Characteristics of On-Road Driving Performance of Persons With Central Vision Loss Who Use Bioptic Telescopes

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PURPOSE. To compare the on-road driving performance of visually impaired drivers using bioptic telescopes with age-matched controls.

METHODS. Participants included 23 persons (mean age = 33 ± 12 years) with visual acuity of 20/63 to 20/200 who were legally licensed to drive through a state bioptic driving program, and 23 visually normal age-matched controls (mean age = 33 ± 12 years). On-road driving was assessed in an instrumented dual-brake vehicle along 14.6 miles of city, suburban, and controlled-access highways. Two backseat evaluators independently rated driving performance using a standardized scoring system. Vehicle control was assessed through vehicle instrumentation and video recordings used to evaluate head movements, lane-keeping, pedestrian detection, and frequency of bioptic telescope use.

RESULTS. Ninety-six percent (22/23) of bioptic drivers and 100% (23/23) of controls were rated as safe to drive by the evaluators. There were no group differences for pedestrian detection, or ratings for scanning, speed, gap judgments, braking, indicator use, or obeying signs/signals. Bioptic drivers received worse ratings than controls for lane position and steering steadiness and had lower rates of correct sign and traffic signal recognition. Bioptic drivers made significantly more right head movements, drove more often over the right-hand lane marking, and exhibited more sudden braking than controls.

CONCLUSIONS. Drivers with central vision loss who are licensed to drive through a bioptic driving program can display proficient on-road driving skills. This raises questions regarding the validity of denying such drivers a license without the opportunity to train with a bioptic telescope and undergo on-road evaluation.

Keywords: bioptic telescopes, driving performance, on-road driving assessment, spotting

Individuals with moderate central vision loss are legally eligible to drive with the aid of spectacle-mounted bioptic telescopes in 43 states in the United States.¹ The telescope is mounted on a carrier lens and provides a magnified view of objects in the driving environment, such as signage, traffic control devices, and pedestrians, which can be resolved at much longer distances than would be otherwise possible for individuals with moderate levels of central vision loss.² There is considerable inconsistency in the visual acuity and visual field requirements for bioptic driving among jurisdictions where bioptic driving is legal, and a wide range of driving restrictions are also imposed.³ This is not surprising, given that limited research has been conducted to evaluate driving performance and safety in this population.

Only a small number of studies have investigated the motor vehicle collision risk of bioptic drivers, and these have reported inconsistent results, with no indication of whether use (or lack of use) of the bioptic telescope elevates crash risk.⁴⁻⁷ In addition, with the exception of the study by Vincent et al.⁷ these studies were conducted more than 20 years ago, and hence do not include drivers using current modern bioptic

designs or training programs; all have methodological shortcomings, including small sample sizes and lack of appropriate control groups.

Three surveys of bioptic drivers have also been conducted.⁸⁻¹⁰ The most recent of these surveyed 58 bioptic drivers and indicated that although most of the drivers rated their bioptic telescope as helpful, only 62% reported always wearing the device when driving.¹⁰ However, the generalizability of these results is questionable, as this survey's response rate could not be computed. More recently, the naturalistic driving of two bioptic drivers was recorded using an analogue video recording system over a number of days.¹¹ As these two drivers also participated in the previously reported survey,¹⁰ it was possible to compare self-reported behavior with objective measures, which revealed that the actual use of the bioptic telescope was less than had been self-reported.¹¹

The paucity of research on bioptic driving means there is little scientific basis underlying the design of bioptic driving programs, including how to set the visual requirements and determine what kinds of restrictions (if any) are likely to facilitate driver safety in this population. This is problematic,

given that lack of driving licensure is associated with reduced employment options and has economic and social ramifications.^{12,13} The aim of this study was to compare the on-road driving performance of persons with moderate central visual loss who are licensed to drive with the use of biotopic telescopes with that of age-matched controls, and to identify the types of driving errors and difficulties that characterize biotopic drivers. We were also interested in identifying, through evaluation of video recordings, how often the biotopic drivers viewed through their telescope while driving, given previous suggestions that biotopic drivers tend to use the biotopic device only to obtain their driving license.¹⁴

