minutes, driving on the right along rural undivided roads with one lane (4.0 meters wide) in each direction and light oncoming traffic. There were hard shoulders on the edges of the roads, but no curbs. The six test drives included the three used in the prior study with simulated vision impairment[24] and an additional

Figure 3. Screen-shot of a sign+pedestrian event, when the vehicle was about 70 meters from the sign and 35 meters from the pedestrian. The pedestrian was programmed to appear, run across the road ahead of the driver for about 1 second, and disappear, all while the participant was reading the sign through the bioptic. The pedestrian was within the ring scotoma area in the monocular visual field (shown by grey shading for illustration purposes only). The small area around the sign, without shading, is the field of view through the telescope. That field of view when magnified covers the full extent of the ring scotoma. Only the central monitor of the simulator is shown; the inset on upper right is the rearview mirror.

three developed for the current study using the same criteria. Three drives were undertaken with binocular viewing (fellow eye was open) and three drives with monocular viewing (fellow eye was patched). Binocular and monocular drives were interleaved with the order counterbalanced across subjects. To ensure consistency of event timing, a speed cap was set at 35 mph and participants were asked to drive as close as possible to this maximum speed. Participants could increase speed up to the maximum using the accelerator and could use the brake to slow down the car when necessary. They also had full control of vehicle steering. Participants were asked to use their bioptic to read information from road signs, to press the horn on the steering wheel as soon as they detected any pedestrian, either running or stationary, and to obey all the normal rules of the road. They were not instructed to prioritize one task over another; rather, they were encouraged to perform all tasks as well as they could. For all participants, a 5-point calibration of the Smart Eye tracker was performed before experimental data collection commenced.

Prior to data collection, each subject had at least 30 minutes of driving practice in the driving simulator, to become familiar with vehicle control, reading road signs through the bioptic telescope in the simulator, and driving with the fellow eye patched. Former drivers and participants with no driving experience were given additional time, as needed, to practice driving in the simulator. The two participants without driving experience learned to control the speed and steering of the virtual vehicle very quickly as it was not dissimilar to a video game. The driving scenarios did not involve making any turns at intersections or interactions with other vehicles; therefore, these driving skills were not included in the driving training provided to the two nondrivers. Experimental data collection did not commence until the participant demonstrated good control of vehicle steering.

Sign-Reading and Hazard-Detection Tasks

In the six test drives, besides vehicle control, there were two main tasks for participants: sign reading and pedestrian detection. Details of the tasks are given elsewhere.[24] In brief, directional road signs based on Standard Highway Signs in color, font, and text spacing (Manual of Uniform Traffic Control Devices http://mutcd.fhwa.dot.gov/ser-shs_millennium.htm) were added to each drive. The custom navigational information on each road sign consisted of the road name ("Massachusetts Pike" or "Massachusetts Ave") and the distance ("0.8 Miles" or "0.3 Miles"; Fig. 3). The signs appeared at pseudo-random time intervals when the participant's car was about 88 meters away from the predetermined sign location. When a highway sign appeared, the participant was asked to identify the words on it through the bioptic telescope, and verbally report "Pike" or "Ave" and "8" or "3."

In addition to the road signs, pedestrians were programmed to appear at pseudo-random time intervals, including pedestrians standing at the side of the road and pedestrians running across the participant's driving lane from left to right or from right to left. Across the 6 drives, there were a total of 26 occasions when a running pedestrian appeared at the same time as a highway sign (sign+pedestrian events). The pedestrian was programmed to appear approximately 1 second after the highway sign when the participant was expected to have already tilted their head down to look into the bioptic.[24] The pedestrian appeared in an area of the lower visual field that would be within the ring scotoma when reading the sign through the bioptic (Fig. 3). It ran for about 1 second ahead of the participant's car and then disappeared before the sign-reading task was anticipated to be completed. Whether the pedestrian was totally within the area of the ring scotoma on any particular trial depended on vehicle heading and speed, as well as when and for how long participants looked through the telescope.

To keep the participants naïve about the purpose of this study, a variety of events were programmed. In addition to the 26 sign+pedestrian events across the 6 test drives, there were 35 signs without a pedestrian, 14 running pedestrians without a sign, and 33 stationary pedestrians without a sign. Only responses to the sign+pedestrian events and running pedestrians without a sign (*No-sign*) were analyzed.

Timing of Sign+Pedestrian Events

For each sign+pedestrian event, a plot of vertical head position with the timings of sign appearance, and pedestrian appearance and disappearance was generated (Figs. 4 and 5). The timing of the bioptic use was then determined from the vertical head position data using a custom MATLAB program based on data cursor mode. The program was used to mark and save the coordinates of the time points at which the downward head movement started and the upward head movement finished, t1 and t2, respectively, in Fig. 4. The median time from the sign appearance to the pedestrian appearance was 1.0 second (interquartile range [IQR], 0.9–1.0 second), and the median time from the pedestrian appearance to the pedestrian disappearance was 1.1 seconds (IQR, 1.0–1.2 seconds). Thus, the timing of sign+pedestrian events was very consistent across subjects.

Categorizing Sign+Pedestrian Events

Sign+pedestrian events were split into four categories, No-head-tilt, No-overlap, Part-during-Tx (Fig. 5), and All-during-Tx (Figs. 4), based on the amount of overlap between the period of bioptic telescope use and the period of time for which the pedestrian was in the scene (Table 1). The period of telescope use was defined as the time between the eyes beginning to move up into the telescope (as the head was moving down) and the time when the eyes completed their downward movement out of the

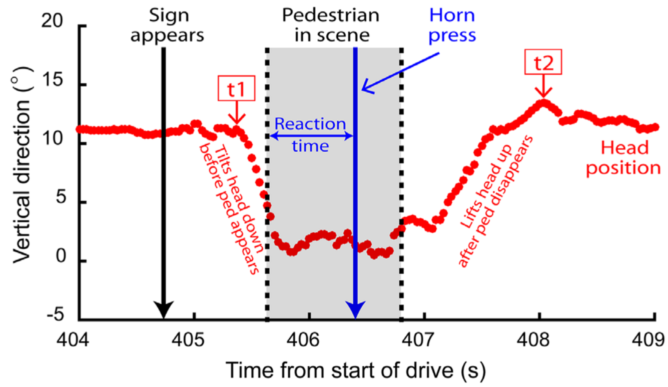


Figure 4. Vertical head position and event timing for a sign+pedestrian event in the binocular viewing condition. The participant started to tilt their head down to look through the bioptic about 0.6 seconds after the sign appeared with the end of the upward head movement about 2.5 seconds later. Because the pedestrian was in the scene (grey-shaded region) only while the subject was looking into telescope, this event was classified as an All-during-Telescope event (All-during-Tx; Table 1). In this example, the pedestrian was detected (as indicated by the horn press <1 second after pedestrian appearance), because in binocular viewing, the fellow eye was open and able to compensate for the ring scotoma. t1 marks the start of the downward tilt. t2 marks the end of the upward movement.

