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Characteristics of on-road driving by persons with central vision loss: Learning to drive with a bioptic telescope

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ABSTRACT
There is limited research on the driving performance and safety of bioptic drivers and even less regarding the driving skills that are most challenging for those learning to drive with bioptic telescopes. This research consisted of case studies of five trainee bioptic drivers whose driving skills were compared with those of a group of licensed bioptic drivers (n = 23) while they drove along city, suburban, and controlled-access highways in an instrumented dual-brake vehicle. A certified driver rehabilitation specialist was positioned in the front passenger seat to monitor safety and two backseat evaluators independently rated driving using a standardized scoring system. Other aspects of performance were assessed through vehicle instrumentation and video recordings. Results demonstrate that while sign recognition, lane keeping, steering steadiness, gap judgments, and speed choices were significantly worse in trainees, some driving behaviors and skills, including pedestrian detection and traffic light recognition were not significantly different from those of the licensed drivers. These data provide useful insights into the skill challenges encountered by a small sample of trainee bioptic drivers which, while not generalizable because of the small sample size, provide valuable insights beyond that of previous studies and can be used as a basis to guide training strategies.

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KEYWORDS
bioptic telescopes; on-road driving assessment; trainees; training

Introduction

Under current driver licensing standards persons with moderately impaired central visual acuity (worse than 20/40) would be denied driving licensure in some states across the United States and in many other countries in the world. However, there are over 40 states in the United States (AAA Foundation for Traffic Safety, n.d.; American Association of Motor Vehicle Administrators, 2006; American Geriatrics Society, 2010), three provinces or territories in Canada, (AAA Foundation for Traffic Safety, n.d.) and the Netherlands where persons with moderate central vision loss are allowed to obtain a driver's license if they demonstrate proficiency in using a bioptic telescope while driving, as well as meeting other program requirements which vary between different U.S. states and countries (American Medical Association, 2010).

Bioptic telescope devices consist of a telescope that is mounted in the upper section of the spectacle lens, known as the "carrier" lens (distance refractive correction or a plano lens if no distance correction is needed), or attached to the top of the spectacle frame; Figure 1 shows two common types of bioptic telescopes. The bioptic telescope provides a magnified view of objects in the driving environment, such as signage, brake lights, directional signals, traffic control devices, and pedestrians, which can be resolved at much longer distances than would be otherwise possible for a visually impaired driver (Huss & Corn, 2004). Most individuals use a monocular bioptic telescope, although binocular telescopes are sometimes prescribed, with the most common telescope magnifications used for driving being between 2× and 4×, providing a field of view between 6° and 16°. For the vast majority of the time when driving, the bioptic driver views the roadway environment through the carrier lens while occasionally dipping the head briefly to identify signs, traffic signals, brake lights, pedestrians, and other potential obstacles through the telescope.

Despite the use of bioptic telescopes for driving for several decades in some states in the United States, their impact on driver performance and safety has not been widely explored. A small number of studies have investigated the motor vehicle collision risk of bioptic drivers, and have reported inconsistent results, with no indication of whether the use (or lack of use) of the bioptic telescope is associated with increased crash risk (Janke, 1983; Korb, 1970; Lippman, Corn, & Lewis, 1988; Vincent, Lachance, & Deaudelin, 2012). Importantly, most of these studies have a number of methodological shortcomings including small sample sizes and lack of appropriate control groups, or were conducted more than 20 years ago, and hence do not include drivers using current modern bioptic telescopic designs. In the only recent study (Vincent et al., 2012), crash risk was not significantly different between a group of bioptic

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Figure 1. Photograph of two common types of bioptic telescope: (1) Ocutech VES-Sport (top) and (2) DVI BIO 4 × fixed focus (bottom).

drivers and either a comparison group matched in terms of license restrictions or the regional population. Recently, in the first experimental study to assess the driving performance of licensed bioptic drivers relative to controls, the majority (22/23) of the bioptic drivers were rated as safe to drive by the backseat evaluators and by a certified driver rehabilitation specialist (CDRS) (Wood, McGwin, Elgin, Searcey, & Owsley, 2013). In addition, while the bioptic drivers displayed some minor deviations in lane position, steering steadiness, and road sign recognition, they were indistinguishable from the control drivers in many other driving skills including pedestrian detection, speed, gap judgments, braking, and obeying signs.