METHODS

Participants

Potential participants consisted of those who were legally licensed to drive through Alabama's biotopic driving program and had been seen in the Driving Assessment Clinic at the University of Alabama at Birmingham (UAB). A certified driving rehabilitation specialist (CDRS) in the clinic evaluates applicants who wish to drive in Alabama using a biotopic telescope. The CDRS also provides training in the use of the biotopic telescope for driving, including focusing, tilting the head, or dipping to view through the telescope, finding objects when viewing through the telescope, and tracking. If a driver has been licensed to drive with a biotopic telescope in another state and is considered to drive safely with the biotopic during the driving assessment by the CDRS, no further training through Alabama's biotopic driving program is required. As per Alabama's biotopic driving regulations, biotopic drivers must have visual acuity with the carrier lens of 20/200 or better in each eye and 20/60 or better through the biotopic telescope; visual fields without the biotopic telescope must extend 110 degrees across the horizontal and 80 degrees across the vertical; both monocular and binocular telescopes are legal in Alabama. The etiology of visual impairment must be identified as a nonprogressive condition, which is verified on an annual basis by an ophthalmologist or optometrist at the time of annual licensure renewal. A reference control group of drivers was also enrolled who were licensed to drive in Alabama through the standard licensing process and were visually normal. Control participants were required to have visual acuity of 20/60 or better in at least one eye (vision requirement for licensure in Alabama). For each biotopic driver who was enrolled, a control driver was enrolled whose age was within ± 2 years of the biotopic driver's age. The protocol was approved by the Institutional Review Board for Human Use at UAB. After the purpose of the study was explained, participants were asked to sign a document of informed consent before enrolling.

Procedures

Demographic information, including age, sex, and race, was obtained by medical record review and confirmed by interview. The Driving Habits Questionnaire¹⁵ was used to confirm driving status and licensure. The drivers with biotopic telescopes also completed a questionnaire that collected information about the characteristics of the driver's biotopic telescope, years of wear, training, and the primary cause of vision impairment; this information was also confirmed through their eye medical record. All questionnaires were interviewer-administered by trained staff.

Visual acuity was assessed using the standard protocol of the Electronic Visual Acuity tester (EVA) and expressed as the

logarithm of the minimum angle of resolution (logMAR).¹⁶ Letter contrast sensitivity was measured using the Pelli-Robson chart under the recommended testing conditions¹⁷ and scored by the letter-by-letter method.¹⁸ Visual acuity and contrast sensitivity were evaluated both monocularly and binocularly, with habitual correction (whichever optical correction the person used while driving, if any) and also through the biotopic telescope. All participants had undergone a comprehensive eye examination within the past year.

On-road driving performance was assessed under in-traffic conditions in an instrumented automatic transmission vehicle (2007 Chevrolet Impala). The vehicle's instrumentation measured acceleration and deceleration, lateral/longitudinal forces, and vehicle speed (Vigil Vanguard System, Brisbane, Australia). The system also included four video cameras that recorded the driver and the external driving environment; two of the cameras were positioned within the vehicle and directed toward the driver and two faced forward and were positioned on the roof of the vehicle.¹⁹

The driving performance of each participant was assessed along the same route under in-traffic conditions consisting of 14.6 miles of noninterstate driving in residential and commercial areas of a city. A CDRS who was also a licensed occupational therapist with low vision specialty certification sat in the front passenger seat of the vehicle; at the time of the study the CDRS had 12 years of clinical experience in driving assessment and rehabilitation of patients with a wide variety of medical conditions. The CDRS had access to the vehicle's dual brake system, and was responsible for monitoring safety.

Before beginning the on-road assessment, participants completed a series of basic driving maneuvers in a church parking lot to ensure they had adequate vehicle control and to become familiar with the vehicle and driving tasks. Once the CDRS was satisfied that the participant exhibited adequate control, and the participant indicated being comfortable with the vehicle and driving tasks, the on-road driving protocol began. It started on low-traffic streets in a residential neighborhood and proceeded to busier roads, including those in the vicinity of business and commercial areas, then driving on a multilane highway with both controlled access ramps and traffic control devices, and, finally, city driving in a congested urban area. The route was selected to include numerous traffic lights (25) and road signs (58) in order to compare the ability of the biotopic drivers relative to the controls to accurately detect and recognize these features. Drivers were asked to provide a commentary of their driving observations, including traffic signal colors, traffic signs, and any pedestrians/cyclists/road workers encountered who were either on the road or considered likely to enter the road in the path of the vehicle and hence presented a threat to safety. This exercise of calling out signals, signs, and pedestrians is a routine component of standard biotopic driver training, where the CDRS instructs drivers to call out the road signs, the color of traffic light signals, and other relevant road users to ensure that drivers are looking for these road features and accurately recognizing them in a timely fashion. Video recordings of the driver were also used to determine the extent to which biotopic drivers used their biotopic telescope to view traffic lights, signs, and "pedestrians." Driving evaluations were held between 9 AM and 3 PM to avoid rush hour traffic and were canceled if it was raining.