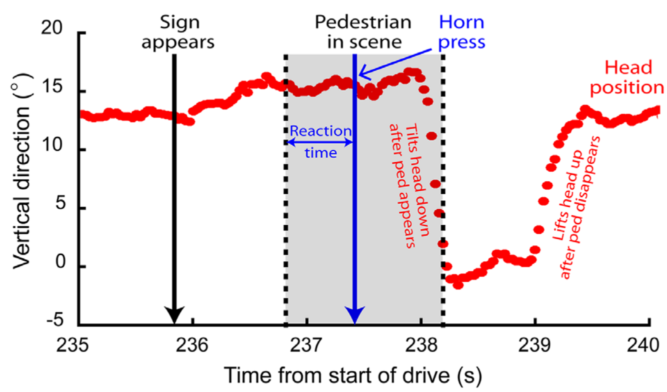


Figure 5. Vertical head position and event timing for a sign+pedestrian event in the monocular viewing condition. The pedestrian appeared about 1 second after the sign. However, the participant did not start the downward head movement until 1.1 seconds later, such that there was only a brief period of overlap (0.2 seconds) between the telescope use and the pedestrian being in the scene. Thus, the event was categorized as a Part-during-Telescope event (Part-during-Tx; Table 1). In this case, the view of the pedestrian before looking into the telescope was sufficient for detection by the telescope eye despite the monocular viewing conditions.

Table 1. Classification of Sign+Pedestrian Events ($n = 413$) Based on the Amount of Overlap Between the Pedestrian and Telescope Use

Category	Description	*N* (%)
No-head-tilt*	Participant did not look into the telescope	35 (8)
No-overlap*	Participant looked into the telescope, but the period of telescope use did not overlap with the time that the pedestrian was in the scene	44 (11)
Part-during-Tx†	There was some overlap between the telescope use and the pedestrian, but the pedestrian either appeared before the start of the telescope use or disappeared after the telescope use (Fig. 5)	147 (36)
All-during-Tx†	Participant looked through the telescope for the entire time the pedestrian was in the scene i.e., the pedestrian appeared after the start and before the end of the telescope use (Fig. 4)	187 (45)

*Combined into one category Never-during-Telescope (Never-during-Tx) for main analyses.
†Tx is used as an abbreviation for telescope.

telescope (as the head was moving back up at the end of the telescope use). However, for the majority of participants, eye movements were not tracked sufficiently well to be able to derive the start and end of the telescope use from the eye position data. Therefore, we recorded eye and head data from a group of normally sighted participants who used a monocular bioptic to read the highway signs while driving in the simulator. From those recordings, we established that the eye started to move up about 200 ms before the start of the downward head movement (t1), whereas at the end of the telescope use, the eye completed the downward movement on average about 400 ms before the end of the upward head movement (t2). For the categorization of the sign+pedestrian events we, therefore, defined the start of the telescope use as 200 ms before t1 and the end of the telescope use as 400 ms before t2.

Head movement data were available for 413 of the total 416 sign+pedestrian events. The three events without head movement data were excluded from analyses. The categorization of the remaining 413 events is summarized in Table 1. There were relatively few No-head-tilt and No-overlap events. As they shared the common characteristic that the telescope was not being used while the pedestrian was in the scene, they were combined into one category (Never-during-Tx) for the main statistical analyses. In All-during-Tx events, pedestrians appeared median 0.4 seconds *after* the head tilt down, whereas in Part-during-Tx events, pedestrians appeared median 0.27 seconds *before* the head tilt down.

Speed and Lane Position on Straight Road Segments

Using a bioptic telescope could potentially affect vehicle control. Participants might slow down when reading a sign through the bioptic or might have more unstable steering. We, therefore, evaluated vehicle control on three types of straight road segments: segments without sign-reading or pedestrian events ($n = 24$ total per participant), segments with sign-reading events but no pedestrians ($n = 20$), and segments with sign+pedestrian events ($n = 24$). All segments were approximately 70 meters long. Vehicle control measures[26] included the vehicle's average speed over each predetermined segment, the lateral lane position (the average position of the center of the car relative to the center of the travel lane over each predetermined segment), and the standard deviation of the lane position (the variability of the vehicle's lane position). This latter measure quantified steering stability: the higher the variability, the less stable the steering. As simulator data were recorded at 30 Hz, a straight segment 70 meters long driven at 35 mph (15.7 m/s) would have 134 samples from which each of the measures was computed. In addition, the number of lane boundary crossings to the left and right of the travel lane were automatically determined for each segment.[26] Data for speed and lane position analyses were only available for a subset of the participants, including five current drivers, three former drivers, and one participant with no prior driving experience.

Statistical Analysis

Mixed effects binary logistic regression analyses were used to evaluate the effects of three factors on pedestrian detection. In the first model, viewing condition (monocular or binocular) and event category (No-sign, Never-during-Tx, All-during-Tx, or Part-during-Tx) were entered as fixed factors along with their interaction. In the second model, driving status (current or noncurrent) and event category were entered as fixed factors along with their interaction. Subjects were included as a random factor in both models. The effects of a scotoma on pedestrian detection were examined separately for each of the four participants with a scotoma in the inferior binocular visual field.

Reaction time data were analyzed for events where the pedestrian was detected. Reaction times did not conform to a normal distribution, even after a log transform. Median reaction times were, therefore, computed for each subject across all events in each category. The medians did not differ from a normal distribution. Parametric statistics (*t*-tests and repeated measures ANOVA) were used to evaluate the effects of event category, viewing condition, and driving status on median reaction times.

For sign+pedestrian events where the bioptic telescope was used, four variables were used to quantify the timing of the use: the time from the pedestrian appearance to the start of the downward head tilt, t1, the durations of the downward and upward head movements, and the duration of the whole bioptic use (i.e., the time between the start of the downward head movement and the end of upward head movement, t2). Median values were computed for each subject for each variable and the medians were analyzed with nonparametric statistics.

For the analysis of the effects of bioptic use on vehicle speed, lane position, and variability of lane position, median values were computed (as the data differed substantially from a normal distribution) for each subject for each of the three straight segment types. Differences in medians between the segment types were then analyzed with nonparametric statistics. For the analysis of lane boundary crossings, each straight segment was classified as having no boundary crossing or at least one boundary crossing. This classification was applied separately to each segment for left and right boundary crossings. A mixed effects binary logistic regression analysis was then used to evaluate the effect of bioptic use on right lane boundary crossings. Segment type was entered as a fixed factor and subject was included as a random factor. (There were insufficient leftward crossings to analyze the effect of bioptic use on boundary crossings in that direction.) All statistical analyses were performed with STATA/IC 14 (College Station, TX, USA). A value of $\alpha = 0.05$ was taken to indicate statistical significance.

Results

Sample Characteristics

The 16 participants (50% men) ranged in age from 17 to 80 years (median 52.5 years; Table 2). The majority had congenital vision loss, including albinism ($n = 6$), congenital cataracts ($n = 3$), nystagmus ($n = 2$), and retinopathy of prematurity ($n = 1$). The four participants with adult onset vision loss had optic nerve damage ($n = 1$), macular holes ($n = 1$), Stargardts disease ($n = 1$), and age-related macular degeneration ($n = 1$). For the telescope eye, median visual acuity was 0.70 logMAR (20/100) without the bioptic and 0.26 logMAR (20/36) with the bioptic. Median acuity of the fellow eye was 0.80 logMAR (20/126). Four participants had a scotoma in the inferior binocular field when viewing through the telescope. For one subject, the scotoma was a result of macular disease, whereas for the other three subjects, the scotoma resulted from the rectangular housing (Fig. 1b) of an Ocutech VES bioptic telescope (see Appendix). Three of the four participants who had stopped driving had a scotoma in the lower binocular field (one had a disease scotoma and two had device scotomas).