There have also been surveys of bioptic drivers (Bowers, Apfelbaum, & Peli, 2005; Owsley, McGwin, Elgin, & Wood, 2014; Park, Unatin, & Park, 1995; Taylor, 1990). The most recent of these explored driving difficulties and behaviors of bioptic drivers and compared self-reported perceptions of driving with actual performance (Owsley et al., 2014). While the bioptic drivers had lower driving exposure and reported more difficulty under poor visibility conditions and in unfamiliar areas than normally sighted drivers, for many driving situations they reported no or little difficulty. Importantly, bioptic drivers' judgments about the quality of their driving were similar to that of the driver safety ratings. There have also been reports of the naturalistic driving of two bioptic drivers recorded using an analog video recording system over a number of days (Luo & Peli, 2011); however, larger scale studies are needed to better understand a bioptic driver's performance under everyday driving conditions.

Another important gap in the literature is that little is known about which skills are most problematic for drivers with central visual loss as they learn to drive with a bioptic telescope (Owsley, 2012). While a number of publications have described the different components of training (Jose & Butler, 1975; Levin & Kelleher, 1975), none have evaluated the relative efficacy of these training processes or the optimum length of time required for training.

The purpose of this study was to examine the on-road driving characteristics of drivers with bioptic learner's permits who had never previously been licensed to drive, and compare them to bioptic drivers who were already successfully licensed. We were particularly interested in which driving skills are most problematic for "trainee bioptic drivers." There are many anecdotal reports from CDRS and driver educators regarding the challenges faced by visually impaired persons learning to drive who wear bioptic telescopes (Huss & Corn, 2004), yet there has been no systematic scientific study of this issue. Thus this description of a small number of cases will provide useful objective and descriptive data that, while not generalizable, provide valuable insights beyond that of previous studies.

Methods

This research was part of a larger study of bioptic driving which compared the on-road driving performance of bioptic drivers who were successfully licensed with age-matched normally sighted drivers. In that study, 23 of the bioptic drivers were already licensed through the State of Alabama's bioptic licensure program; these data have already been published (Owsley et al., 2014; Wood et al., 2013). We also evaluated the five drivers being seen in the clinic who had learner's permits at the time of the study but had never been licensed to drive either with or without a bioptic telescope (henceforth known as "trainees"); this article compares the driving performance data of these trainees with that of the licensed bioptic drivers.

Participants

Potential participants consisted of individuals with central vision loss who were legally licensed through the State of Alabama's bioptic driving program or were in the process of training to learn to drive using a bioptic telescope in the Driving Assessment Clinic at the University of Alabama at Birmingham (UAB). As per Alabama's bioptic driving regulations, all of the bioptic drivers had visual acuity with the carrier lens of 20/200 or better in each eye and 20/60 or better through the bioptic telescope; binocular visual field extent was at least 110 degrees across the horizontal and 80 degrees across the vertical without the bioptic telescope; both monocular and binocular telescopes are legal in Alabama. The etiology of visual impairment was non-progressive, which had been verified annually by an ophthalmologist or optometrist at the time of annual licensure renewal. The protocol was approved by the Institutional Review Board for Human Use at UAB. After the purpose and the nature of the study had been explained, participants were asked to sign a document of informed consent before enrolling.

Bioptic driving training

A CDRS in the clinic evaluates and trains applicants who wish to drive in the state of Alabama using a bioptic telescope. For those who have never driven before, this process involves on-road driver training together with practice in using the bioptic telescope while driving, involving extended periods of practice similar to that involved in learning to drive in normally sighted individuals. For experienced drivers, whose visual loss occurred after obtaining a licence, this involves on-road driver training along with training in using the bioptic telescope while driving and reinforcement of already learned driving skills. For both categories of potential bioptic drivers, training involves learning how to use the telescope, including focusing the telescope, tilting the head or dipping to view through the telescope, finding objects when viewing through the telescope, and tracking objects through the telescope (first outside the driving environment and then in the driving environment, as a passenger initially and then as a driver). Table 1 summarizes the range of skills involved in this component of bioptic driving training. Trainees may spend several training sessions in the passenger seat and in the parking lot learning how to use the vehicle controls and basic maneuvering skills. Once trainees have demonstrated the ability to maneuver the car in the parking lot, training moves into more challenging traffic situations, where mid-range driving skills, such as lane changes, are introduced. While there is no set amount of training required for a new driver to become a licensed driver, a minimum of a year of training is typical. For those who were previously licensed as a normally sighted driver, this period tends to be shorter depending on a range of factors. If a driver has been licensed to drive with a bioptic telescope in another state and is judged to be safe on the road by the CDRS, no further training through Alabama's bioptic driving program is required.