Performance was rated by two independent "backseat evaluators" at 41 locations along the route on a previously developed 3-point scale,²⁰ with respect to eight different behaviors/skills; 28 locations were in suburban streets, 11 on a multilane highway, and 2 in city streets. One backseat evaluator, designated as the primary evaluator, sat in the middle of the backseat (positioned so that the evaluator did not

obscure the driver's view of the rearview mirror), with the second evaluator sitting behind the driver. At each location, the eight driving behaviors evaluated included the following: *scanning* and attention to other road users, signs, and markings; *lane position* of the vehicle; *steering steadiness*, involving smoothness of steering at any point of the drive; appropriate use of *speed* relevant to road conditions and the speed limit; *gap judgment* between the driver and other cars when entering traffic flow or intersections or passing moving or parked cars and following distance; appropriate use of *braking* to allow smooth driving and stopping as required; *directional indicator use* to signal to other road users intention to change direction; and *obeying signs and signals*. If a given maneuver was not relevant at a given location, it was not rated (e.g., using the indicator signal would not be relevant if there was no turn or lane change involved at a given location). *Pedestrian detection* was determined by identifying the number of times that participants correctly reported the presence of a pedestrian, road worker, or cyclist encountered when they were considered relevant to the driving task and this was scored after testing from the video recordings. In real-world driving assessments such as these, it is impossible to control pedestrian events; for the 46 drivers, there were a total of 77 pedestrians (45 for the bioptic drivers and 32 for the control drivers). *Road sign recognition* was also recorded for each of the 58 traffic signs encountered along the driving route. *Traffic light detection rate* was determined by calculating the percentage of the 25 traffic lights where the signal light was correctly reported.

After the drive was complete, each evaluator also provided a global rating of performance for each behavior on a 5-point scale, which summarized the evaluator's overall impression of the quality of driving for that behavior; this was done separately for driving performance on the route that involved no multilane high-speed highways and then the route that involved the multilane high-speed highway. The 5-point scale included the following scoring criteria: 1 = driver is unsafe and the drive was, or should have been, terminated; 2 = driver is unsafe, the drive was completed; 3 = driver's performance was unsatisfactory but not unsafe; 4 = driver was safe but demonstrated several minor flaws; and 5 = driver was safe and demonstrated either flawless or near flawless driving performance.

Scoring of Instrumented Vehicle Output and Video Recordings

The data collected by the instrumented vehicle were exported as text and graphical files and examined using the Vigil Vanguard software that automatically generated outcome scores of driving speeds and excessive force events, defined as jerky cornering, sudden braking, and jerky acceleration. These outcome measures were provided as a function of the speeds driven in the ranges of 0 to 15 miles per hour (mph), 15 to 35 mph, 35 to 55 mph, and 55 mph and over, as described previously.¹⁹

The videos of the external vehicle environment and driver were analyzed by an independent rater who was masked to the driving category (safe/unsafe) of each of the participants. The rater viewed the video recordings of the internal vehicle environment for each participant to record the number of head movements, including spotting through the telescope for the bioptic drivers. The head movements made during each drive were categorized by direction (left or right) and into small and large head movements as described previously.¹⁹ Any instances of dipping, where the bioptic telescope user visibly lowered his or her head to view the road scene through the bioptic telescope, were also recorded. Apart from the total number of

dips per drive, we were also interested to know which specific tasks were undertaken while viewing through the bioptic telescope, given that it has been suggested that bioptic telescope wearers may only use their device to pass the visual licensing standards, rather than to assist their driving decisions and safety.¹⁴ Thus, the rater counted the number of dips for each driver, where the object of that dipping behavior was obvious, and these were divided into the following categories after initial inspection of the data: road signs, traffic lights, pedestrians, signal/brake lights of the vehicle ahead, lane markings on road, or at intersections.

