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Evaluation of a Paradigm to Investigate Detection of Road Hazards when Using a Biotopic Telescope

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Abstract

Significance—A new driving simulator paradigm was developed and evaluated which will enable future investigations of the effects of the ring scotoma in biotopic drivers with diverse vision impairments and different telescope designs.

Purpose—The ring scotoma may impair detection of peripheral hazards when viewing through a biotopic telescope. To investigate this question, we developed and tested a sign-reading and pedestrian-detection paradigm in a driving simulator.

Methods—12 normally sighted subjects with simulated acuity loss (median 20/120) used a 3.0× monocular bioptic to read 36 road signs while driving in a simulator. Thirteen of 21 pedestrian hazards appeared and ran on the road for 1 s within the ring scotoma while participants were reading signs through the bioptic. Head movements were analyzed to determine whether the pedestrian appeared before or only while using the bioptic. Six subjects viewed binocularly and six viewed monocularly (fellow eye patched). Two patients with real visual acuity loss in one eye and no-light perception in the other performed the same tasks using their own telescopes.

Results—For the monocular simulated acuity loss group, detection rates were significantly higher when the pedestrian appeared before using the bioptic than when it appeared while using the bioptic and was likely within the area of the ring scotoma; 77% vs. 28%, $p < 0.001$. For the binocular simulated acuity loss group, there was no significant difference in detection rates for pedestrians that appeared before or while using the bioptic; 80% vs. 91%, $p = 0.20$. The two monocular patients detected only 17% of pedestrians that appeared while looking through the bioptic.

Conclusions—Our results confirm the utility of the testing paradigm and suggest that the fellow eye of normally-sighted observers with simulated acuity loss was able to compensate for the ring scotoma when using a monocular bioptic telescope in a realistic driving task.

Keywords

bioptic telescope; scotoma; hazard detection; low vision; driving; central vision loss

Bioptic telescopes, small spectacle-mounted telescopes for people with central vision loss, are now permitted for driving in 45 US states,¹ The Netherlands,^{2,3} and the province of Quebec, Canada.⁴ However, the safety of bioptic use for driving has been questioned by some.^{5,6} Bioptic drivers look through the carrier lens most of the time.⁷ When magnification is needed, *e.g.*, to read a road sign, the wearer tilts his or her head down to view through the telescope.⁸ Glances through the telescope are usually brief and infrequent.⁷ When viewing through a telescope, the magnified view on the retina covers part of the image available in the unmagnified view creating a ring scotoma, an annulus-shaped area not visible to the eye viewing through the telescope.⁹ Some have claimed that the ring scotoma impairs detection of important objects and events^{10,11} while others have argued that the fellow (non-telescope) eye can compensate.^{12,13} If monocular telescopes are used, the ring scotoma surrounds the magnified view in the telescope eye only, so it may be possible for the fellow eye to compensate.⁹ However, if binocular telescopes are used (as permitted in some states¹⁴), then the fellow eye cannot compensate because the ring scotoma is present in the binocular view.

When using a monocular telescope, the difference in retinal image size between the magnified and unmagnified views may cause binocular rivalry,¹⁵ which could impair the ability of the fellow eye to compensate if the magnified image predominates. In the extreme case, the fellow eye might even be suppressed. We have conducted a series of studies^{9,16,17} to evaluate the ability of the fellow eye to compensate for the ring scotoma when using a monocular bioptic telescope in perimetry-like conditions (which did not include any driving tasks). In a relatively simple situation, with static stimuli presented over stationary backgrounds, we found that the fellow eye was able to fully compensate for the ring

scotoma.⁹ In more realistic conditions, however, which involved detection of hazards in driving videos, the fellow eye was not able to fully compensate, but still detected 50% of hazards.¹⁷ When using a video background, the increase in motion velocity in the magnified view, compared to the unmagnified fellow eye view, could enhance binocular rivalry,¹⁸ which may explain the reduced fellow-eye detection for hazards in the driving videos¹⁷ compared to the stationary background condition in the earlier study.⁹

Although our prior studies demonstrated that people with central vision loss are able to compensate for the ring scotoma through bi-ocular multiplexing,¹⁹ participants did not perform any driving tasks such as steering or controlling vehicle speed while using the telescope. Moreover, the test paradigms involved viewing through the telescope either for several minutes^{9,16} or several seconds,¹⁷ which is not representative of how bioptic telescopes are used when driving. In on-road driving, even if the ring scotoma were to obscure a hazard, the bioptic driver might still have a chance to see the hazard if he looks only briefly through the bioptic.