Procedures

A detailed description of the assessment procedures involved in this study are provided elsewhere (Wood et al., 2013). In brief, demographic information was obtained by medical record review and confirmed by interview by trained staff, while a modified Driving Habits Questionnaire was used to obtain information about licensure, characteristics of the driver's bioptic telescope, years of wear, training, and the primary cause of vision impairment; this information was also confirmed through their eye medical record. Visual acuity (measured using the Electronic Visual Acuity tester) and contrast sensitivity (measured with the Pelli-Robson chart) were evaluated both monocularly and binocularly with the habitual correction (whichever optical correction the person used while driving, if any) and also through the bioptic 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 (Chevrolet Impala 2007) as described previously (Wood et al., 2013). The vehicle's instrumentation measured acceleration and deceleration, lateral/longitudinal forces, and vehicle speed (Vigil Vanguard System, Brisbane, Australia) and included four video cameras which recorded the driver and the external driving environment (Wood et al., 2011)

In brief, driving performance was assessed along 14.6 miles of non-interstate 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 and had access to the vehicle's dual brake system, and was responsible for monitoring safety. Participants were allowed a short familiarization period in a quiet parking lot prior to the driving assessment which began on low traffic streets and proceeded to busier roads, then driving on a controlled access highway and finally, city driving. The route included numerous traffic lights (25) and road signs (58) and drivers provided a commentary of their driving observations including traffic signal colors, traffic signs, and any pedestrians/cyclists/road workers (collectively known as "pedestrians") encountered. Video recordings of the driver were also used to determine the extent to which they used their bioptic 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" who are highly experienced vision and driving researchers with an excess of 20 years of experience each. Performance was assessed independently by each rater at 41 locations along the route; 28 locations were in suburban streets, 11 on a multi-lane highway and two in city streets. These backseat raters have an established record of good agreement in their ratings, and also as compared to the CDRS's ratings that has been documented in the peer-review literature. At each location, eight driving behaviors were evaluated including: *scanning* and attention to other road users,

Table 1. Summary of the range of skills that need to be developed prior to commencement of bioptic driver training.

Visual rehabilitation specialist should circle "Yes" or "No" as to whether the applicant is proficient in each named skill	Yes/No
Demonstrates good walking mobility while looking through the carrier lens	
Demonstrates the ability to spot through the telescope by aligning it with the target and spotting through it	
Demonstrates good horizontal and vertical scanning techniques through the carrier lens	
Demonstrates ability to scan, spot, and identify the characteristics of stationary targets of varying size and distance from a stationary position (practice should incorporate stationary targets associated with driving including traffic signals, street signs, highway markers, etc.)	
Demonstrates ability to scan, spot, identify, and track moving targets of varying size and distance from a stationary position (practice should incorporate moving targets associated with driving including automobiles, bicycles, motorcycles, pedestrians, etc.)	
Certified Driving Rehabilitation Specialist (CDRS) should circle "Yes" or "No" as to whether the applicant is proficient in each named driving skill	**Yes/No**
Demonstrates ability to scan, spot, identify, *stationary* targets of varying size and distance while moving (as a passenger in a car, bus or other vehicle; practice should incorporate stationary targets associated with driving including traffic signals, street signs, highway markers, etc.)	
Demonstrates ability to scan, spot, and track *moving* targets of varying size and distance while moving as a passenger in a car bus or other vehicle (practice should incorporate moving targets associated with driving including automobiles, bicycles, motorcycles, pedestrians, etc.)	

