On-Road Driving Performance in Patients with Moderate and Advanced Glaucoma

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ABSTRACT

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Purpose:

Glaucoma is an age-related ocular disease that damages peripheral vision, which is necessary for safe driving and traffic vigilance. The purpose of this study is to determine the extent that glaucoma affects driving performance and evaluate factors associated with unsafe driving. Using the gold standard of an on-road driving test (ORDT), we compared the driving performance of patients with moderate or advanced glaucoma to normal age-matched controls.

Methods:

The sample consisted of 22 elder patients (age 55+) with moderate to advanced glaucoma, and 38 age-matched subjects with no ocular disease. Through visual, cognitive and motor tests, participants were clinically assessed for off-road functioning related to the complex task of driving. The main outcome variables for driving ability was a score of pass, marginal pass, or fail on the 12-mile modified Washington University Road Test (mWURT) and a tally of the number of at-fault critical interventions.

Results:

Eleven patients (50%) scored a marginal pass or fail on the ORDT compared to 8 (21%) normal controls. Therefore, patients with moderate or advanced glaucoma were 3.8 times more likely to receive a marginal pass or fail than normal controls (95% CI, 1.20 – 11.76). Participant age, cognitive and motor ability, and traffic knowledge were significantly (p < 0.05) correlated to a marginal pass or fail score. In addition, 7 (32%) glaucoma patients required 1 or more at-fault critical interventions compared to 6 (16%) normal participants.

Conclusion:

In this sample, older drivers with moderate or advanced glaucoma performed worse overall and had a higher proportion of at-fault critical interventions on the on-road driving test than normal age-matched controls. A combination of visual and cognitive factors were associated with poor driving performance, indicating that driving is a complex multifactorial process that needs to be better understood in the elderly and vision impaired. Fostering a safe driving environment where patients are not deterred to participate (out of fear of losing licensure) is needed to obtain a larger sample size and prevent selection bias in subsequent follow-up investigations.
INTRODUCTION AND BACKGROUND

An Overview of Glaucoma, “The Silent Thief”

Glaucoma encompasses a group of ocular conditions that lead to damage of the optic nerve. This crucial nerve carries sensory information from the retina, a layer of light-sensitive tissue in the back of the eye, to the brain, for signals to be processed as images. High fluid pressure in the eye, called increased intraocular pressure (IOP) may lead to damage to the optic nerve, which is known as glaucoma. While there are four major types of glaucoma, the purpose of this study will address patients with the most prevalent type: open-angle glaucoma (OAG), which accounts for approximately 90% of glaucoma cases in the United States.¹

The anterior chamber angle is the junction between the iris and cornea that controls the rate of fluid flow out of the eye and into the circulation via the trabecular meshwork and Schlemm’s canal. Blockage of the angle causes aqueous buildup in the anterior chamber, resulting in an overall increase in eye pressure that could lead to damage of the optic nerve. Such glaucomatous damage can result in reduced peripheral vision and eventually blindness if not treated. In open angle glaucoma, there is degeneration or obstruction of the trabecular meshwork which reduces flow and fluid absorption, causing increased resistance that may lead to glaucoma.² The causes of increased IOP are often unknown.³

This increase in pressure however, is painless, devoid of early warning signs, and develops very slowly.⁴ Most people with open-angle glaucoma do not notice any change in vision in the early stages because visual acuity (VA) or sharpness is maintained, and any initial loss in visual field (VF) is barely perceptible in the
peripheral vision. Reports show that only half the people with glaucoma are aware of it. By the time the patient perceives any symptoms of vision loss, the disease is quite advanced, and the damage is permanent. Hence, glaucoma is often called “the silent thief of sight”. There is no known cure or primary prevention for this silent disease. If diagnosed in the early stages, effective medications such as eye drops or surgical intervention can at best lower IOP and maintain eyesight. Untreated, glaucoma can severely restrict the visual field and eventually progress to irreversible blindness.