It would be impractical to conduct an on-road study to systematically evaluate the effects of a ring scotoma on hazard detection while driving. However, it is possible to do so within the safe, controlled and repeatable environment of a driving simulator. For the present study we, therefore, developed a paradigm to measure detection of driving hazards with natural use of a telescope in a driving simulator. The paradigm involved three main tasks: (1) Viewing through a bioptic telescope to read road signs; (2) Pressing the horn whenever a pedestrian hazard was seen; and (3) Controlling vehicle steering. Some of the pedestrian hazards were programmed to appear within the expected area of the ring scotoma when participants were performing the sign-reading task with the bioptic telescope (named sign+pedestrian events). Using these sign+pedestrian events we were able to test the ability of the fellow eye to compensate for the ring scotoma when using a monocular bioptic telescope. Specifically, we expected higher detection rates for pedestrians that appeared during the period of telescope use when participants were viewing binocularly and the fellow eye could compensate than when they were viewing monocularly with the fellow eye patched so that it could not compensate.

There were a number of design challenges to overcome in developing the driving simulator paradigm, not least ensuring that the pedestrian hazards appeared in the scene around the time the bioptic telescope was being used. Before embarking on our main study of bioptic drivers with real central vision loss, we conducted an initial study to thoroughly test the paradigm using normally-sighted observers with simulated visual acuity loss. The study had two aims: (1) To quantify event timings to ensure that the paradigm was robust; and (2) To test our main hypothesis that pedestrian detection rates would be higher in binocular than monocular viewing conditions when using a monocular bioptic telescope.

A simulation of vision impairment was used for two main reasons. Firstly, the simulated vision loss required the normally-sighted subjects to use the telescope in order to be able to read the signs and imposed a realistic level of difficulty in detecting the pedestrians through either of the carrier lenses. Secondly, the bioptic driving population is very heterogeneous in nature²⁰ with a wide range of ocular conditions, type and degree of vision impairment,

amount of bioptic driving experience, amount and type of bioptic training, and types of telescope used, all of which could affect detection of hazards when using a bioptic. Therefore, by using normally-sighted subjects with simulated acuity loss who all used the same bioptic and were given the same amount of training, we were able to study the ability of the fellow eye to compensate for the ring scotoma without potential confounding factors likely to be present in a group of bioptic drivers with real acuity loss.

METHODS

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.

Driving Simulator Task

Apparatus—The simulator was a DE-1500 (FAAC Corp., Ann Arbor, MI), with five LCD monitors (42" diagonal, 1366×768 pixels, 60Hz) providing 225° field of view. The simulator had controls typical for a car with automatic transmission and a 3 degrees-of-freedom motion seat. Data from the simulator stream, including the location and status of all programmed objects and the driver's car in the virtual world, were continuously recorded at 30Hz. A Smart Eye remote six-camera IR system (Smart Eye Pro 6.1, Gothenburg, Sweden) was used to track head movements based on facial features at 60Hz. Eye position was also recorded; however, the data were very noisy with many drop outs due to difficulties in tracking the eyes through the diffusing filters. Therefore, only head data were used in analyses. 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.

Scenarios—Three driving scenarios were developed using the Scenario Toolbox software (FAAC Corp., Ann Arbor, MI). Each scenario was about 10 minutes and involved driving on rural roads with light oncoming traffic. Directional road signs were added to each scenario, based on Standard Highway Signs in color, font, and text spacing (as defined in the Manual of Uniform Traffic Control Devices http://mutcd.fhwa.dot.gov/ser-shs_millennium.htm). Signs were custom designed with navigational information relevant to a telescope user while driving (Figure 1). Participants verbally reported two pieces of information from each sign: the distance (0.3 or 0.8 miles) and the last part of the street name (Ave or Pike). There were four possible permutations.

The signs appeared at pseudo-random time intervals with 12 sign events in each of the three scenarios ($12 \times 3 = 36$ total events). Each sign was programmed to appear when the participant's car was approximately 88 m away. For 13 of the total 36 sign events, a pedestrian (2m tall) was programmed to appear on the road ahead within the area of the monocular ring scotoma while the participant was reading the sign through the telescope (sign+pedestrian event; Figure 2). The pedestrian ran across the participant's driving lane either from left to right or right to left. In addition to these 13 sign+pedestrian events, there were eight other events across the three scenarios in which running pedestrians (included in analyses) appeared without signs (no-sign events), as well as stationary pedestrians ($n = 10$

total, 3 to 4 per scenario; not included in analyses) to add variety to the detection task and obfuscate the demand characteristics.