signs and markings; *lane position* of the vehicle, *steering steadiness* indicating smoothness of steering; appropriate use of *speed* relevant to road conditions and speed limits; *gap judgment* between the driver and other cars when entering traffic flow or intersections or passing moving or parked cars and following distance; *braking* to allow smooth driving and stopping; *directional indicator* use to signal to other road users intention to change direction and *obeying traffic signals*, as described previously (Wood et al., 2009). Scoring was on a 3-point scale, where 1 = failure to execute skill/behavior; 2 = some problems with executing skill/behavior but not complete failure; and 3 = good execution of skill/behavior. 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 post-testing from the video recordings. Road sign recognition was recorded for all traffic signs encountered along the route which were classified as regulatory (stop signs, speed limits) and non-regulatory (warning, advisory); we were interested in whether bioptic drivers might prioritize time spent scanning certain signs which are most important in terms of safety and road regulations (regulatory) as opposed to warning or advisory signs (non-regulatory). Traffic light detection rate was determined by calculating the percentage of traffic lights where the color of the signal light was correctly reported.

After the drive was complete, each backseat evaluator also provided a global rating of performance for each behavior on the 3-point scale, which summarized the evaluator's overall impression of the quality of driving for that skill (Wood et al., 2013) as well as an overall rating of driving safety on a 5-point scale. 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 using the Vigil Vanguard system included scores on 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 0–15 mph, 15–35 mph, 35-55 mph, and 55 mph and over as described previously (Wood et al., 2011). Videos of the external vehicle environment and driver were analyzed by an independent rater masked to the global rating of performance for each participant. The rater recorded the number of head movements, categorized by direction (left or right) and by small and large head movements as described previously (Wood et al., 2011), as well as the number of dipping head movements to spot through the telescope. 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, drove off the tarmac. When the rater coded the above driving characteristics outside the vehicle, he was masked with respect to whether the driver was wearing a bioptic telescope or was a normally sighted driver.

Statistical analysis

The Kruskal-Wallis test was used to compare continuous variables between the licensed and trainee groups; for categorical variables, Fisher's exact test was used. *P*-values of ≤ 0.05 (two-sided) were considered statistically significant.

Results

The demographic, vision, telescope, and training program characteristics of the five trainees are given in Table 2 along with that of the licensed bioptic drivers whose data are presented elsewhere (Wood et al., 2013). Overall the characteristics of the trainee bioptic drivers were similar to those of the licensed bioptic drivers with some exceptions. While oculocutaneous albinism was the most common cause of visual impairment in the trainees (3/5), none of the licensed bioptic drivers had this condition, with hereditary optic atrophy, ocular albinism and Stargardt's disease being the most common etiologies of visual impairment in licensed bioptic drivers. The majority of the trainee bioptic drivers exhibited nystagmus (4/5) while only 9/23 of the licensed bioptic drivers exhibited nystagmus. In addition, while none of the trainees had non-bioptic driving experience, seven of the licensed bioptic drivers reported having had non-bioptic driving experience (an average of 21.7 years) and had driven with a bioptic telescope for an average of 6 years (Owsley et al., 2014; Wood et al., 2013).

In terms of the type of bioptic telescope used, the characteristics of the trainee and licensed drivers were similar. Most of the licensed bioptic drivers used a monocular rather than a binocular telescope and wore it more commonly over the right than the left eye; all of the bioptic trainees wore a monocular telescope, with the majority wearing it over the left eye (4/5). A manual rather than fixed focus telescope was more commonly used, as was a 4× magnification compared to 2.2× magnification and this was the case for both the licensed and trainee bioptic drivers. The majority of the licensed bioptic drivers (22/23) and all of the trainee drivers had received some form of behind the wheel training with a bioptic telescope with a CDRS.

Figure 2 shows how drivers were distributed on the 5-point rating scale of overall global driving performance. There were significant differences between the trainee and licensed bioptic drivers ($p = 0.003$), with only two of the five trainees being rated as safe to drive at the time of the study, compared to 22/23 of the licensed bioptic drivers. The trainee bioptic drivers who were rated as unsafe demonstrated unsteady steering and lane positioning and drove at speeds that were too fast for their driving ability or the driving environment and the CDRS was required to intervene numerous times (using the brake or steering wheel up to 63 times during one drive) to avoid an incident.

Table 2. Demographic, vision and eye disease, bioptic, and training program characteristics of the individual trainee bioptic drivers, and mean (*SD*) values for the licensed bioptic drivers.