Glaucoma Epidemiology and Public Health Concerns

Glaucoma is a leading cause of blindness in the U.S. and worldwide, second only to cataracts. However, glaucoma presents an even greater challenge to public health because in contrast to cataracts, any vision lost is irreversible. Open-angle glaucoma is the number one cause of blindness in African Americans, also disproportionately affecting women and Asians. Glaucoma affects one in 200 people aged 50 and below, yet increases to one in 10 for people age 80 and above. This cumulates in over 60.5 million people with glaucoma in the world today, 2.7 million of these being Americans of the ages 40 and above. By 2020, the prevalence is projected to quickly increase to 79.6 million worldwide (74% being OAG cases) and 3.4 million the U.S. From these statistics, glaucoma is clearly in and of itself an ocular disease that needs to be urgently addressed through intervention and prevention. The disproportionate morbidity of glaucoma on the elderly, a formidable and growing population in the world and U.S., especially in
regards to the “baby-boomer” generation, underscores the severity of the public health burden. Since many older adults with glaucoma are still driving, its impact on the ability to drive safely is of key public health and safety concern.

The Relationship of Vision and Driving

The U.S. will have an estimated 1 in 4 drivers on the road the ages of 65 and over by 2024, and a projected 19 million population the ages of 85 and older by 2050.17 Bilateral vision loss can negatively affect mobility and interfere with driving. Therefore, vision and health measures need to be thoroughly explored in order to inform public policy and ensure safety on the roads. In the U.S. there are between 30,000 and 40,000 fatal motor vehicle accidents each year (34,767 in 2012, rates rising for the past 2 years).15 Low vision driving, especially with older adults, is not surprisingly an emotionally valent and highly debated topic. Optometrist and lead investigator Joanne Wood16 illustrates this point by noting:

Older people constitute the fastest growing sector of the driving population and are believed to represent a high risk to road safety, given their high crash rate per distance travelled. The crash characteristics of the elderly also differ from those of younger drivers and generally involve multiple vehicles and more complex driving situations. Although the reasons for this deterioration in driving performance are multi-factorial, the age-related changes in vision are likely to be a significant factor, given the important role of vision in driving.

Many would intuitively move to discourage or ban older drivers with glaucoma from driving on the roads for fear that they would add to annual crash rates and deaths. However, there has been no research to date that definitively supports the limitation of older drivers with poor vision, with some scientific data being in fact contradictory. Public traffic policy should based on evidence, rather than on general
sentiment. Thus the relationship between vision, especially visual field as impacted by glaucoma, and driving is an important topic that demands further investigation.

Legal Vision Requirements for Driving

The Department of Motor Vehicles (DMV) in all states specifies VA limitations for driving. In most states, a VA of 20/40 or better, with an adequate VF will grant an eligible driver an unrestricted license. With vision between 20/40 and 20/70, most states would restrict nighttime driving or operating on the interstate. If combined vision in both eyes is worse than 20/70 but better than 20/100, many states require one to pass a DMV road test for a restricted driver’s license that would allow daytime driving only, inhibit interstate driving, and restrict speeds to under 45 miles per hour.

Currently, only 10 of the 50 states require a special provisions license renewal for older drivers that includes a screening vision exam. While most states have VA requirements for driving licensure, only 36 of the 50 states have peripheral VF requirements, and only 12 states set minimum VF requirements for a restricted license. Missouri (MO) is one of the few states that sets 70° binocular VF requirements for both unrestricted (may drive anywhere, anytime) and restricted (limitation of driving hours or location) licenses. Restrictions are imposed if VF of the worse eye is below 55°, yet VF of the better eye must also be larger than 85°.

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1 Dr. Kunimatsu-Sanuki, lead investigator in a glaucoma driving study recognizes that “integrating the visual field test into the requirements for a driver’s license could save lives” and advocates for creating mandatory vision screening guidelines for glaucoma patients to ensure public safety on our roadways.
Therefore, MO paradoxically may impose driving restrictions even if the binocular VF is wider than the minimum 70°. MO regulation is an example of the lack of uniformity across states regarding who can drive and how limited different people may be in terms of time and place of driving. This variability may be attributed to the lack of reliable empirical information currently available on the threshold of VF necessary for safe driving, and emphasizes the need for further thorough investigation.