To assist in designing the sign+pedestrian events, we collected head-tracking data from four experienced bioptic drivers while they performed a pilot version of the sign-reading task in the driving simulator. Typically, they started to dip their head to look into the bioptic about 0.7 s after the sign appeared. We therefore programmed pedestrians to appear about 1 s after the sign, i.e., after the head dip was likely to have started. To create a brief but very imminent hazard, pedestrians were programmed to run for about 1 s across the travel lane ahead of the participant's car and then disappear before the sign-reading task was anticipated to be finished. Ultimately, 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.

Driving Simulator Procedures—Participants were instructed to use the 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. Before data collection, participants completed a series of practice drives to become familiar with controlling the vehicle, using the telescope while driving in the simulator and responding to pedestrians by pressing the horn. For normally-sighted subjects, the practice drives were conducted with the simulated visual acuity loss and the bioptic telescope under binocular viewing conditions for the binocular group and monocular viewing conditions (fellow eye patched) for the monocular group. Normally-sighted subjects practiced using the telescope to read signs for at least 10 to 15 minutes.

For all participants, a 5-point calibration of the SmartEye tracker was performed before experimental data collection commenced. Participants then completed three test scenarios in counterbalanced order. After accelerating at the start of each scenario, speed was then maintained at a maximum of 35 mph to control the timing of events across participants. Participants could use the brakes to slow down when necessary and the accelerator to increase speed back to 35 mph. They had full control of vehicle steering and were encouraged to keep the vehicle within the travel lane. The driving simulator session typically lasted about 90 minutes including practice and test drives.

Timing and Categorization of Sign+Pedestrian Events—For each sign+pedestrian event, a plot of vertical head position with the timings of sign appearance, pedestrian appearance and disappearance was generated. The plots were then manually examined to determine the timing of (a) the pedestrian appearance relative to the start of the downward head movement (T1 on Figure 3), and (b) the pedestrian disappearance relative to the end of the upward head movement when the participant emerged from the telescope (T2 on Figure 3). A binary classification was used: the pedestrian was either present in the scene only during telescope use (All-during-Tx) or for part of the telescope use (Part-during-Tx). All-during-Tx events included those events when the pedestrian appeared after T1 and disappeared before T2. Part-during-Tx events included those events when the pedestrian appeared before T1 and/or did not disappear until after T2.

Plots were reviewed and classified by author BH and then independently checked by author AD. Any disagreement or classification uncertainties were reviewed and discussed with authors ARB and LS. Subsequently, a computer program was developed to mark the time points T1 and T2 on each plot for final verification of the classifications. The timing of the start of the downward head movement was quantified by computing the time between the sign appearing and T1, and the time between the pedestrian appearing and T1.

Normally-sighted Subjects

Twelve normally-sighted current drivers (age 24-32 years, 58% male) with at least two years of driving experience were recruited from the subject database at Schepens Eye Research Institute. They were aged between 24 and 32 years, representative of the age at which individuals with congenital or early onset vision loss are often first licensed to drive with a bioptic telescope.²⁰ They all had binocular visual acuity of at least 20/20 (either without spectacle correction or with contact lenses) and stereo acuity of at least 30' (Randot Stereo Test, Stereo Optical, Chicago, IL). They were screened to ensure there was no history of ocular disease, binocular vision problems, strabismus or amblyopia. All were naïve to bioptic telescopes. They all used a monocular 3.0× spectacle-mounted Galilean bioptic telescope (Designs for Vision Inc., Ronkonkoma, NY) on their sighting dominant eye, which was determined using the hole-in-the-card test.²¹

Vision measurements, ring scotoma measurements and a laboratory bioptic practice task were all completed prior to the driving simulator session. Normally-sighted subjects were randomly assigned to one of two groups. The binocular group (n = 6) completed the driving simulator task under binocular viewing conditions while the monocular group (n = 6) completed the driving simulator task under monocular viewing conditions with the fellow eye patched.

Simulated Acuity Loss—Vision loss was simulated using Bangerter diffusing filters (Fresnel Prism & Lens Co., Eden Prairie, MN), which reduced both visual acuity and contrast sensitivity (Tables 1 and 2). A 0.1 grade Bangerter filter was placed on the back surface of the plano carrier lenses in the spectacles on which the bioptic was mounted. A 0.1 filter was also placed on the back of the bioptic eyepiece. The aim was to reduce visual acuity so that it was within the range typical for bioptic users (e.g., 20/60 to 20/200)^{20, 22, 23} and to also ensure that subjects could not read the signs in the driving simulator through the carrier lens. If visual acuity with the 0.1 filter was better than 20/60 through the carrier lens, an extra 0.4 filter was added to the front surface of that lens (but not the telescope eyepiece due to difficulties with adherence of the extra filter). Reading caps were used to focus the telescope at the viewing distance used for the visual acuity measurement with the telescope and when driving in the simulator.