	Trainee 1	Trainee 2	Trainee 3	Trainee 4	Trainee 5	Mean data (*SD*) for Licensed Bioptic Drivers (Wood et al., 2013)
Age (years)	32	20	27	21	18	32.8 (12.3)
Sex	M	F	F	F	M	5 F; 18 M
VA without bioptic Snellen (logMAR)	20/160 (0.90)	20/200 (1.00)	20/160 (0.90)	20/100 (0.70)	20/100 (0.70)	$20/100^{+1}$(0.68)
VA with bioptic Snellen (logMAR)	20/25 (0.10)	20/40 (0.30)	20/32 (0.20)	20/20 (0.00)	20/20 (0.00)	$20/25^{-2}$ (0.14)
CS OU (log units)	1.35	1.20	1.75	1.95	1.80	1.65 (0.20)
Aetiology	Cone dystrophy	Oculocutaneous albinism	Peter's Anomaly	Oculocutaneous albinism	Oculocutaneous albinism	7 (30%) hereditary optic atrophy 6 (26%) ocular albinism 3 (13%) Stargardt's Disease 2 (9%) cone dystrophy 5 (22%) other
BTW CDRS training hours (private vehicle non-CDRS)	30 (10)	50 (0)	50 (40)	15 (0)	4 (400)	15.08 (13.50) 19.17 (23.02)
Years in the bioptic training program	1.0	2.0	3.0	0.5	1.0	0.74 (0.26)
Bioptic telescope	Ocutech VESK 4× (red color shield), 12.5°, focusable, monocular (LE)	Designs for Vision, 4×, 9° (green color shield), focusable, monocular (LE)	Ocutech, VESK 4×, 12.5°, focusable, monocular (LE)	Ocutech, VESK 4×, 12.5°, focusable, monocular (RE)	Designs for Vision, full diam 4×, 6°, focusable, monocular (LE)	8 (35%) Designs for Vision; 15 (65%) Ocutech 21 (91%) monocular: 14 R (67%); 7 L (33%); 2 binocular (9%)
Driver safety rating	Safe	Unsafe	Unsafe	Unsafe	Safe	22/23 safe

Notes. VA = Visual Acuity; logMAR = Log Minimum Angle of Resolution; CS = Contrast Sensitivity; BTW = Bioptic Telescope Wearers; CDRS = Certified Driver Rehabilitation Specialist; RE = Right Eye; LE = Left Eye; OU = Both Eyes

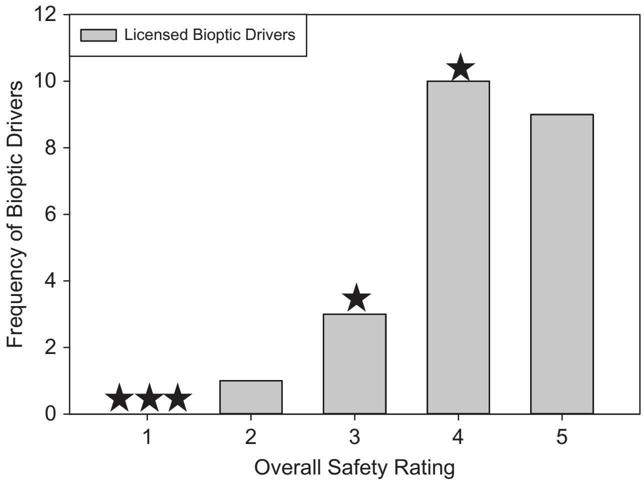

Figure 2. Overall global rating of driving performance by the backseat evaluator for the licensed bioptic drivers and the individual trainee bioptic drivers (represented by stars).

Data on the component driving behaviors are given in Table 3 and demonstrate that the trainees performed significantly worse compared to the licensed drivers for several driving behaviors, including lane keeping, gap judgments, speed choices, steering steadiness, scanning, and use of the directional indicator. However, there were no significant differences for obeying signals and braking was marginally significant.