The video recordings of the road ahead of the vehicle were also analyzed to derive a measure of lane keeping, where the rater recorded the number of times a participant crossed either the outer border of the left or right lane markings or, in cases where the right edge of the lane was not delineated, moved off the tarmac. The total time out of the lane, both to the left and the right, was recorded. The time spent driving on the left/center/right lines was *not* recorded; only those times when the line was crossed. When the rater coded the above driving characteristics outside the vehicle, the rater was masked with respect to whether the driver was wearing a bioptic telescope or was a normally sighted driver.

Analysis

An intraclass correlation coefficient (ICC) was used to evaluate the agreement between the two backseat evaluators' ratings of participants' performance with respect to the driving safety ratings. This demonstrated an ICC of 0.93; thus, for analytic purposes, the driving performance score of the primary evaluator was used. To account for the pair-matched nature of the study design, paired *t*-tests and McNemar's tests (or Stuart-Maxwell tests) were used to compare driving performance between participant groups. *P* values of less than or equal to 0.05 (two-sided) were considered statistically significant.

RESULTS

A total of 43 persons had been seen in the Driving Assessment Clinic for bioptic driving since the inception of the bioptic driving law in Alabama and had been licensed. All of these individuals were invited to participate. Twenty-three consented to participate and completed the protocol; an additional person consented and completed part of the protocol but did not participate in the on-road portion because of thunderstorms. Reasons for nonenrollment among the remaining 19 included the following: unable to contact (10); ineligible because recovering from broken arm (1); and 8 declined participation because of transportation problems (6), inability to get off from work (1), or disinterest (1). The distributions of age, sex, and visual acuity were not different for participants versus nonparticipants. Twenty-three visually normal drivers were age-matched with the bioptic drivers. The demographic characteristics of the two groups, as well as their visual acuity and contrast sensitivity are given in Table 1. The control group was not significantly different in age or race/ethnicity compared with the bioptic drivers, but there were significantly more male drivers in the bioptic driver group compared with the controls. The bioptic drivers had a lower annual mileage than did the controls (mean annual mileage 9217 ± 6445 miles vs. $18,347 \pm 9282$ miles); a more detailed description of the driving habits of the bioptic drivers will be provided in a separate article. The bioptic drivers had significantly poorer visual acuity and contrast sensitivity compared with the controls, as would be expected, with the group mean visual

TABLE 1. Demographic, General Health Characteristics, Visual Acuity, and Contrast Sensitivity of Participants With Bioptic Telescopes and Visually Normal Participants

	Licensed Bioptic Drivers, <i>n</i> = 23	Licensed Drivers With Normal Central Vision, <i>n</i> = 23
Age, y, mean (SD)	32.8 (12.3)	33.0 (12.3)
Sex, <i>n</i> (%)		
Female	5 (22)*	13 (56.5)
Male	18 (78)*	10 (43.5)
Race, <i>n</i> (%)		
White, non-Hispanic	20 (87)	19 (83)
African American	3 (13)	4 (17)
Binocular visual acuity, logMAR, mean (SD)	0.68 (0.12)†	−0.11 (0.12)
Visual acuity through the bioptic, logMAR, mean (SD)	0.14 (0.13)	
Contrast sensitivity, log units, mean (SD)	1.65 (0.20)†	1.92 (0.05)

Significant differences compared with controls are denoted at the * $P < 0.05$ and † $P < 0.01$ levels.

acuity through the bioptic telescope being 0.14 logMAR (equivalent to 20/28).

The causes of visual impairment in the bioptic drivers are given in Table 2, with the most common causes being hereditary optic atrophy, ocular albinism, and Stargardt's disease; most bioptic drivers (61%) did not exhibit nystagmus. Table 2 also provides an overview of the characteristics of the bioptic telescopes used by the drivers. The vast majority of the bioptic drivers used a monocular rather than a binocular telescope, wearing it more commonly over the right than the left eye. A manual rather than fixed-focus telescope was more commonly used, as was a $\times 4.0$ magnification compared with $\times 2.2$ magnification. Overall, participants reported having driven with a bioptic telescope for an average of 6 years and most (22/23) had received some form of bioptic training.

Table 3 shows how drivers were distributed on the 5-point rating scale of overall global driving performance, in which ratings of 3, 4, or 5 signify that the backseat evaluator rated the participant as engaging in safe driving behaviors. There were no significant differences between the bioptic drivers and controls for either the overall rating ($P = 0.8912$) or for the divided highway only ($P = 0.7865$). Importantly, based on this 5-point global rating scale, all drivers with normal central

vision (23/23) and 96% (22/23) of the bioptic drivers were rated as safe to drive. The bioptic driver who was rated as unsafe demonstrated unsteady steering and lane positioning and the CDRS was required to intervene on a number of occasions to avoid an incident.