Vision Measures—Single letter visual acuity was measured (TestChartPro2000, Thomson Software Solutions, Herts, England) monocularly and binocularly with and without the diffusing filters at 1 m (similar to the viewing distance in the driving simulator). Acuity was also measured monocularly through the telescope at 1 m (Table 1). Contrast sensitivity was

measured with and without the diffusing filters at 45 cm using a custom computerized program for letters subtending 2.5° of visual angle, equivalent to the Pelli–Robson chart.

Measuring the Ring Scotoma—A computerized tangent-screen perimetry system²⁴ was used to plot the ring scotoma. Participants sat 1 m from a large rear-projection screen (1.65 × 1.25m) displaying a white cross (0.2°×1.2°, 140 cd/m²) against a uniform black background (0.21 cd/m²). To measure the size of the ring scotoma, the fellow eye was patched and participants fixated on the cross through the telescope while in a chin rest. The experimenter moved a white square stimulus (1.9°) along 7 meridians (180°, 210°, 240°, 270°, 300°, 330° and 0°) to map the lower extent of the ring scotoma starting in an area occluded by the ring scotoma and moving either toward or away from the cross to measure the inner and outer boundaries, respectively. Participants pushed a button as soon as they saw the stimulus inside or outside the telescope. Only the lower extent of the ring scotoma was mapped because this was the area in which the pedestrian hazard would appear in the driving simulator. The median field of view through the telescope was 10° diameter and the median width of the lower area of the ring scotoma (the distance between the inner and outer edges of the annulus, see Figure 2) was 9°, consistent with the 3.0× magnification.

Laboratory Bioptic Practice Task—All normally-sighted subjects practiced using the bioptic under binocular viewing conditions while sitting 1 m from a large rear-projection screen. They practiced locating alphanumeric characters while viewing through the diffusing filter on the carrier lens and then dipping the head to view the detail through the bioptic. The characters were presented over driving video backgrounds and could not be resolved through the blurring filter on the carrier lens. While subjects were reading the characters through the bioptic, peripheral detection performance was probed by the presentation of checkerboard targets within and outside of the area of the monocular ring scotoma. All of the normally-sighted subjects were able to detect targets presented inside the ring scotoma area with the fellow eye when reading through the telescope. This laboratory bioptic practice task typically took about 15 minutes and was completed before subjects practiced reading signs with the bioptic while driving in the simulator.

Monocular Patients with Real Acuity Loss

Two bioptic telescope users who each had only one functioning eye completed the same series of tests as the monocular simulated acuity loss group. They each used their own 3× Ocutech mini bioptic telescope. Participant S1 (32 years) with monocular vision since birth due to retinopathy of prematurity had been using a bioptic for 9 years. Participant S2 (64 years) with monocular vision for 3 years resulting from ocular injuries in a road accident had been using a bioptic for 2 years. Their vision data are summarized in Tables 1 and 2.

Statistical Analyses

All statistical analyses were performed with STATA/IC 14 (College Station, TX). A value of $\alpha = 0.05$ was taken to indicate statistical significance.

Normally-sighted Subjects with Simulated Acuity Loss—For the normally-sighted subjects, head movement data were available for 155 of the total 156 sign+pedestrian events.

For four of these events (all in the binocular group), the subject never looked into the telescope; these four events were excluded from analyses.

A mixed effects binary logistic regression analysis was used to evaluate the effects of group (monocular or binocular), event category (All-during-Tx or Part-during-Tx) and their interaction on whether pedestrians were detected in the sign+pedestrian events. Subject was included as a random factor. Visual acuity and contrast sensitivity with blur through the carrier lens varied amongst the subjects. However, preliminary analyses indicated that neither acuity nor contrast sensitivity was a significant factor affecting whether a pedestrian was detected.

Reaction time data for events where the pedestrian was detected did not conform to a normal distribution, even after a log transform. Median reaction times were therefore computed for each subject for All-during-Tx, Part-during-Tx and no-sign pedestrian events and were analyzed with non-parametric statistics. Reaction times were measured from the time of the pedestrian appearance to the horn-press response (Figure 3).

The timing, T1, of the start of the downward head tilt was examined for sign+pedestrian events. Median values were computed for each subject for the time between the sign appearing and T1, and the time between the pedestrian appearing and T1. The medians were analyzed with non-parametric statistics.

Monocular Patients with Real Acuity Loss—For the two participants with real acuity loss, head movement data were available for all of the sign+pedestrian events (13 per participant). Detection rates, reaction times and head tilt timings were summarized with descriptive statistics.