Table 4 presents median data for percent correct detection of traffic light colors, pedestrians, and correct reporting of road signs (separated into regulatory and non-regulatory) for licensed and trainee bioptic drivers. The majority of traffic light colors were correctly detected by drivers in both groups (bioptic licensed drivers median = 96%; trainee bioptic drivers median = 92%). While the licensed bioptic drivers correctly detected the traffic signal color more often than did the trainees, this difference did not reach significance. Similarly, both licensed and trainee drivers detected most of the pedestrians (with median values of 100%) and there were no between group differences. However, as a group, the licensed bioptic drivers correctly reported road signs more often than did trainee bioptic drivers, regardless of whether the signs were classified as regulatory or non-regulatory though these differences were not significant. It is interesting to note, however, that for both licensed and trainee drivers, the regulatory signs were more likely to be detected and recognized, suggesting that the bioptic drivers prioritized detection of those signs that were most critical to road safety, and that would result in a potential traffic violation if not obeyed.

Table 5 presents the number and direction of head movements, dipping head movements, and lane keeping for the licensed and trainee drivers. The trainee drivers made significantly less small rightward head movements and crossed the right hand lane markings significantly more often and were out of the lane to the right for longer than were the licensed bioptic drivers. While the trainee bioptic drivers made more dipping movements than did those who were licensed, these differences were not significant, possibly because there was such a wide variation in dipping behavior in each group (licensed bioptic drivers: minimum: 0, maximum: 318; trainee bioptic drivers: minimum: 1, maximum: 194).

Table 6 summarizes the data for the reports generated by the instrumentation in the vehicle; we have focused on the speed bands of 0–15 mph and 15–35 mph as in our previous study; bioptic drivers drove the majority of the route within these speed bands (Wood et al., 2013). However, while our previous study found significant differences in a number of outcome measures including braking events and jerky cornering between the bioptic versus control drivers, here the only significant difference

Table 3. Component ratings of driving performance by back seat evaluator.

	Licensed Bioptic (n = 23)			Trainee Bioptic (n = 5)			
	Rating, n (%)						
Driving Behaviors	1	2	3	1	2	3	Trainee bioptic drivers vs. Licensed (p-value)
Scanning	0 (0)	1 (4)	22 (96)	0 (0)	3 (60)	2 (40)	0.0115*
Lane position	0 (0)	8 (35)	15 (65)	3 (60)	2 (40)	0 (0)	0.0005**
Steering steadiness	1 (4.3)	8 (35)	14 (61)	3 (60)	1 (20)	1 (20)	0.0230*
Speed	0 (0)	14 (61)	9 (39)	3 (60)	2 (40)	0 (0)	0.0016**
Gap judgment	0 (0)	3 (13)	20 (87)	1 (20)	3 (60)	1 (20)	0.0077**
Braking	0 (0)	8 (35)	15 (65)	1 (20)	3 (60)	1 (20)	0.0534
Using directional indicator	0 (0)	5 (22)	18 (78)	1 (20)	3 (60)	1 (20)	0.0121*
Obey traffic signals	0 (0)	1 (4)	22 (96)	0 (0)	1 (20)	4 (80)	0.3307

Notes. *p < 0.05, **p < 0.01.

Table 4. Median values (minimum–maximum values) for the percentage of correct detection of traffic light color, presence of pedestrians on the road way, and traffic signs.

Measure	Licensed Bioptic n = 23	Trainee Bioptic n = 5	p
Traffic light score (%)	96.0 (84.0–100.0)	92.0 (76.0–100.0)	0.1869
Pedestrian detection rate (%)	100.0 (25.0–100.0)	100.0 (66.7–100.0)	0.5390
Regulatory signs recognized (%)	63.3 (33.3–90.0)	53.3 (16.7–73.3)	0.0573
Non-regulatory signs recognized (%)	43.3 (23.3–73.3)	33.3 (3.3–43.3)	0.0531

Notes. *p < 0.05, **p < 0.01.

Table 5. Median values (minimum–maximum) for the number of head movements and lane position deviations for licensed bioptic drivers and trainee bioptic drivers as derived from the video recordings collected by the Vigil Vanguard System.