Table 4 shows how drivers were distributed on the 3-point rating scale for each of the component driving behaviors. Overall, the bioptic drivers were more likely to have ratings of 2 for lane position and steering steadiness compared with the drivers with normal vision; however, these differences reached statistical significance only for lane position when driving on the divided lane highway.

The data for correct detection of traffic light color, correct reporting of road signs, and detection of pedestrians encountered on each drive are presented as the average percentage correct for drivers in the bioptic and control groups in Table 5. Most of the traffic light colors were correctly detected by drivers in both groups (bioptic drivers mean = 96%; control drivers mean = 98%); although the control drivers as a group correctly detected significantly more traffic light colors than the bioptic drivers, these differences are not likely to be practically significant. The controls as a group also correctly reported road signs significantly more often than did bioptic

TABLE 2. Primary Ocular Pathology and Characteristics of the Bioptic Telescope for Bioptic Drivers

Characteristic	
Primary eye condition that caused visual impairment, <i>n</i> (%)	7 (30) hereditary optic atrophy 6 (26) ocular albinism 3 (13) Stargardt's disease 2 (9) cone dystrophy 5 (22) other (congenital cataract, aniridia, high myopia, optic neuropathy, optic nerve trauma at birth)
Nystagmus, <i>n</i> (%)	9 (39) yes 14 (61) no
Monocular or binocular bioptic telescopes, <i>n</i> (%)	21 (91) monocular: 14 (67) right and 7 (33) left 2 (9) binocular
Manufacturer of bioptic telescope, <i>n</i> (%)	8 (35) Designs for Vision 15 (65) Ocutech
Years of driving with a bioptic telescope, mean (SD)	6.05 (7.99)
Received bioptic training, <i>n</i> (%)	22 (96) yes 1 (4) no
Bioptic telescope focus, <i>n</i> (%)	6 (26) fixed focus 17 (74) manual focus
Magnification, <i>n</i> (%)	5 (22) $\times 2.2$ 18 (78) $\times 4$

TABLE 3. Overall Global Rating of Driving Performance by Back-Seat Evaluator

Rating	Overall, <i>n</i> (%)		Divided Highway Driving, <i>n</i> (%)	
	Licensed Bioptic Drivers	Controls	Licensed Bioptic Drivers	Controls
1	0	0	0	0
2	1 (4.5)	0	1 (4.5)	0
3	3 (13.0)	1 (4.5)	4 (17.5)	0
4	10 (43.5)	4 (17.5)	8 (34.5)	4 (17.5)
5	9 (39.0)	18 (78.0)	10 (43.5)	19 (82.5)

drivers; however, there was no significant difference in the number of pedestrians detected between the groups.

Data for each group with respect to the number and direction of head movements, (including dipping head movements for the bioptic drivers) and lane keeping are given in Table 6. The bioptic drivers made a greater number of small rightward head movements and crossed the right-hand lane significantly more often than did the controls; however, the correlation between rightward head movements and right lane crossings was not significant ($r = -0.18$; $P = 0.58$). Although the control drivers did not exhibit any dipping head movements, the bioptic drivers made on average 77 dipping head movements during the drive in order to view the driving scene through the bioptic telescope; however, there was wide individual variability in the number of dipping movements exhibited by the bioptic drivers (min: 0, max: 318). The object of dipping behavior was obvious for a mean of 67% of the dipping head movements across the group; road signs were the most frequent target of these dipping head movements ($46.2\% \pm 14.5\%$), followed by traffic lights ($39.6\% \pm 13.7\%$), pedestrians ($6.7\% \pm 8.3\%$), the vehicle ahead ($5.1\% \pm 5.4\%$), and the roadway at intersections ($2.4\% \pm 3.3\%$). Interestingly, there was no significant correlation between the number of times the bioptic drivers dipped their head to view through the telescope and the number of signs correctly recognized ($r = 0.18$; $P = 0.40$).

The reports generated by the instrumentation in the vehicle are summarized in Table 7. They demonstrate that both the

drivers with bioptic telescopes and controls spent almost half of the drive at speeds between 15 and 35 mph and just under a third of the drive at speeds of 0 to 15 mph, so we have focused our analysis on the outcomes measures within these speed bands. There were no significant group differences in speeds driven or jerky acceleration; however, compared with control drivers, there were more than twice as many braking events and more jerky cornering events for the bioptic drivers in the lower speed band, although the mean number of jerky cornering events was less than one for both groups.