Negative Implications of Driving Cessation

Driving is not simply a way to travel, but the primary and preferred mode of transportation for adults in the U.S. and other countries.\textsuperscript{20} The ability to drive has significant implications for overall health and well-being. Regardless of voluntary or mandated license revocation, driving cessation has many adverse consequences for both mental and physical health. Driving cessation has been shown to increase the risk of depression and social isolation, as well as decrease health-related quality of life.\textsuperscript{21-24} Termination of driving also limits access to healthcare services and increases the chances of placement in a long-term-care facility.\textsuperscript{24} Consequently, the inability to drive creates new and expensive problems for both the individual and society that likely requires taxpayer expenditure. The rapidly growing sector of older people in the U.S., with an impending increase from the “baby-boomer” generation, will likely add an additional public health burden requiring alternate modes of transportation, such as public transportation, para-transit systems, taxis, etc. if independent driving is severely limited.\textsuperscript{24} This could prove very difficult to
feasibly implement, given the rural and geographically variable regions people live in.

The Challenges of Detecting a Driving Problem

As reviewed mentioned, because the progression of glaucoma and vision impairment is so gradual, an individual—especially an older adult who has been driving for decades—may not notice any changes in vision, let alone riskier driving behavior. Even physicians may not conceive of glaucoma as a challenge to driving. A patient with advanced glaucoma may score a 20/25 or 20/30 from a standard vision chart, because VA may still be proficient, despite a severely reduced VF. That VA score would qualify the patient to drive in all states, but is that truly safe for public roads? Current research has not reached a consensus on that point yet.

With cataract evaluation, the ophthalmologist almost always brings up concerns for driving-related vision due to the obstruction of central vision. With glaucoma however, conversations about driving often do not come up due to the allotted time constraints of a clinical exam. Instead, the follow-up discussion is usually focused on IOP and diagnostic results, compliance to medication schedule, and side effects of treatment. Dr. Miller-Ellis notes, “Unfortunately, the reality is that most of use are seeing dozens of patients a day, and if the subject of driving doesn’t come up, we probably don’t bring it up. It’s easy for a problematic driver to slip through undetected,” vocalizing the common problems ophthalmologists face with their glaucoma patients. Since ophthalmologists are the first ones to diagnose glaucoma and detect any changes in vision, they are a primary and crucial
point of intervention for elderly drivers. Because glaucoma patients may pose a higher risk for car accidents than non-vision-impaired drivers,¹⁷ as the first point of contact, physicians arguably hold responsibility in protecting their patients and the public.

*A Review of Visual Field, Glaucoma, and Driving Relation: What Do We Know, What Do We Need to Know?*

Studies involving driving and vision impairment usually concentrate on driver safety or driver performance.³³⁻³⁴⁶⁻⁴⁻¹⁵⁻³⁸ Safety is typically measured in terms of *motor vehicle collisions* (MVCs) and then expressed statistically as an odds ratio,²⁵ where the vision-impaired group of drivers is compared to a control group with respect to occurrence of collisions. Only extreme adverse events like crashes are reported and recorded in DMV databases. Since collisions are relatively rare occurrences, very large samples (i.e. hundreds of drivers)²⁶ are necessary to adequately inform us on safety questions such as: what aspects of visual impairment increase risk of MVCs. This opens the need for investigations into the specific causality of glaucoma and VF loss on MVCs and driving performance. Certain literature links VF loss and glaucoma diagnosis to higher incidences of MVCs, yet the evidence surrounding the impact of VF loss on driving ability is still contradicting and unclear at best. Despite numerous studies, researchers have still not reached a definitive conclusion on the minimum VF necessary for safe driving. VF, crucial in peripheral vision of oncoming cars and pedestrians, is arguably one of the most important factors in driving and collision avoidance. Therefore the act of
investigators and practitioners converging on a standard minimum VF recommendation could greatly inform public road policy and effectively influence vision requirements for driving licensure.

**DMV Crash Data**

Through a combination of crash data, meta-analyses, driving case studies, and personal on-road tests, Danielson\[^{27}\] assessed 680 high risk drivers due to either VF defects or extensive accident history and found no motor vehicle accidents where VF defects were deemed to be the primary cause. Danielson’s conclusion is supported by multiple studies finding no correlation between crash rates and defective VFs.\[^{28-32}\] Conversely, Johnson and Keltner\[^{29}\] found that people with severely reduced VF in both eyes had twice the rate of crashes and traffic violations than people with normal VFs.