	Licensed Bioptic Drivers $N = 23$	Trainees $N = 5$	
Number	Median (minimum–maximum)		p
Head movements (large) right	5.0 (1.0–9.0)	7.0 (2.0–8.0)	0.1918
Head movements (small) right	11.0 (4.0–30.0)	7.0 (3.0–10.0)	0.0122*
Head movements (large) left	10.0 (1.0–17.0)	11.0 (7.0–14.0)	0.9519
Head movements (small) left	13.0 (6.0–35.0)	11.0 (5.0–15.0)	0.1853
Dipping head movements	61.0 (0–318.0)	91.0 (1.0–194.0)	0.6966
Lane crossings left	3.0 (0.0–18.0)	4.0 (0.0–33.0)	0.7396
Lane crossings right	2.0 (0.0–1)	7.0 (4.0–16.0)	0.0058**
Lane crossings total	6.0 (0.0–21.0)	18.0 (4.0–40.0)	0.0581
Time(s)			
Time out of lane—left(s)	5.6 (0.0–58.1)	6.0 (0.0–116.9)	0.6519
Time out of lane—right(s)	3.4 (0.0–33.1)	15.2 (5.4–26.4)	0.0319*
Time out of lane—total(s)	10.5 (0.0–63.4)	31.0 (5.4–132.1)	0.1586

Notes. $^{*}p < 0.05$, $^{**}p < 0.01$.

Table 6. Median values (minimum–maximum) for the outcome measures for the automated scores derived from the Vigil Vanguard System for licensed bioptic drivers and trainee bioptic drivers.

	Licensed Bioptic Drivers $N = 23$	Trainees $N = 5$	
	Median (min-max)		p
Percent of course spent 0–15 mph	29.0 (21.0–90.0)	38.0 (32.0–43.0)	0.0115*
Percent of course spent 15–35 mph	52.0 (9.0–57.0)	49.0 (40.0–51.0)	0.0709
Number of events			
Jerky acceleration 0–15 mph	1.0 (0.0–9.0)	1.0 (0.0–11.0)	0.9506
Jerky acceleration 15–35 mph	0.0 (0.0–3.0)	0.0 (0.0–2.0)	0.4064
Sudden braking 0–15 mph	2.0 (0.0–6.0)	1.0 (0.0–8.0)	0.7132
Sudden braking 15–35 mph	2.0 (0.0–8.0)	2.0 (0.0–3.0)	0.4093
Jerky cornering 0–15 mph	1.0 (0.0–3.0)	0.0 (0.0–1.0)	0.5064
Jerky cornering 15–35 mph	0.0 (0.0–3.0)	0.0 (0.0–2.0)	0.8221

Notes. $^{*}p < 0.05$, $^{**}p < 0.01$.

was in speed, where the trainee drivers drove more often in the lower speed band of 0–15 mph.

Discussion

This study is the first to provide subjective and objective evaluations of the driving ability and behaviors of trainee bioptic drivers and compare them with those of licensed bioptic drivers. Overall, our results demonstrate that while only 2/5 of the trainees were rated as safe to drive at the time of the study, there were some driver behaviors and skills that were not significantly different to those of the licensed bioptic drivers. For example, pedestrian detection and traffic light recognition were not significantly worse in the trainees, nor was their driving characterized by extreme forces as measured using the in-vehicle instrumentation. However, other aspects of driving including sign recognition, lane keeping, steering steadiness, gap judgments, and use of appropriate speeds were significantly worse in the trainees.

Interestingly, many of the driving behaviors and skills that were poorer in the trainees relative to the licensed bioptic drivers were also those that were impaired in the licensed bioptic drivers compared to control drivers as reported previously (Wood et al., 2013). For example, maintaining steady steering and a central lane position were problems common to both the licensed bioptic drivers as well as the trainees, but were significantly worse for the trainees relative to the licensed bioptic drivers. In particular, both the licensed and trainee bioptic drivers drove over the right-hand lane markings more often relative to visually normal control drivers (Wood et al., 2013). While the reasons for this are not clear, this behavior may represent a compensatory action to avoid oncoming traffic (in countries where driving is on the right side of the road); it would be useful to confirm this hypothesis by exploring whether bioptic drivers in countries where vehicles drive on the left hand side of the road exhibit a tendency to drive over the left-hand lane markings of the road.