DISCUSSION

This study compared the on-road driving performance of drivers with moderate central visual impairment who are licensed to drive with a bioptic telescope with an age-matched control group of normally sighted drivers. The findings demonstrate that the majority (22/23) of the licensed bioptic drivers were rated as safe to drive in suburban, city, and divided-highway settings. Despite having a significant reduction in visual acuity, all but one of the bioptic drivers in our sample proficiently executed driving maneuvers in everyday roadway environments and exhibited behaviors consistent with safe driving. These findings are in accord with those of a recent study of 10 bioptic drivers who were followed for 2 years after completing a bioptic training program, which

TABLE 4. Component Ratings of Driving Performance by Back-Seat Evaluator

Driving Behaviors	Rating, <i>n</i> (%)						<i>P</i> Value Bioptic Drivers vs. Controls
	Licensed Bioptic Drivers, <i>n</i> = 23			Controls, <i>n</i> = 23			
	1	2	3	1	2	3	
Overall							
Scanning	0 (0)	1 (4.3)	22 (95.7)	0 (0)	1 (4.3)	22 (95.7)	1.0000
Lane position	0 (0)	8 (34.8)	15 (65.2)	0 (0)	1 (4.3)	22 (95.7)	0.1420
Steering steadiness	1 (4.3)	8 (34.8)	14 (60.9)	0 (0)	2 (8.7)	21 (91.3)	0.2035
Speed	0 (0)	14 (60.9)	9 (39.1)	0 (0)	8 (34.8)	15 (65.2)	0.4625
Gap judgment	0 (0)	3 (13)	20 (87)	0 (0)	0 (0)	23 (100)	0.3916
Braking	0 (0)	8 (34.8)	15 (65.2)	0 (0)	2 (8.7)	21 (91.3)	0.2123
Using directional indicator	0 (0)	5 (21.7)	18 (78.3)	1 (4.3)	3 (13)	19 (82.6)	0.6823
Obedying traffic signals	0 (0)	1 (4.3)	22 (95.7)	0 (0)	1 (4.3)	22 (95.7)	1.0000
Divided Highway Driving							
Scanning	0 (0)	3 (13)	20 (87)	0 (0)	0 (0)	23 (100)	0.3916
Lane position	0 (0)	9 (39.1)	14 (60.9)	0 (0)	0 (0)	23 (100)	0.0293*
Steering steadiness	1 (4.3)	8 (34.8)	14 (60.9)	0 (0)	1 (4.3)	22 (95.7)	0.0919
Speed	3 (13)	8 (34.8)	12 (52.2)	0 (0)	4 (17.4)	19 (82.6)	0.2276
Gap judgment	0 (0)	3 (13)	20 (87)	0 (0)	0 (0)	23 (100)	0.3916
Braking	1 (4.3)	5 (21.7)	17 (74)	0 (0)	0 (0)	23 (100)	0.1116
Using directional indicator	0 (0)	0 (0)	23 (100)	0 (0)	0 (0)	23 (100)	1.0000
Obedying traffic signals	0 (0)	0 (0)	23 (100)	0 (0)	0 (0)	23 (100)	1.0000

* $P < 0.05$.

TABLE 5. Group Mean and SD of the Percentage of Correct Detection of Traffic Light Color, Signs and the Presence of Pedestrians on the Roadway

Measure	Licensed Bioptic Drivers, <i>n</i> = 23	Controls, <i>n</i> = 23	<i>P</i>
Traffic light score, % (SD)	95.8 (3.8)	98.0 (2.6)	0.0122*
Signs detected, % (SD)	54.0 (12.4)	83.1 (10.0)	<0.0001†
Pedestrian detection rate, % (SD)	91.2 (24.2)	92.7 (25.1)	0.67

* *P* < 0.05.† *P* < 0.01.

indicated that they did not have increased collision or violation rates compared with age-matched control drivers or a reference population of regional drivers.⁷