The majority (12/16) of participants used Galilean telescopes with 3.0 × being the most common level of magnification (range 2.2 × to 6.0 ×) and a median 19.5 years since the first bioptic telescope had been prescribed. The telescopes were mostly used every day (10/16) and were reported to be very helpful (12/16). Current and noncurrent drivers differed neither in age nor VA in the fellow eye and the telescope eye without the telescope (Table 2). However, current drivers had significantly more years of experience using bioptic telescopes and were more likely to use them every day than noncurrent drivers (Table 2). Noncurrent drivers had better VA through the telescope than current drivers, possibly because their current telescopes were likely to have been prescribed for nondriving tasks and may have been of a higher power than is permitted in some states for driving.

Of the 10 current drivers, 7 drove >100 miles per week (median 151.5; IQR, 84–252). The main tasks for which the bioptic was used while driving included: reading road/traffic signs (90%), seeing traffic light signals (90%), reading street name signs (80%), seeing pedestrians crossing the road/hazards ahead (80%), and judging when it was safe to turn at an intersection without traffic lights (80%). Less common tasks included seeing brake lights and signal lights on cars in front (40%), judging the distance to the car in front (40%), and judging when it was safe to overtake another car (30%).

Sign Reading Performance

In the sign reading task, the correct response rate was the proportion of signs on which both the street name and the distance were identified correctly. All the participants had relatively high correct response

Table 2. Characteristics of the Participants

Category	All Participants ($n = 16$)	Current Drivers ($n = 10$)	NonCurrent Drivers ($n = 6$)	*P* Value for Between-Group Difference*
Age, y, median (IQR)	52.5 (35–65)	55.5 (47–66)	52 (19–65)	0.63
Male, *n* (%)	8 (50)	5 (50)	3 (50)	1.00
VA of telescope eye without bioptic telescope, logMAR, median (IQR)	0.70 (0.60–0.80)	0.70 (0.60–0.80)	0.71 (0.30–0.90)	1.00
VA of telescope eye with bioptic telescope, logMAR, median (IQR)	0.26 (0.10–0.40)	0.35 (0.20–0.40)	0.15 (0.00–0.20)	**0.02**
VA of fellow eye, logMAR, median (IQR)	0.80 (0.70–1.00)	0.75 (0.70–0.80)	0.91 (0.80–1.00)	0.31
Number of years using bioptic telescope, median (IQR)	19.5 (1–26)	23 (19–36)	1 (1–1)	**0.001**
Number of participants using bioptic telescope every day, *n* (%)	10 (63)	8 (80)	2 (33)	**0.03**
Number of participants reporting bioptic telescope is very helpful, *n* (%)	12 (75)	8 (80)	4 (67)	0.43

*Difference between current and noncurrent drivers; significant differences are shown in bold.

rates (ranged from 80%–100% across participants). Additionally, the correct response rates did not differ between monocular and binocular viewing conditions (median 94% and 97%, respectively; $P = 0.06$), and did not differ between sign-reading tasks with and without concurrent pedestrian hazards (median 97% and 96%, respectively; $P = 0.209$).

Effects of Viewing Condition and Driving Status on Sign+Pedestrian Event Categories

The proportion of each category of sign+pedestrian event did not differ between monocular and binocular viewing (data pooled across current and noncurrent drivers; Fig. 6a). However, noncurrent drivers had a higher proportion of All-during-Tx events but a lower proportion of Part-during-Tx and No-head-tilt events than current drivers (Fig. 6b). The most common kind of Part-during-Tx event was the situation where the pedestrian appeared just before the start of the telescope use and was still in the scene after the end of the telescope use.

Effects of Viewing Condition and Driving Status on Bioptic Use Timing Variables

For sign+pedestrian events in which the bioptic telescope was used, the median time from the sign appearance to the start of the head tilt down was 0.75 seconds and the median duration looking through the telescope was 1.86 seconds (Table 3). On average, the downward head movement was about 0.1 seconds shorter than the upward head movement ($z = 3.08$; $P = 0.002$; Table 3). Viewing condition (monocular vs. binocular) did not affect any of the bioptic use timing measures. There was also no effect of driving status (current vs. noncurrent) on the time between the sign appearing and the start of the head tilt down ($z = 0.22$; $P = 0.83$; Table 3). However, current drivers looked through the telescope for a significantly shorter period of time than noncurrent drivers ($z = 2.44$; $P = 0.015$)

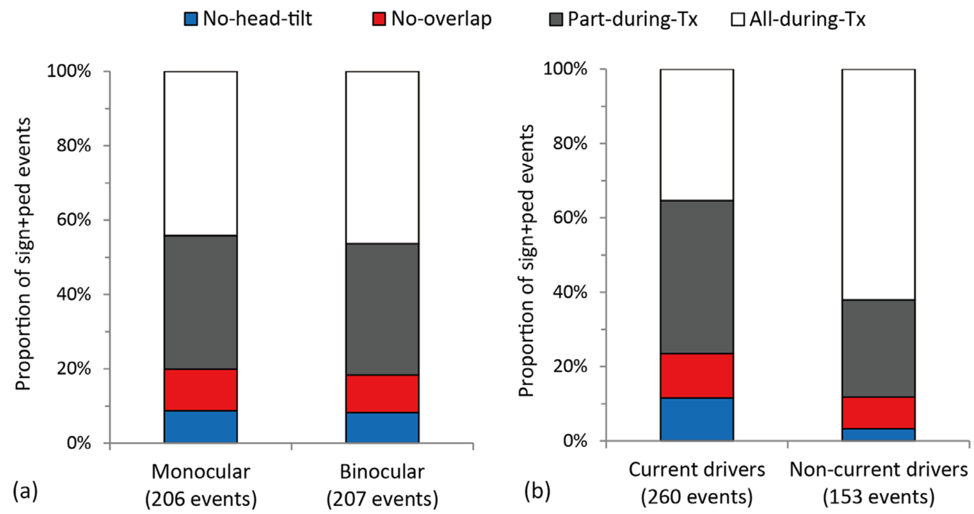


Figure 6. Percentage of each category of sign+pedestrian events (**a**) in monocular and binocular viewing conditions (**b**) for current drivers and non-current drivers. The distribution of the four categories did not differ between monocular and binocular viewing, but did differ between current and noncurrent drivers.

Table 3. Median (IQR) Times for Bioptic Use Timing Variables for Noncurrent and Current Drivers

Driving Status	Time from Sign to Head Tilt Down (s)	Total Duration of Bioptic Use (s)	Duration of Downward Head Movement (s)	Duration of Upward Head Movement (s)
Noncurrent ($n = 6$)	0.75 (0.60–0.92)	2.95 (1.90–3.12)	0.50 (0.47–0.57)	0.70 (0.47–1.05)
Current ($n = 10$)	0.82 (0.57–1.30)	1.66 (1.30–1.90)	0.38 (0.33–0.40)	0.48 (0.38–0.57)
All participants ($n = 16$)	0.75 (0.57–1.08)	1.86 (1.50–1.97)	0.42 (IQR 0.33–0.50)	0.51 (0.40–0.68)

and also took less time to complete both the downward ($z = 2.72$; $P = 0.007$) and upward ($z = 1.63$; $P = 0.10$) head movements (Table 3).