RESULTS

Sign-reading Task Performance

Correct response rates (correctly identifying both pieces of information on the sign) were uniformly high for signs without pedestrians and signs with pedestrians. This was true for both the monocular and binocular acuity loss groups (range 98 - 99%) and also for the two patients with real acuity loss (range 94% to 100%). For sign+pedestrian events, there was no difference in correct response rates on the sign reading task between when the pedestrian was seen and not seen (98% and 100%, respectively, data pooled across the two simulated acuity loss groups).

No-sign Events Detection Performance

Detection rates for pedestrians not coincident with signs (no-sign events) were at ceiling in both the monocular and binocular groups (100% and 100%, respectively, Figure 4) and reaction times did not differ between the two groups (medians 0.88 s and 0.85 s, respectively, $z = 0.33$, $p = 0.75$). For the two patients with real acuity loss, S1 detected 89% (7/8) of no-sign pedestrians with a median reaction time of 1.00 s and S2 detected 100% of no-sign pedestrians with a median reaction time of 0.80 s.

Sign+Pedestrian Events

Timing of Events—The median time between the sign appearing and the pedestrian appearing was 1.0 s (interquartile range (IQR) 0.9 to 1.0 s) and the pedestrian was in the scene for median 1.1 s (IQR 0.9 to 1.4 s).

For subjects with simulated acuity loss (data pooled across monocular and binocular groups), the median time between the sign appearing and the start of the downward head tilt was 0.79 s (IQR 0.69 to 0.87 s) with the pedestrian appearing median 0.21 s (IQR 0.12 s to 0.28 s) after the start of the head tilt. Interestingly, the binocular group looked into the telescope more quickly than the monocular group after the sign appeared (Table 3; $z = 2.25$, $p = 0.025$) which meant that pedestrians appeared relatively later after the start of the downward head tilt for the binocular than the monocular group (Table 3; $z = 2.33$, $p = 0.02$).

A more detailed breakdown of event timings for the binocular and monocular simulated acuity loss groups, and the two patients with real acuity loss, for All-during-Tx and Part-during-Tx events are reported in Table 3. The time from the start of the head tilt down to the pedestrian appearance is plotted in Figure 5.

Event Categorization—For subjects with simulated acuity loss, the majority of sign +pedestrian events were All-during-Tx events (73%; 110/151) in which the pedestrian appeared *after* the start of the downward head tilt and disappeared before the end of the upward head movement. The remaining events (27%; 41/151) were Part-during-Tx events, in which the pedestrians mostly appeared *before* the subject looked into the telescope (39/41 events). Because the binocular group looked into the telescope more quickly than the monocular simulated acuity loss group (Table 3), the proportion of All-during-Tx events was significantly higher in the binocular than the monocular simulated acuity loss group (Figure 6; $\beta = 1.46$, $z = 3.55$, $p < 0.001$). The proportion of All-during-Tx and Part-during-Tx events for the binocular and monocular simulated acuity loss groups, and the two patients with real acuity loss are summarized in Figure 6.

The proportion of All-in-Tx events was similar in the first two drives of the simulator session (67% and 66% respectively), but higher (83%) in the third drive, suggesting a lack of learning effects. If, after a sign appearance, participants had purposefully waited before looking into the telescope to determine whether a pedestrian appeared, then we would have expected a lower proportion of All-in-Tx events in the last drive of the session, but we found the opposite.

Detection Performance—For subjects with simulated acuity loss, overall pedestrian detection rates were significantly lower for All-during-Tx than Part-during-Tx events (65% and 80%, respectively, data pooled across the two groups, $\beta = -2.73$, $z = 4.06$, $p < 0.001$). However, there was a significant interaction between event classification and group ($\beta = 4.09$, $z = 3.12$, $p = 0.002$). Specifically, pedestrian detection rates were significantly lower for All-during-Tx than Part-during-Tx events in the monocular simulated acuity loss group (28% vs. 77%; $\beta = -2.47$, $z = 3.86$, $p < 0.001$, Figure 4) but not the binocular group (91% vs. 71%; $\beta = 1.6$, $z = 1.28$, $p = 0.20$, Figure 4). For Part-during-Tx events, the likelihood of a pedestrian being detected depended on the time between the pedestrian appearance and the

start of the downward head tilt (Figure 7). If the pedestrian appeared more than 0.5 s before the start of the head tilt, it was always seen. However, if it appeared less than 0.5 s before the head tilt, it was sometimes not seen.