In spite of the bioptic drivers exhibiting safe driving skills, some of them did reveal some differences in driving characteristics compared with controls, including lane position and steering steadiness, particularly on the divided-lane highway. The poor steering control often consisted of drifting across the lane boundaries rather than lane deviations that were clearly linked with fixation of road objects through the bioptic telescope. However, it is important to highlight that many other aspects of their driving behavior were indistinguishable from normally sighted drivers. Maintaining lane position and steady steering are likely to rely on the processing of information in the peripheral visual field,¹⁹ which may be more difficult to access when viewing through the bioptic telescope to spot objects. Bioptic drivers' problems with lane keeping typically involved crossing over the right-hand lane marker, which may reflect their higher level of caution in avoiding oncoming traffic to their left side. The bioptic drivers also made significantly more small rightward head movements, which supports other studies that suggest that drivers tend to steer in the same direction as their head and eye movements^{19,21}; however, interrogation of the video recordings did not reveal that the rightward lane crossings occurred at the same time as the rightward head movements.

Although it has been previously suggested that bioptic drivers tend to use their telescope only to obtain their driver's license and then fail to use it thereafter under in-traffic conditions,¹⁴ our video data reveal that this is not the case for most of our drivers. Many did frequently spot through the telescope (12 of 23 bioptic drivers spotted ≥ 60 times during the 45-minute drive), yet it is also important to point out that 5 of the 23 drivers spotted fewer than 30 times, with 1 driver not

spotting at all. The frequency of dipping thus appears to be an individual characteristic and not necessarily indicative of the efficient use of the telescope for safe driving. In our study, the telescope was used most often to view road signs and traffic lights, which is consistent with survey data, suggesting that bioptic telescopes are mainly used for tasks that require heightened resolution.¹⁰ Interestingly there was no significant relationship between the number of dips and signs correctly recognized across participants. This lack of relationship is likely to have arisen because many of the participants did not need to dip to view signs, given they had adequate visual acuity through the carrier lens and some of the signs could be recognized by virtue of their shape and color and did not require high levels of resolution. However, we also found that bioptic drivers used the telescope to identify the presence of pedestrians and the vehicle ahead, thus highlighting the important safety role that telescopes play in alerting drivers to the presence of other roadway users, such as other drivers, pedestrians, cyclists, and road crews. The dipping behavior also enables accurate judgments, in that bioptic drivers correctly detected 96% of traffic light signal colors they encountered and 91% of pedestrians, rates of detection that were very similar to that of the normally sighted drivers. Although the bioptic drivers reported significantly fewer traffic signs correctly than did the controls (54% vs. 83%), one might argue that many of these signs (e.g., left curve in road ahead) are less critical to safety than is detection of pedestrians and traffic light colors, where incorrect detections are likely to lead to collisions involving injury or death.

It is important to note that in our study drivers were instructed to call out road signs, traffic signal colors, and pedestrians so we could record the accuracy of these observations; this also allowed us to link road objects detected with dipping behavior. Although verbalizing these road features

TABLE 6. Means and SDs for the Number of Head Movements and Lane Position Deviations for Bioptic Drivers and Control Drivers as Derived From the Video Recordings Collected by the Vigil Vanguard System

Number	Mean (SD)		<i>P</i>
	Licensed Bioptic Drivers, <i>n</i> = 23	Controls, <i>n</i> = 23	
Head movements, large, right	4.83 (2.23)	5.61 (1.90)	0.2601
Head movements, small, right	12.44 (5.84)	9.52 (2.98)	0.0107*
Head movements, large, left	10.44 (4.18)	10.35 (2.42)	0.9070
Head movements, small, left	16.74 (8.43)	19.30 (7.48)	0.3325
Dipping head movements frequency	77.13 (68.99)	0.00 (0.00)	<0.0001†
Lane crossings left	4.91 (5.06)	5.13 (5.40)	0.9013
Lane crossings right	2.57 (2.83)	1.09 (1.16)	0.0368*
Lane crossings total	7.22 (6.32)	6.22 (5.54)	0.6009
Time, s			
Time out of lane, left, s	9.74 (13.47)	9.21 (11.39)	0.9017
Time out of lane, right, s	6.20 (9.15)	2.68 (3.43)	0.1202
Time out of lane, total, s	15.94 (17.49)	11.89 (11.46)	0.4122

* *P* < 0.05.† *P* < 0.01.