Pedestrian Detection Rates

Effects of Event Category

Detection rates (pooled across viewing condition and driving status) were close to ceiling for Never-during-Tx events and did not differ from detection rates for No-sign events (95% vs. 96%; $z = 0.36$; $P = 0.72$). By comparison, detection rates were significantly lower in Part-during-Tx (81%) and All-during-Tx events (51%) than No-sign events (96%; all $z > 4.3$; $P < 0.001$), and were significantly lower in All-during-Tx than Part-during-Tx events ($z = 5.44$; $P < 0.001$).

Effects of Viewing Condition

The effects of viewing condition were evaluated with data collapsed across driving status. Consistent with our hypothesis, there was a significant interaction between event category and viewing condition ($\chi^2 = 15.84$; $P = 0.001$; Fig. 7a). Detection rates were significantly higher in binocular than monocular viewing for All-in-Tx events ($z = 5.27$; $P < 0.001$), but did not differ between binocular and monocular viewing for Part-in-Tx events ($z = 0.62$; $P = 0.53$), and also did not differ between monocular and binocular viewing for No-sign ($z = 0.38$; $P = 0.71$) and Never-during-Tx events ($z = 0.05$; $P = 0.96$).

Effects of Driving Status

The effects of driving status were first evaluated with data collapsed across viewing condition. A significant interaction between event category and driving status was found ($\chi^2 = 9.79$; $P = 0.02$; Fig. 7b). Current drivers had significantly higher detection rates than noncurrent drivers for Part-during-Tx ($z = 2.18$; $P = 0.03$) and All-during-Tx events ($z = 2.48$; $P = 0.013$). However, detection rates for current and noncurrent drivers did not differ for Never-during-Tx ($z = 1.34$; $P = 0.18$) and No-sign events ($z = 0.60$; $P = 0.55$).

In a follow-up analysis, we examined the effects of viewing condition within the current and noncurrent driver groups for No-sign and All-during-Tx events. (There were insufficient data for Never-during-Tx and

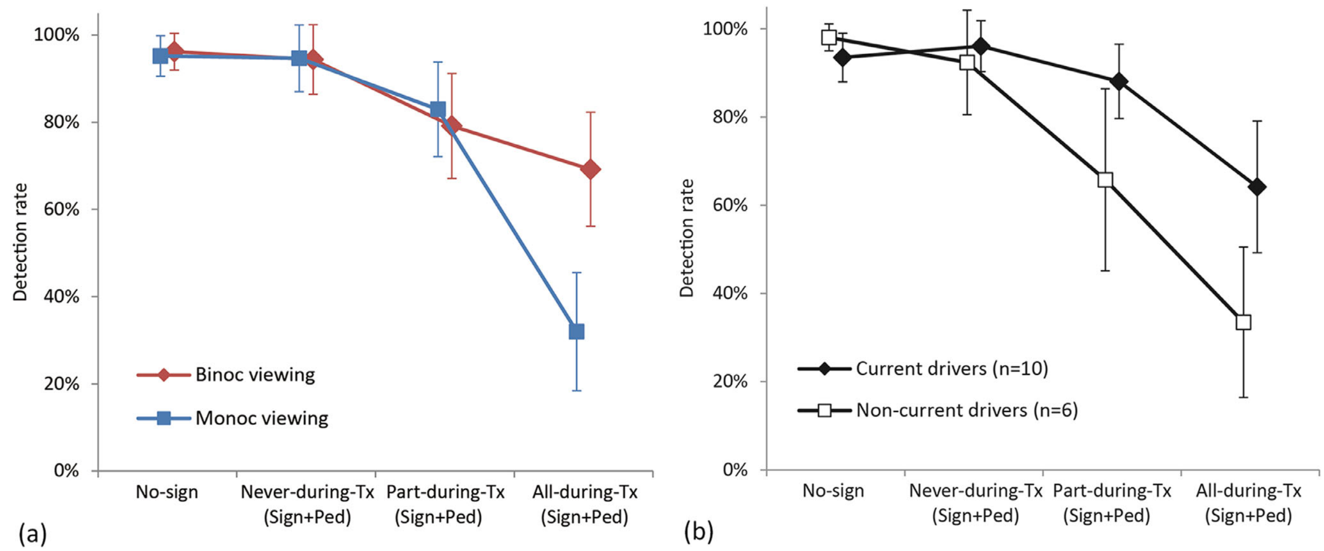


Figure 7. Mean detection rates for No-sign and sign+pedestrian (Sign+Ped) events for (**a**) binocular and monocular viewing conditions and (**b**) current and noncurrent drivers. Errors bars are 95% confidence intervals.

Table 4. Detection Rates by Driving Status and Viewing Condition for No-Sign and All-during-Tx Events

		No-Sign		All-during-Tx	
Driving Status Group	*n*	Monoc Viewing	Binoc Viewing	Monoc Viewing	Binoc Viewing
Current drivers	10	92%	96%	50%	78%
Noncurrent drivers	6	98%	97%	16%	59%
Former drivers	4	100%	100%	23%	60%
Nondrivers	2	94%	91%	6%	56%

Part-during-Tx events.) Both current and noncurrent drivers had higher detection rates in binocular than monocular viewing for All-during-Tx events, but not No-sign events (Table 4). Within the noncurrent group, both the four former drivers and the two nondrivers had higher detection rates in binocular than monocular viewing for All-during-Tx events, but not No-sign events. These results suggest that current, former, and nondrivers were all able to use the fellow eye to compensate for the ring scotoma in binocular viewing conditions.

Effects of a Scotoma in the Binocular Field

Four participants had a scotoma in the inferior binocular visual field (see Appendix) that might have impeded detection of pedestrians in binocular viewing. We examined the data for each of these participants separately. We expected that detection rates would not differ between monocular and binocular viewing for All-during-Tx events. Data are reported separately for each participant because they each behaved in a different way. No statistical analyses were conducted as there were insufficient data.

Participant S1, a highly experienced current driver with a complete device scotoma (Appendix Fig. A1), had too few All-during-Tx events to draw any conclusions about detection rates in monocular and binocular viewing (Table 5). Interestingly, among all participants, participant S1 had the highest rate of Never-during-Tx events in both monocular (46%) and binocular (69%) viewing. These results suggest that participant S1 may have been aware of the device scotoma in binocular viewing and attempted to compensate by waiting to see whether a pedestrian appeared before looking into the telescope to read a sign, as evidenced by the high rate of Never-during-Tx events. None of the other participants exhibited this behavior.