Interestingly, the trainee bioptic drivers were also characterized by inappropriate speed choices, where they drove faster than was appropriate either for their driving ability or for the driving situation (in terms of driving challenges on curves approaching upcoming intersections) or too slowly. Problems with driving too fast may reflect the lack of experience of the trainees and be characteristic of their younger age profile, plus lack of insight and awareness of other road users. While slow driving is less of a safety issue it is also problematic given that it holds up traffic flow and can frustrate other road users. Interestingly, while the trainees were on the whole rated as driving at speeds that were too high for their ability, the instrumented vehicle data suggest that they drove at slower speeds than did the licensed bioptic drivers. This discrepancy is an important one to note when interpreting data from instrumented vehicles, in that it does not take into account the prevailing traffic conditions or the capacity of the driver to respond to particular situations which the backseat evaluators are only too aware of. Similarly, while it is clear from the backseat evaluator's ratings that the trainees exhibited poor steering steadiness, this was not identified as a particular issue in the instrumented vehicle output. This may be because these movements are not extreme enough to trigger the sensors, but are unsteady enough to be a problem in maintaining good lane control. Thus while the instrumentation provides useful information regarding vehicle control, the data need to be considered in the context of the overall driving situation and changing traffic conditions and challenges.

The finding that pedestrian detection and correct traffic signal recognition were not significantly worse in the trainees relative to the licensed bioptic drivers, or when licensed bioptic drivers were compared with visually normal controls, suggests that these skills are more highly prioritized than other driving skills. This may be because spotting traffic signals, pedestrians, and other road hazards are a particular focus of bioptic driver training or that these skills are more easily learned; regardless of the reason it is a very positive finding given that both of these driving outcomes are critical in terms of road safety. Interestingly, the trainees recognized lower numbers of road signs than did the licensed bioptic drivers, but like the licensed bioptic drivers, appeared to prioritize recognition of the regulatory signs, where they did this correctly for over half of the signs (53%), while a third of the non-regulatory signs were correctly recognized (33%). This suggests a strategic allocation of attention to those signs that are more critical to road safety and must be obeyed (e.g., stop sign, speed sign) rather than non-regulatory signs which while providing useful information (e.g., advice of a stop sign ahead, or a pedestrian crossing ahead) are not essential in order to avoid violating road rules.

The data derived from analysis of the video records of the trainees indicate that most use their bioptic telescopes frequently while driving (median of 91 times during the drive), which while more frequent than that for the licensed bioptic drivers was not significantly greater and the range of spotting was wide in both groups. The fact that the trainee drivers correctly recognized around half of the regulatory signs, and nearly all of the traffic signals and pedestrians/cyclists suggests that their use of the bioptic telescope was relatively effective. Overall, the trainees made less small head movements throughout the drive than did the licensed drivers, with these differences reaching significance for those in the rightward direction. Scanning behavior was also rated as being significantly worse overall for the trainees compared to the licensed drivers, suggesting that these skills need to be an area of focus in effective training.

The findings of this small case series of trainee bioptic drivers should be considered in light of its strengths and weaknesses. A major strength is that it establishes the feasibility of studying those in training for bioptic driving in order to provide insights into more challenging aspects of driving as well as highlighting those skills that are more easily learned. The study also allows for the generation of ideas and hypotheses that can be evaluated in future larger scale systematic studies in order to better understand the process of learning to drive with a bioptic telescope. For example, based on our findings we hypothesize that detecting traffic lights and pedestrians are easier skills for trainees to learn, while lane-keeping, steering steadiness, speed control, gap judgment, proper use of blinker, braking, and identifying advisory signs are more difficult. In addition, we hypothesize that trainees tend to drive over the right hand lane boundary in order to avoid oncoming traffic, make fewer head turns than licensed bioptic drivers, and while they often make inappropriate speed choices, extreme vehicle forces are not more likely in trainees than licensed bioptic drivers.

The results of this study must also be considered in light of limitations, which include a relatively small sample size, which limits the ability to generalize to the population as a whole, and the fact that our driving assessment provides only a single 45-minute time-frame of trainees' on-road behavior and does not address the learning process or the change in skills over time. This study also only considered a single bioptic training program, whereas it would be useful to consider the relative effectiveness of several training programs. In addition the driving behaviors were assessed on a set route and in the presence of other persons in the vehicle rather than under naturalistic conditions.

In conclusion, this study provides a useful insight into the problems encountered by bioptic drivers who are still within the training process and can be used to guide training strategies. While the sample size was relatively small, our results imply that there are some driving skills for the trainees that appeared to be relatively easy to learn while other driving skills are more challenging and need more practice and focused training. Future studies should longitudinally assess the relative efficacy of a range of bioptic training programs on a large sample of potential bioptic drivers to further investigate the hypotheses generated from this study.

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