TABLE 7. Group Mean Data and SDs for the Outcome Measures for the Automated Scores Derived From the Vigil Vanguard System for Bioptic Drivers and Control Drivers

	Mean (SD)		P
	Licensed Bioptic Drivers, <i>n</i> = 23	Controls, <i>n</i> = 23	
% course spent 0–15 mph	31.83 (14.50)	29.52 (6.57)	0.5146
% course spent 15–35 mph	49.52 (10.21)	48.22 (5.71)	0.6353
Number of events			
Jerky acceleration 0–15 mph	1.91 (2.27)	1.04 (1.19)	0.1485
Jerky acceleration 15–35 mph	0.35 (0.78)	0.52 (1.20)	0.5904
Sudden braking 0–15 mph	2.04 (1.64)	0.35 (0.57)	<0.0001†
Sudden braking 15–35 mph	2.52 (2.06)	0.83 (1.03)	0.0013†
Jerky cornering 0–15 mph	0.69 (0.82)	0.22 (0.52)	0.0455*
Jerky cornering 15–35 mph	0.26 (0.69)	0.48 (0.85)	0.3472

* *P* < 0.05.† *P* < 0.01.

is not an entirely natural part of daily driving, the requirement to search and recognize these objects in the road environment certainly is. This requirement may have increased dipping behavior and head movements for some bioptic drivers, but this was clearly not the case for others; importantly, the task was the same for both the bioptic and control groups. Future studies are planned to assess naturalistic driving in bioptic drivers to investigate their use of bioptic telescopes under habitual driving conditions, relative to that recorded in the current study during an on-road driving assessment.

Our finding that persons with central visual loss can effectively use their bioptic telescope to dip and then correctly recognize objects in the peripheral roadway environment (e.g., pedestrians) is in accord with a laboratory study on target detection using bioptic telescopes.²² This laboratory study also demonstrated that recognition speeds, even after training, were slower than those measured when viewing with normal vision, which may explain the lower percentage of road signs recognized by bioptic drivers as compared with normally sighted drivers.

Sudden braking events were more common in the bioptic drivers, particularly for the lower speed band, which may reflect more cautious behaviors at intersections and traffic lights, which generally involve slower speed choices. Alternatively, the sudden braking may have resulted because the bioptic drivers took longer to identify that a braking response was required and so braking was more sudden than for the control drivers. The vehicle instrumentation demonstrated that bioptic drivers also exhibited jerkier cornering at lower speeds than did the controls, which may relate to the reduction in steering steadiness ratings recorded by the backseat evaluators. These issues with steering steadiness and jerky cornering may reflect problems that bioptic drivers have in detecting lane markings and roadway edges through the carrier lens. Further research is required to explore these findings to better understand the driving characteristics of bioptic drivers.

This study should be considered in terms of both strengths and limitations. A primary strength is that this is the first study to compare the driving performance of bioptic drivers with that of an age-matched group of drivers who were normally sighted from the standpoint of obtaining driver licensure. It was conducted in a range of commonly encountered on-road environments with real traffic challenges. In addition, a standardized scoring system was used to subjectively evaluate driving performance, with the judgment of the primary back-seat evaluator being shown to be highly reliable, with strong agreement with a second back-seat evaluator, who made an independent assessment of driving performance. In addition,

objective measures of driving were made through the instrumented vehicle and video recordings interpreted by independent evaluators. Limitations include a relatively small sample of bioptic drivers. The backseat evaluator ratings were subjective, yet were based on a standard rating scheme¹⁹ and interrater agreement was high. Also, the evaluators' ratings were thematically in accord with the objective measures obtained by the in-vehicle instrumentation (e.g., steering steadiness). It was not possible to mask the backseat evaluators with respect to whether the driver was a bioptic driver or not, as the bioptic driver was very obviously wearing the bioptic telescope. This was also true for the rater who coded bioptic driver behaviors from the video of the driver regarding head movements, but the ratings of lane-keeping were made separately without viewing the driver's face and whether or not the driver was wearing a bioptic telescope.

In summary, our study investigated the on-road driving performance of bioptic drivers as compared with normally sighted drivers. We have demonstrated that the vast majority of the drivers in our study with moderate central vision loss who had undergone training exhibit proficient on-road driving skills when using a bioptic telescope as compared with that of normally sighted drivers. This raises the practical policy question regarding the validity of denying persons with moderate central vision loss a driver's license without the opportunity to train to use a bioptic telescope and undergo on-road evaluation. Further research should focus on providing the evidence basis for informing licensing policies and optimizing the efficacy of training programs to ensure the driving safety of these drivers. For example, our data highlight that steering steadiness and lane keeping are particular issues for bioptic drivers, suggesting that it may be useful to focus training on these aspects of driving behavior and performance.

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