The three other participants with scotomas had all stopped driving. Participant S2 had an incomplete device scotoma in the lower visual field in binocular viewing (Appendix Fig. A2) and had higher detection rates for All-during-Tx events for binocular than monocular viewing (Table 5). Participant S3 had a

Table 5. Detection Rates for All-during-Tx Events in Monocular and Binocular Viewing for Each Subject with a Scotoma in the Lower Visual Field in Binocular Viewing

				Detection Rate: All-during-Tx Events	
Participant	Driving Status	Fellow Eye VA	Scotoma	Monoc Viewing	Binoc Viewing
S1	Current	20/126	Device, complete	1 of 3 (33%)	1 of 2 (50%)
S2	Former	20/126	Device, incomplete	4 of 9 (44%)	10 of 10 (100%)
S3	Former	20/200	Device, complete	0 of 5 (0%)	0 of 3 (0%)
S4	Former	20/502	Disease, 8° diameter	0 of 11 (0%)	4 of 11 (36%)

large, complete device scotoma in the lower visual field (Appendix Fig. A3) and, consistent with expectations, did not detect any pedestrians in either monocular or binocular viewing (Table 5). Finally, participant S4 with a small disease scotoma (8° diameter; Appendix Fig. A4) and very low fellow-eye VA had slightly higher detection rates in binocular than monocular viewing for All-during-Tx events suggesting that the fellow eye was partially able to compensate (Table 5). However, participant S4 still failed to detect the majority of pedestrians in binocular viewing indicating that either the scotoma and/or the low VA impaired detection to some extent in binocular viewing.

Reaction Times

Reaction times to pedestrians did not differ in binocular and monocular viewing conditions for any of the event categories (paired t-tests; all $P > 0.23$) and also did not differ between current and noncurrent drivers (independent sample t-tests; all $P > 0.10$). Reaction time data were, therefore, pooled across viewing condition and driving status for analyses and a repeated-measures ANOVA was conducted with event category as the within-subjects factor and median reaction times as the dependent variable. A highly significant effect of event category was found ($F(3,38) = 17.84$; $P < 0.001$). Compared to the No-sign events, reaction times were significantly longer for Part-during-Tx ($P < 0.001$) and All-during-Tx sign+pedestrian events ($P < 0.001$), but did not differ from reaction times in Never-during-Tx events ($P = 0.63$; Fig. 8). Furthermore, reaction times were significantly longer for All-during-Tx than Part-during-Tx events ($P = 0.006$).

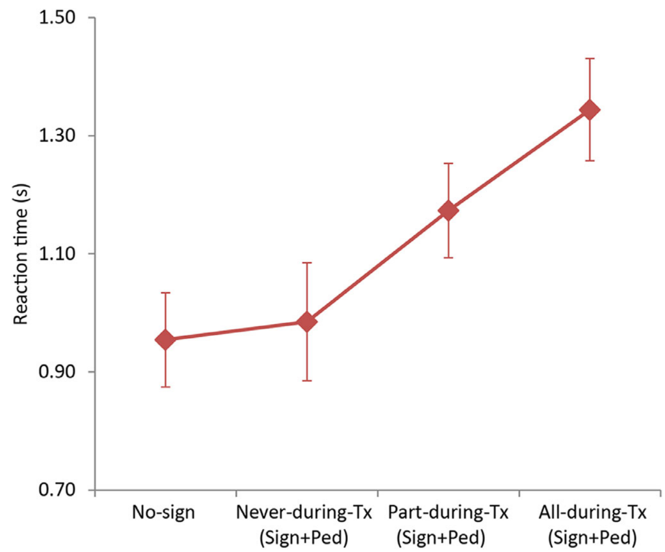


Figure 8. Mean reaction times for No-sign and Sign+Ped events. Errors bars are 95% confidence intervals.

Speed and Lane Position on Straight Road Segments

Participants drove at or very close to the maximum speed of 35 mph on all straight road segments, with no significant differences in speed between the three segment types (no sign and no pedestrian, sign but no pedestrian, and sign+pedestrian). There were also no significant differences in lane position between the three segment types; the average lane position of the participant's vehicle was median 0.34 meters (IQR, 0.13–0.57 meters) to the right of the center of their travel lane. In contrast, lane position variability was significantly greater in straight segments with sign+pedestrian events than in straight segments with only sign-reading events (medians 0.16 meters vs. 0.13 meters; $z = 2.03$; $P = 0.04$) and straight segments without either pedestrian or sign-reading events (medians 0.16 meters vs. 0.12 meters; $z = 2.61$; $P = 0.009$). Participants crossed the left boundary of the driving lane in only 2% of segments, but crossed the right boundary in 19% of segments. The proportion of straight road segments with at least one right boundary crossing was higher for sign+pedestrian events than sign-reading-only events (19% vs. 12%; $z = 1.92$; $P = 0.06$) and straight segments without either pedestrian or sign-reading events (19% vs. 7.4%; $z = 3.60$; $P < 0.001$).

Discussion

Consistent with our hypothesis, pedestrian detection rates were higher in binocular than monocular viewing for events where the pedestrian was in the scene only while participants were looking through their telescope (All-in-Tx events; Fig. 7a). In addition, as expected, for events where drivers had a glimpse of the pedestrian either before or after the brief telescope use (Part-during-Tx events), pedestrian detection rates did not differ between monocular and binocular viewing (Fig. 7a). These results provide strong evidence that the fellow eye was able to compensate for the ring scotoma when using a monocular bioptic telescope and are consistent with the results from our prior study[24] of normally sighted observers with simulated VA reductions using monocular bioptic telescopes.

Nevertheless, even in binocular viewing, detection rates were significantly lower for events where the pedestrian overlapped at least partially with the sign-reading task (Part-during-Tx and All-during-Tx events) than pedestrian events where there was either no overlap between the pedestrian and sign-reading task (Never-during-Tx events) or no sign-reading task (No-sign). Similar results were found in our prior study[24] in which normally sighted participants with simulated vision impairment used a monocular bioptic telescope to perform the same sign-reading task. A similar effect was also found in a separate study[23] when patients with reduced VA completed a reading task without a bioptic telescope while performing a video-based hazard perception task. Hazard detection rates were reduced when performing the reading task compared to when not performing the task, even when the task was performed without the telescope.[23] Taken together, these findings suggest that the additional processing resources devoted to engagement in using the telescope and/or reading the sign reduced those available for other tasks, such as detection of pedestrians. Performance on the sign-reading task was relatively high with correct response rates that did not differ between sign-reading with and without concurrent pedestrian hazard appearances. Thus, there was no evidence to suggest that participants were less engaged in the sign-reading task when there was a pedestrian hazard in the scene.

In contrast to detection rates, reaction times to pedestrian hazards did not differ between monocular and binocular viewing for any event type. However, reaction times did differ across event types. Reaction times were longer for All-during-Tx than Part-during-Tx events suggesting that detection was more difficult when the pedestrian was visible to the fellow eye only while looking through the telescope (All-during-Tx) than when there was a glimpse of the pedestrian available to both eyes before/after looking into the telescope (Part-during-Tx). It also took longer to respond to pedestrians in Part-during-Tx and All-during-Tx events than No-sign and Never-during-Tx events, again suggesting that additional processing resources devoted to using the telescope and/or reading the sign reduced those available for pedestrian detection.

Detection rates and reaction times did not differ for No-Sign and Never-during-Tx events (Figs. 6 and 7). Because Never-during-Tx events were those with no bioptic use (No-head-tilt) or with pedestrians in the scene only before or after the bioptic use (No-overlap), the sign-reading task was less likely to interfere with the detection task than when the two tasks were performed concurrently (Part-during-Tx and All-during-Tx events). Hence, pedestrian detection performance in Never-during-Tx events was likely to be similar to that in the No-sign events.