In regards to glaucoma specifically, McGwin et al\[^{33}\] at first found that glaucoma in itself was not correlated with an increased crash risk, yet their more recent study\[^{34}\] shows moderate or advanced glaucoma patients with VF loss in the central 24° radius of the worse eye to be at higher risk for crashes. However, the data in McGwin’s recent study is ambiguous because mild to moderate VF loss in the better eye was not associated with increased crash risk, and association of severe loss in the better eye to increased accident risk was not statistically significant.\[^{34}\] The findings of Szlyk et al\[^{35}\] using self-reported on-road accidents further compound this data, since patients with VF loss report a significantly higher rate of accidents than subjects with no VF loss. Therefore, the impact of VF defects on motor vehicle accidents as represented in existing crash data and self-reports remains
contradictory and may greatly vary depending on severity of VF loss.

From his literature review on VF and driving, North\textsuperscript{36} concludes that further research is required to adequately determine a minimum VF requirement for safe driving, and cautions medical practitioners from advising patients on driving until investigators can agree on one recommendation based on better definitive evidence. Along the same lines, Bowers\textsuperscript{26} also notes that there is no worldwide consensus as to which Goldmann (VF test) target should be used to determine functional VF for driving licensure: currently, the UK, US, and Australia all use different targets. This shows that VF parameters for driving are more arbitrary than evidence based, and highlights the need for investigators to reach a consensus on minimum VF for safe driving so that a standard legal requirement can be applied fairly and ubiquitously.

**Direct Driving Observation**

While there is a greater abundance of vision and driving studies utilizing DMV crash data, their analyses are more one-dimensional. These studies only report the most extreme cases: MVCs, and do not directly observe driving performance. As a result, crash-rate based research cannot enlighten us on driving behavior and habits, which are more relevant to daily driving and long-term risk. As shown, the relationship of VF deficit to driving is less conclusive when analyzed through MVC data. VF extent is more strongly and consistently correlated to driving ability when driving performance is evaluated directly. However the relevant studies of driving performance are sparse, and with limitations.

Wood and Troutbeck\textsuperscript{37} found that drivers with normal vision who wore VF constricting goggles while driving on a closed-road circuit took significantly longer
to reverse park and react to peripheral stimulus. However, it is questionable how accurately these VF-reducing goggles actually simulate driving with glaucomatous VF loss, since VF impairment with glaucoma is typically gradual rather than concentric, and deficits vary with eye position.\textsuperscript{38} Furthermore, degree of correlation between closed-road performance and real-world performance is unknown.

A number of studies have utilized \textit{driving simulators} to evaluate driving ability with VF loss under a controlled environment. Lovsund et al\textsuperscript{39} found that patients with VF loss were significantly worse at target detection through a driving simulator than normally sighted subjects – however, their findings do not enlighten on the task of driving itself. In another driving simulator test comparing patients with mild to moderate VF loss (mean horizontal field diameter 130° ± 21) to normal vision controls, Szlyk et al\textsuperscript{40} found glaucoma patients to have a higher accident rate than controls. Aside from that, no other differences in driving performance measures were found, perhaps due to the limited sensitivity of testing. Furthermore, Szlyk’s\textsuperscript{40} study population focused on a milder subset of glaucoma patients and did not include patients with more severe VF loss, which could account for the similarity in results between the glaucoma group and control group. Szlyk’s\textsuperscript{40} driving simulation was also only 5 min long, so it may not have been able to adequately assess driving execution in such a short period of time. On the other hand, in their driving simulator study, Coeckelbergh et al\textsuperscript{41} found that patients with moderate peripheral VF deficit (mean horizontal field diameter 84° ± 35°) had increased lane position variability, crossed more lane boundaries, and displayed less steering stability than drivers with central or mild VF loss that affected the
paracentral or midperipheral areas of vision. While these direct observation studies find a strong relationship between multiple severities of VF loss and driving performance, the controlled simulation environment may not be representative of reality, and the specific VF cut-off needed for safe driving remains to be determined.

Different forms of vision and driving research will inevitably exhibit different limitations. Driving studies featuring DMV crash data and retrospective assessment of records are limited in their ability to inform us on unsafe driving behavior that does has not yet resulted in accidents; self-reports can be subjective and biased; VF-limiting goggles do not accurately represent glaucoma, and direct-observation driving simulation may not translate to real-world driving performance under true open-road driving conditions. There are very few studies in existence using the gold standard methodology for determining fitness to drive: an on-road driving test (ORDT) that reflects actual driving and associated risks. Peli,\textsuperscript{19} is one investigator using an ORDT who “found significant correlations between residual VF size and driving performance on various skills and maneuvers for which a wise VF was likely to be important”. Similarly, in their ORDT, Bowers et al\textsuperscript{26} found that only 43% of drivers with more restricted peripheral VFs passed the fitness to drive test. However, Bowers\textsuperscript{Error! Bookmark not defined.} study does not involve a control group. Peli\textsuperscript{Error! Bookmark not defined.} and Bowers\textsuperscript{Error! Bookmark not defined.} also only focus on patients with mild or moderate glaucoma, and lack research on advanced glaucoma patients, a prevalent and especially risky driving population.