For the monocular patients with real acuity loss, detection rates were also very low for All-during-Tx events with S1 detecting only 1/8 pedestrians and S2 detecting 2/10 pedestrians. For the Part-during-Tx events, the pedestrian appeared median 0.20 s for S1 and 0.07 s for S2 before the start of the head tilt with S1 detecting 2/5 pedestrians and S2 detecting 0/3 pedestrians. This low number of detections in the Part-in-Tx events by the two patients is likely because the pedestrian appeared less than 0.5 s before the head tilt.

Reaction times to pedestrians in sign+pedestrian events did not differ between the monocular and binocular simulated acuity loss groups (medians 1.2 s and 1.1 s, respectively, $z = 0.24$, $p = 0.81$); therefore, the data were combined across the two groups for analyses. Reaction times to pedestrians were significantly longer for All-during-Tx than Part-during-Tx events ($z = 2.07$, $p = 0.038$; Figure 8). However, reaction times to no-sign pedestrians were significantly shorter than to pedestrians in All-during-Tx ($z = 2.81$, $p = 0.005$) and Part-during-Tx events ($z = 2.90$, $p = 0.004$; Figure 8). The two patients with real acuity loss detected a total of only 5 pedestrians in sign+pedestrian events, therefore summary statistics were not computed; however the reaction times were in the range 1.3 to 3.8 s.

DISCUSSION

We developed and implemented a new paradigm to evaluate detection of pedestrian hazards presented in the ring scotoma when reading a road sign through a bioptic telescope in a driving simulator. The results confirmed that the timing of the pedestrian appearance coincided well with use of the bioptic telescope by naïve normally-sighted observers with simulated visual acuity loss (median 20/120) and two bioptic users with real acuity loss. Consistent with our main study hypothesis, under monocular viewing conditions the bioptic greatly impaired the detection of pedestrians in the ring scotoma area (detection rates of 28% for the All-during-Tx events compared to 100% without the telescope for subjects with simulated acuity loss). However, under binocular viewing conditions, the fellow eye was largely able to compensate for the ring scotoma (detection rates of 91% for All-during-Tx events for subjects with simulated acuity loss). Nevertheless, using a bioptic did impair hazard detection to some extent. Even in binocular viewing, detection rates of subjects with simulated acuity loss were lower and reaction times were longer than for hazards which appeared when not using the bioptic.

Results from the All-during-Tx events for the monocular simulated acuity loss group and the two monocular bioptic users confirmed that most of the pedestrians remained within the ring scotoma area, as planned, because the majority was not detected. Nevertheless, some of the All-during-Tx pedestrians were detected possibly because part of the pedestrian, such as the lower legs, was visible below the ring scotoma. Pedestrian location relative to the monocular ring scotoma depended on vehicle speed and heading as well as the participant's head position, all of which could vary. On the one hand, this could be considered as a limitation in our experimental design. However, we argue that it is not a limitation, but rather creates

conditions more similar to the real world, where it is quite possible that a hazard is partially within the area of the ring scotoma.

In on-road driving it is also unlikely that a pedestrian hazard would only be present when looking through a telescope. Thus, the Part-during-Tx events provided results relevant to situations in which a hazard might appear while a driver is preparing to look through a telescope. Importantly, both the binocular and monocular simulated acuity loss groups had relatively high detection rates (at least 80%) when they had a glimpse of the hazardous pedestrian before looking into the telescope (Figure 4). Pedestrians that appeared more than 0.5 s before the start of the downward head tilt were all detected, whereas some of the pedestrians appearing within 0.5 s of the head tilt were not detected (Figure 7). For the two patients with real acuity loss, all pedestrians in the Part-during-Tx events appeared less than 0.5 s before the start of the downward head tilt (median 0.20 s for S1 and 0.07 s for S2), which likely accounts for why only 2 of 8 were detected.

Interestingly, subjects in the monocular simulated acuity loss group were slower to look into the telescope than subjects in the binocular group which resulted in a higher proportion of Part-during-Tx events for the former group. The reason for this between-group difference in the timing of the downwards head tilt is unknown. It might be that subjects with simulated acuity loss in the monocular group were more hesitant to look into the telescope when driving under the unfamiliar monocular viewing conditions.