The sample of bioptic users included in the study was heterogeneous, as would be the case in clinical practice. Of the various demographic and vision characteristics that varied across the sample, we examined the effects of driving status and the presence of a scotoma in the inferior binocular visual field on the ability of the fellow eye to detect pedestrians within the area of the telescope-eye ring scotoma. Our findings suggest that driving status was not a major factor affecting the ability to use the fellow eye. Current, former, and nondrivers were all able to compensate, at least to some extent, and had detection rates that were higher in binocular than monocular viewing for All-during-Tx events (Table 4). However, it is important to note that overall detection rates were lower for noncurrent (former and nondrivers) than current drivers for events where the pedestrian appearance overlapped at least partially with the telescope use (All-during-Tx and Part-during-Tx events; Fig. 7b). Several factors could account for this difference, including the higher proportion of participants with a scotoma in the lower field in the noncurrent than the current driver group, as well as fewer years using a bioptic telescope and lower levels of daily bioptic use in the noncurrent driver group. In contrast, when pedestrians were detected, then reaction times did not differ between current and noncurrent drivers.

Consideration of the data from the participants with a scotoma in the inferior binocular field suggested that, in some cases, the scotoma did impact the ability to use the fellow eye. Two participants had a complete inferior device scotoma from the rectangular housing of an Ocutech VES Keplerian bioptic telescope: participant S1 appeared to adopt a strategy of waiting to see whether there would be a pedestrian before reading the sign, while participant S3 did not use any strategies and did not detect any pedestrians in either monocular or binocular viewing. In contrast the incomplete inferior device scotoma of participant S2 seemed to have no effect on pedestrian detection with 100% detection rates in binocular viewing. Participants S1 and S3 used higher magnification telescopes (4 × and 6 ×, respectively), than participant S2 (3 ×) resulting in larger inferior device scotomas, especially for participant S3. Thus, the results from these three participants suggest that a device scotoma, such as that from a monocular Ocutech VES Keplerian telescope, may impair detection of hazards and should be considered when prescribing a bioptic telescope specifically for driving.

Current drivers had better bioptic-use skills than noncurrent drivers. Although there was no significant difference between the two groups in the time taken to initiate the downward head movement after the sign appearance, current drivers took less time than noncurrent drivers to complete both the downward and upward head movements to look into and out of the telescope (Table 3). Furthermore, the total duration of the bioptic use was substantially shorter for current than noncurrent drivers (1.66 vs. 2.95 seconds, respectively). These results suggest that the current drivers were more skilled in using a bioptic telescope when driving and were consistent with the higher rates of self-reported daily bioptic use in the current than the noncurrent group (Table 2). Because the overall duration of the bioptic use was shorter for current than noncurrent drivers, there was a higher probability that the pedestrian would still be on the road after the end of the telescope use, which may, in part, explain the higher proportion of Part-during-Tx events and lower proportion of All-during-Tx events for current than noncurrent drivers (Fig. 6). By contrast, the longer bioptic-use durations for the noncurrent drivers meant that the pedestrians were more likely to disappear from the scene before the end of the bioptic use, and, thus, noncurrent drivers had more All-during-Tx events than Part-during-Tx events (Fig. 6). Interestingly, the proportion of All-during-Tx events for the group of noncurrent drivers in the current study was very similar to that found in our prior study[24] with normally sighted participants with simulated acuity loss who had little experience of using a bioptic telescope when driving. Being able to quickly exchange between looking through the bioptic and looking through the carrier lens (and vice versa), and looking only briefly through the bioptic are basic skills that bioptic drivers need to acquire to decrease the likelihood of a hazard being obscured by the ring scotoma.

In a recent naturalistic driving study, 477 hours of driving data were analyzed from recordings of daily driving of 19 bioptic drivers.[8] The median duration (1.4 seconds) for each bioptic use event in this habitual, on-road driving was very similar to the median duration of each bioptic use event for the current drivers in the current study (1.66 seconds). The similarity in the duration of bioptic uses between the two studies suggests that the bioptic use behaviors of the current bioptic drivers in our driving simulator were representative of real-world bioptic-use behaviors.

In a subset of participants ($n = 9$), we evaluated the effects of using a bioptic telescope on vehicle control. Bioptic use had no significant effects on average speed or lane position, but did have slight adverse effects on lane position variability. Average speed was close to 35 mph on all straight road segments suggesting that participants followed the instructions to drive as close to the maximum speed of 35 mph as possible. Average lane position was slightly (0.34 meters) to the right of lane center, consistent with the magnitude of the rightward lane positions of normally sighted and visually impaired observers driving along similar roads in prior studies in the same driving simulator.[26,27] Lane position was more variable in segments with sign+pedestrian events, compared with segments when not using the bioptic. However, the magnitude of the difference was relatively small and the variability was still well within the range of normally sighted participants in prior studies.[26,27] More variable lane position suggests that steering was less stable in sign+pedestrian events when using the bioptic and also responding to pedestrians. The average rightward lane position resulted in participants going out of lane to the right more often than to the left. The proportion of segments with rightward boundary crossings was significantly higher for segments with sign+pedestrian events than segments when not using the bioptic. Crossing the left lane boundary put drivers at risk for collisions with oncoming traffic, whereas crossing the right lane boundary had fewer consequences because the vehicle went onto the hard shoulder at the edge of the road. Interestingly, in an on-road study (also driving on the right),[28] bioptic drivers received worse ratings than controls for lane position and steering steadiness and drove more often over the right-hand than the left-hand lane marking. In that study,[28] bioptic drivers were tasked with using their bioptic to read every road sign along the route. However, it is not known whether lane position and steering steadiness were specifically worse when using the bioptic.

In summary, the results of this study suggest that both current and noncurrent bioptic drivers were able to use the fellow eye to compensate, at least in part, for the ring scotoma. However, a scotoma in the binocular visual field, either from a device or from ocular disease may limit the ability to compensate. The sign+pedestrian events were specifically designed to maximize the likelihood of a pedestrian being in the scene only during the period of bioptic telescope use. In the real world, however, it may be rare that a hazard would only be in the driving scene while the driver was looking through the telescope. In that regard, the Part-during-Tx events where the pedestrian was visible either before and/or after the telescope use are somewhat more representative of real world situations. Importantly, in those events there was no difference in detection rates between monocular and binocular viewing. Thus, we suggest that the ring scotoma of a monocular bioptic telescope is not a major safety concern, especially given that bioptic telescopes are typically used for only a very small proportion of total driving time.[7,8] However, detection rates were lower and reaction times longer for pedestrian appearances that overlapped with the bioptic use suggesting that the detection task was more difficult in this dual task situation. In sum, the ring scotoma seems to have little impact on pedestrian hazard detection in binocular viewing when the fellow eye can compensate. However, the divided attention conditions of using the telescope and/or reading a sign coincident with a hazard appearance decreases the likelihood that the hazard will be seen.

Acknowledgments

The authors thank Robert Goldstein for programming software.