Performance on the sign-reading task was very high and there were only 4 of the critical sign +pedestrian events for which a subject with simulated acuity loss did not use the bioptic telescope. There was no evidence to suggest any trade-off between performance on the detection task and the sign-reading task. Our results suggest that normally-sighted subjects were able to learn to use the telescope quickly and effectively, consistent with the findings of a study by Tadin et al.²⁵ in which normally-sighted observers with simulated visual acuity of 20/200 used a bioptic telescope to locate and identify letters in a laboratory task. To place our findings in context, the training requirements for bioptic drivers vary widely in the US from states that require intensive training programs (including classroom, passenger-in-car and behind-the-wheel training) to states that have no specific training requirements.²⁶

Simulated vision impairment has been widely used in prior on-road^{27–30} and laboratory^{31, 32} studies addressing the effects of reduced visual acuity and reduced contrast sensitivity on driving. Although simulations do not reproduce all of the characteristics of real vision impairment, they do enable a more homogeneous level of vision impairment to be created. The behaviors of normally-sighted observers, exposed to simulations for only a short period of time, might differ from those that develop as individuals adapt to their vision impairment over a longer period of time. However, our results suggest that in our driving simulator paradigm, the simulation of acuity loss in normally-sighted subjects resulted in bioptic use behaviors that were within the range of those exhibited by the two patients with real acuity loss.

Subjects with simulated acuity loss all used the same 3× monocular bioptic telescope. We did not evaluate the ability of the fellow eye to compensate when using telescopes of other

powers. Nevertheless, it seems reasonable to suggest that similar results would have been obtained with other levels of magnification (assuming monocular bioptic telescopes of a similar design). We also did not evaluate binocular bioptic telescopes. However, our results suggest that detection of hazards would likely be more impaired when using a binocular telescope, because the ring scotoma would be present in the binocular view, than when using a monocular telescope under binocular viewing conditions where the fellow eye could compensate. Monocular telescopes are more commonly used by bioptic drivers than binocular telescopes,²⁰ which are prohibited in some states.¹⁴

In this study the fellow eye was able to compensate through bi-ocular multiplexing¹⁹ with each eye seeing a different view - the telescope eye saw the magnified view of the scene while the fellow eye saw the non-magnified view. An alternative solution to the problem of the ring scotoma would be to use spatial multiplexing¹⁹ in which the telescope eye can simultaneously see both the magnified and the non-magnified view of the scene at different spatial locations. (For example, spatial multiplexing was previously implemented in the Bilevel Telemicroscopic Apparatus (BITA) micro-Galilean bioptic telescope,^{33, 34} recently implemented by Multilens (Multilens AB, Sweden) in a new bioptic Keplerian telescope, and previously proposed by Peli and Vargas-Martin for their in-the-spectacle-lens telescopic device³⁵). With bi-ocular multiplexing, the magnified and non-magnified views alternate under binocular rivalry which is not fully under the control of the user. By comparison with spatial multiplexing, the two views are available simultaneously and the user can voluntarily attend to either one or even split attention between both. However, the utility of spatial multiplexing as a solution for the ring scotoma has yet to be formally tested in a research study. Our new driving simulator paradigm will enable future investigations of the effects of the ring scotoma in bioptic drivers with more diverse vision impairments and different telescope designs.

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Figure 1.

Examples of the directional road signs used for the sign-reading task. Participants had to report the last part of the street name (Ave or Pike) and the distance (0.8 or 0.3 miles).

Figure 2.

Screen-shot of a pedestrian hazard coincident with a sign-reading task in the driving simulator (a sign+pedestrian event) when the participant's vehicle was about 70 m from the sign and 35 m from the pedestrian. The pedestrian was programmed to appear, run across the driving lane ahead of the driver for about 1 s within the ring scotoma area (shown by gray shading for illustration purposes) and disappear, all within the period when the participant was reading the sign through the bioptic. For this illustration, the ring scotoma was mapped under monocular viewing conditions while the participant looked through the bioptic telescope at the sign (the non-telescope eye was patched). The small area around the sign, without shading, is the field of view through the telescope ($\approx 10^\circ$ diameter). The width of the ring scotoma is the distance between the inner and outer edges of the shaded area ($\approx 12\text{-}14^\circ$ in the region of the pedestrian). Only the central monitor of the simulator is shown; the inset on upper right is the rearview mirror.

Figure 3.

Vertical head position of a subject with simulated visual acuity loss in the binocular viewing group during an “All-during-Tx” sign+pedestrian event. The pedestrian was in the scene only while the participant was looking through the telescope (gray-shaded region) and was therefore classified as an “All-during-Tx” event. The participant made a downward head dip to look through the bioptic about 0.6 s after the sign appeared. The head then remained lowered for about 1.2 s while reading the sign, followed by an upwards movement as the participant finished looking through the telescope. The horn was pressed to indicate detection about 1.2 s after the pedestrian appeared. T1 marks the start of the downward tilt. T2 marks the end of the upwards movement.

Figure 4.

Mean detection rates for running pedestrians for the subjects with simulated acuity loss (data pooled across all subjects) and the individual patients (S1, S2) with real acuity loss. For sign +pedestrian events, detection rates were lower for All-during-Tx than Part-during-Tx pedestrians for the monocular simulated acuity loss group but not the binocular group. Detection rates for no-sign events are plotted for comparison. Patients with real acuity loss had similar detection rates to the monocular simulated acuity loss group for No-sign and All-during-Tx events. Detection rates of patients for Part-during-Tx events should be interpreted with caution as there were very few events. Error bars represent 95% confidence limits.

Figure 5.

Time from the start of the downward head tilt to the pedestrian appearance for the subjects with simulated acuity loss and the individual patients (S1, S2) with real acuity loss. Negative values mean the pedestrian appeared before the head tilt. For simulated acuity loss: the vertical line within each box represents the group median; box length represents the interquartile range (IQR) of the group data; whiskers represent data within 1.5x IQR. For individual patients, the median of their individual data is plotted as a single vertical line.

Figure 6.

Proportion of sign+pedestrian events that were categorized as Part-during-Tx and All-during-Tx for the subjects with simulated acuity loss and the individual patients (S1, S2) with real acuity loss. The number under each column is the number of events from which the proportion was calculated

Figure 7.

Time of pedestrian appearance before the start of the downward head tilt (T1 on Figure 3) for subjects with simulated acuity loss. Data are shown for each Part-during-Tx event in which the pedestrian appeared before the subject looked into the telescope but disappeared before the subject emerged from the telescope (T2 on Figure 3). If the pedestrian appeared within 0.5 s before the start of the head tilt, it was sometimes not seen.

Figure 8.

Boxplots of reaction times for subjects with simulated acuity loss for pedestrians in sign +pedestrian events and no-sign events. Reaction times were significantly longer for sign +pedestrian events than no-sign events and were significantly longer for All-during-Tx than Part-during-Tx events. Median reaction times for patients with real acuity loss are shown for the no-sign events only as there were insufficient detections to compute median reaction times for the sign+pedestrian events. Data are plotted for the binocular and monocular simulated acuity loss groups combined because there were no between-group differences in reaction times. The line within each box represents the median; box length represents the interquartile range (IQR); whiskers represent data within 1.5x IQR.

Table 1

Visual acuity (logMAR units) without and with blur and through 3× monocular telescope.

	Binocular without telescope		Monocular [‡]	
	Without blur	With blur	Without telescope	Through telescope
Normally sighted [*]	−0.08 (20/16) −0.05 to −0.08	0.78 (20/120) 0.58 to 0.92	0.85 (20/140) 0.77 to 0.97	0.23 (20/34) [‡] 0.21 to 0.28
Patient S1	–	–	1.00 (20/200)	0.60 (20/80)
Patient S2	–	–	0.52 (20/66)	0.12 (20/26)

^{*}For normally sighted subjects, data are summarized as median and interquartile range.

[‡]For normally sighted subjects, monocular measurements are with blurring filters.

[‡]The amount of improvement with the telescope was more than expected for 3× magnification because for 8 normally-sighted subjects the telescope eye lens had a lesser amount of blur (0.1 filter) than the carrier lens (0.1 + 0.4 filters). For the four normally-sighted subjects who had a 0.1 filter only on both the carrier lens and the telescope eye lens, the median improvement in visual acuity was 3.3× (close to the expected).

Table 2

Letter contrast sensitivity (log units) without and with blur.

	Without blur	With blur
Normally-sighted *	1.96 1.92 to 2.01	1.33 1.33 to 1.61
Patient S1	1.44	–
Patient S2	1.02	–

* For normally sighted subjects, data are summarized as median and interquartile range.

Table 3

Summary (median values) of the timing of the start of the downward head tilt (T1 on Figure 3) relative to the sign appearing (sign-to-tilt) and the pedestrian appearing (tilt-to-ped) for sign+pedestrian events.

	Overall			Part-during-Tx			All-during-Tx		
	Sign-to-tilt (s)	Tilt-to-ped* (s)	Sign-to-tilt (s)	Tilt-to-tilt (s)	Tilt-to-ped* (s)	Sign-to-tilt (s)	Sign-to-tilt (s)	Tilt-to-ped* (s)	
Binocular simulated acuity loss	0.70	0.28	1.02		-0.36	0.67		0.28	
Monocular simulated acuity loss	0.87	0.12	1.13		-0.23	0.73		0.28	
S1 real acuity loss	0.97	0.03	1.17		-0.20	0.87		0.27	
S2 real acuity loss	0.80	0.17	1.07		-0.07	0.80		0.25	

* Measured from the start of the head tilt down to the pedestrian appearance, positive values mean pedestrian appeared after the head tilt, negative values mean the pedestrian appeared before the head tilt.