Supported by National Institutes of Health (NIH) Grants R01-AG04197, R01-EY025677, R01-EY12890, S10RR028122, and P30EY003790.

Disclosure: **X. Tang,** None; **P.M. Bronstad,** None; **A.L. Doherty,** None; **M. Moharrer,** None; **E. Peli,** In-the-lens bioptic telescope design (P), Ocutech Inc. (F); **G. Luo,** None; **A.R. Bowers,** None

References

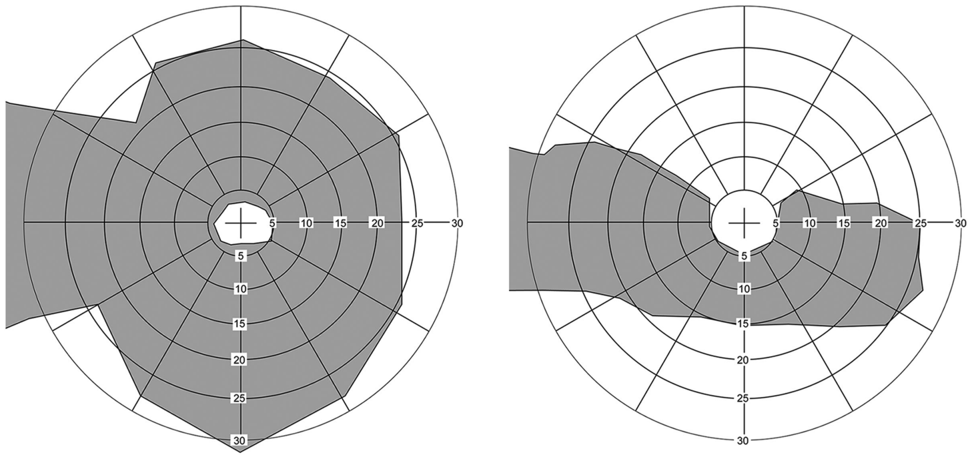
1. Peli E, Peli D. Driving with confidence: A practical guide to driving with Low vision. Singapore, River Edge, London, Hong Kong: World Scientific Publishing; 2002.
2. Peli E, Vargas-Martin F. In-the-spectacle-lens telescopic device. *J Biomed Optics*. 2008;13:1–11.
3. Carr DB, Schwartzberg JG, Manning L, Sempek J. Physician's guide to assessing and counseling older drivers, 2nd Edition. Chicago, IL, USA: American Medical Association: 2010.
4. Kooijman AC, Melis-Dankers BJM, Peli E, et al. The introduction of bioptic driving in the Netherlands. *Vis Imp Res*. 2008;10:1–6.
5. Melis-Dankers BJM, Kooijman AC, Brouwer WH, et al. A demonstration project on driving with reduced visual acuity and a bioptic telescope system in the Netherlands. *Vis Imp Res*. 2008;10: 7–22.
6. Vincent CL, Lachance JP, Deaudelin I. Driving performance among bioptic telescope users with low vision two years after obtaining their driver's license: A quasi-experimental study. *Assist Technol*. 2012;24:184–195.
7. Luo G, Peli E. Recording and automated analysis of naturalistic bioptic driving. *Ophthalmic Physiol Opt*. 2011;31:318–325.
8. Wang S, Moharrer M, Baliutaviciute V, Dougherty BE, Cybis W, Bowers AR, Luo G. Bioptic telescope use in naturalistic driving by people with visual impairment. *Transl Vis Sci Technol*. 2020;9:11.
9. Bowers AR, Apfelbaum DH, Peli E. Bioptic telescopes meet the needs of drivers with moderate visual acuity loss. *Invest Ophthalmol Vis Sci*. 2005;46:66–74.
10. Bowers AR, Sheldon S, deCarlo DK, Peli E. Bioptic telescope use and driving patterns of drivers with age-related macular degeneration. *Transl Vis Sci Technol*. 2016;5:5.
11. Chun R, Cucuras M, Jay WM. Current perspectives of bioptic driving in low vision. *Neuro-Ophthalmology*. 2016;40:53–58.
12. National higyway traffic safety administration. Available at: https://one.nhtsa.gov/people/injury/olddrive/olderdriversbook/pages/Massachusetts.html.
13. Fonda G. Bioptic telescopic spectacle is a hazard for operating a motor vehicle. *Arch Ophthalmol*. 1983;101:1907–1908.
14. Keeney AH. Field loss vs central magnification. *Arch Ophthalmol*. 1974;92:273.
15. Kelleher DK, Mehr EB, Hirsch MJ. Motor vehicle operation by a patient with low vision: a case report. *Am J Optom Arch Am Acad Optom.* 1971; 48: 773–776.

16. Feinbloom W. Driving with bioptic telescopic spectacles. *Am J Optom Physiol Opt*. 1977;54:35–42.
17. Lippmann O, Corn AL, Lewis MC. Bioptic telescopic spectacles and driving performance: A study in Texas. *J Vis Impair Blind*. 1988;82:182–187.
18. Doherty AL, Bowers AR, Luo G, Peli E. Object detection in the ring scotoma of a monocular bioptic telescope. *Arch Ophthalmol*. 2011;129:611–617.
19. Blake R, Zimba L, Williams D. Visual motion, binocular correspondence and binocular rivalry. *Biol Cybern*. 1985;52:391–397.
20. Blake R. A primer on binocular rivalry, including current controversies. *Brain and Mind*. 2001;2:5–38.
21. Dieter KC, Tadin D. Understanding attentional modulation of binocular rivalry: a framework based on biased competition. *Front Hum Neurosci*. 2011;5:155.
22. Doherty AL, Bowers AR, Luo G, Peli E. The effect of strabismus on object detection in the ring scotoma of a monocular bioptic telescope. *Ophthalmic Physiol Opt*. 2013;33:550–560.
23. Doherty AL, Peli E, Luo G. Hazard detection with a monocular bioptic telescope. *Ophthalmic Physiol Opt*. 2015;35:530–539.
24. Bowers AR, Bronstad PM, Spano LP, et al. Evaluation of a paradigm to investigate detection of road hazards when using a bioptic telescope. *Optom Vis Sci*. 2018;95:785–794.
25. Woods RL, Apfelbaum HL, Peli E. DLP-based dichoptic vision test system. *J Biomed Optics*. 2010;15:1–13.
26. Bowers AR, Mandel AJ, Goldstein RB, Peli E. Driving with hemianopia: II. Steering and lane position in a simulator. *Invest Ophthalmol Vis Sci*. 2010;51:6605–6613.
27. Bronstad PM, Albu A, Peli E, Bowers AR. Driving with central field loss III: Vehicle control. *Clin Exp Optom*. 2016;99:435–440.
28. Wood JM, McGwin G, Elgin J, Searcey K, Owsley C. Characteristics of on-road driving performance of persons with central vision loss who use bioptic telescopes. *Invest Ophthalmol Vis Sci*. 2013;54:3790–3797.

Appendix

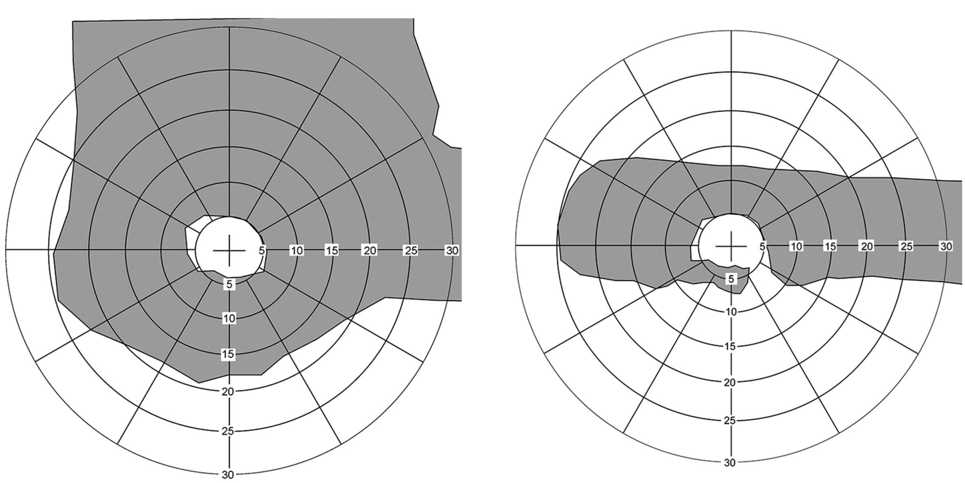
Visual field plots for participants with a scotoma in the binocular inferior field

The binocular visual field with the telescope eye viewing through the bioptic was measured when the subject had central visual field loss in the fellow eye that might overlap with the ring scotoma in the telescope eye to create a scotoma in the binocular visual field, or when the telescope might cause a scotoma in the binocular visual field (such as the Ocutech VES Keplerian telescope). Monocular and binocular visual fields for the four participants, S1, S2, S3, and S4, with a scotoma in the lower visual field are illustrated in Figs. A1–A4, respectively. Participants S1, S2, and S3 wore Ocutech VES 4 ×, 3 ×, and 6 × Keplerian bioptic telescope, respectively, in which the rectangular housing of the telescope is mounted across the top of both spectacle lenses. A large scotoma in the binocular visual field was caused by the rectangular housing of the telescope. Different from the others, participant S4 with macular holes used a 3.0 × Galilean monocular telescope, and the scotoma in the binocular visual field was where the ring scotoma of the telescope eye overlapped with the scotoma from the macula hole in the fellow eye.



(a) (b)

Figure A1. Visual field plots for participant S1 wearing an Ocutech VES 4 × Keplerian bioptic telescope in which the rectangular housing of the telescope is mounted across the top of both spectacle lenses. (**a**) Monocular visual field of the telescope (right) eye with the fellow (left) eye patched. (**b**) Binocular visual field showing a large scotoma in the inferior field and a partial scotoma in the upper field caused by the rectangular housing of the telescope.



(a) (b)

Figure A2. Visual field plots for participant S2 wearing an Ocutech VES 3 × Keplerian bioptic telescope in which the rectangular housing of the telescope is mounted across the top of both spectacle lenses. (**a**) Monocular visual field of the telescope (left) eye with the fellow (right) eye patched. (**b**) Binocular visual field showing an incomplete scotoma in the inferior field with a more complete scotoma in the upper visual field caused by the rectangular housing of the telescope.

translational vision science & technology

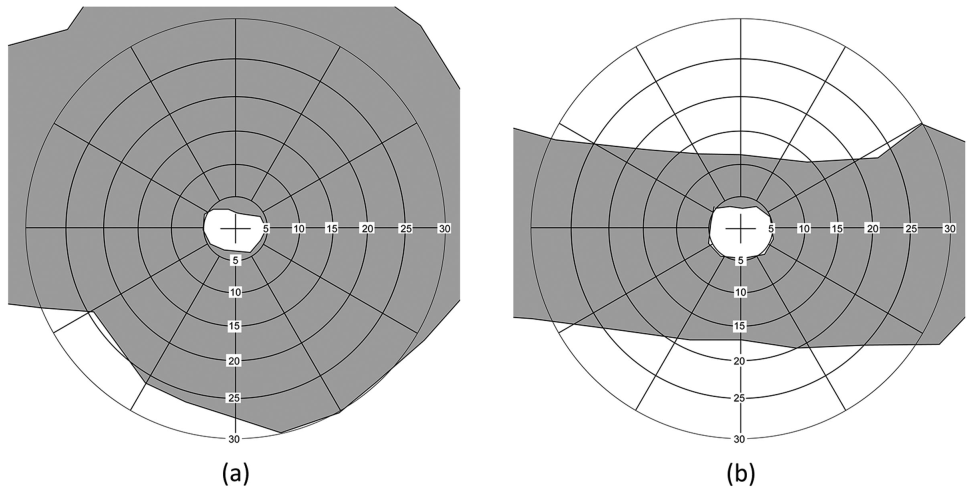


Figure A3. Monocular and binocular visual fields for participant S3 wearing Ocutech VES 6 × Keplerian bioptic telescope in which the rectangular housing of the telescope is mounted across the top of both spectacle lenses. (**a**) Monocular visual field of the telescope (right) eye with the fellow (left) eye patched. (**b**) Binocular visual field showing large scotomas in the superior and inferior fields caused by the larger rectangular housing of the telescope.

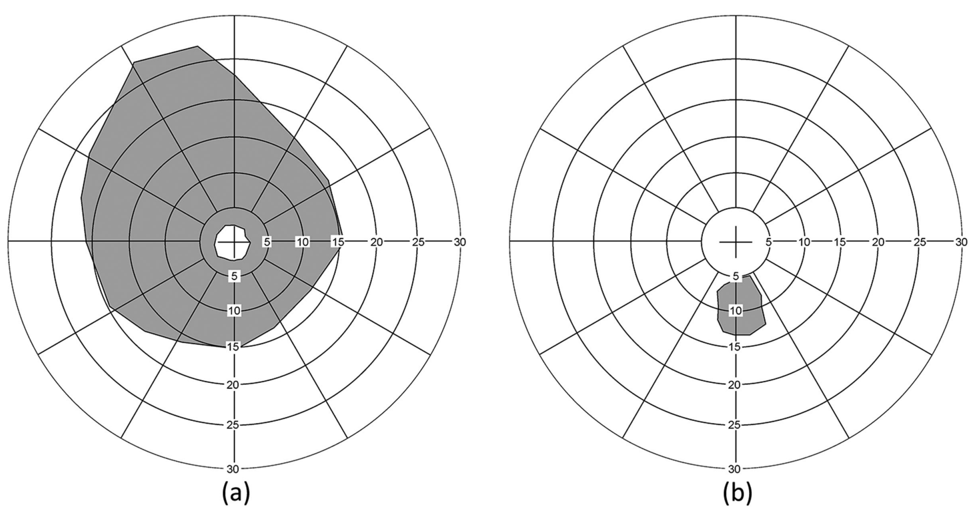


Figure A4. Visual field plots for participant S4 with macular holes (in the right eye) looking through a 3.0 × Galilean monocular telescope. (**a**) Monocular visual field of the telescope (left eye) with the fellow (right) eye patched. (**b**) Binocular visual field showing a small scotoma in the inferior field where the ring scotoma of the telescope eye overlapped the disease scotoma from the macula hole in the fellow (right) eye.