\textit{Our Study: Maintaining the Gold Standard and Filling the Gaps}
Most existing studies on VF loss and driving are lacking in either the rigor of the driving test or the severity of the sample's vision deficit. While an ORDT is most representative of true driving performance under live traffic and road conditions, the more impaired the driver, the riskier it is to administer an ORDT, for both driver and public safety. This is most likely why there is such a lack of research examining a cohort with advanced glaucoma. Prior studies have also been conflicting or inconclusive on the stance that should be taken regarding elder vision-impaired drivers on the road. Our study aims to address these shortcomings and enhance the limited information available on the more severely VF-impaired population. Through an ORDT, we evaluate the driving performance of moderate and advanced glaucoma patients, a greatly understudied group, especially in regards to driving.

PURPOSE

Our objective is propelled by the overarching societal need to enhance public safety on the road. However, the preservation of public safety should not unfairly impinge on the driving freedoms of those individuals who, despite having glaucoma retain the necessary functional skills necessary or who have made the appropriate compensations that allow for safe driving. Thus, the purpose of this study is to:

1) Compare the driving performance of patients with moderate or advanced glaucoma to age-matched controls with normal vision using the gold standard ORDT evaluation

2) Assess factors (e.g. cognition, motor, traffic knowledge etc.) associated
with unsafe driving.

Our ultimate assessment of whether patients with glaucoma can safely be allowed on the road is aimed to inform current vision standards and policy for driving.

METHODS

Participants

The study sample was composed of a group of patients with moderate or advanced glaucoma and a group of healthy control subjects with normal vision. Eligible glaucoma patients were screened and recruited from the Center for Advanced Medicine Eye Clinic, affiliated with Washington University School of Medicine in St. Louis, MO. Control participants with normal vision were recruited from general eye clinics at the same location. All ocular examinations were conducted by a board-certified ophthalmologist.

Inclusion Criteria

Applicable to all groups: All participants were required to be at least 55 years of age residing in the states of Missouri or Illinois, be currently driving under an active driver’s license, meet the minimal the legal vision standards to drive in their state of residence (namely having a VA of 20/70 or better in at least 1 eye), and not have any license restrictions due to a visual deficit.

Control Group: Healthy community dwelling older adults were recruited for the normal group to ideally match the glaucoma sample on demographic characteristics such as age, sex, educational, and race. Individuals were required to
have a normal cognitive screen (<9) and an AD-8 (8-item Alzheimer’s Disease Screening exam)\textsuperscript{42} score of less than 2, as obtained from either the participant or an available reliable informant.

**Glaucoma Group:** Subjects were required to have been diagnosed with moderate or advanced glaucoma (classified using the Glaucoma Staging Scale)\textsuperscript{43} based on VF of the better eye. An informant who was willing to: participate in the consent process, fill out standard questionnaires, and attend the recommendations meeting when the driving evaluation was completed, was also required to be present with these glaucoma participants.

**Exclusion Criteria**

Subjects were excluded from the study if they had any major chronic disease or condition that would cause significant impairment on the outcome measure (road test). Examples include, but are not limited to: advanced cardiopulmonary disease (e.g. COPD requiring oxygen) or unstable disease (e.g. diabetes with recurrent hypoglycemic events, uncontrolled seizures) that would place the driver or examiner at risk; severe orthopedic, musculoskeletal or neuromuscular impairments that would require extensive adaptive equipment to drive; sensory (hearing), and/or language impairments that would interfere with participating in the psychometric measures or road test; any neurological impairment/disease that would confound results (e.g. stroke, dementia). Exclusion also applied if subjects had less than 10 yrs of driving experience; were taking sedating drugs (e.g. new or chronic use of narcotics or anxiolytics that causes sedation); were unable to
communicate effectively in the English language; had a previous driving evaluation with the last 12 months, or did not have an active permanent driver’s license.

In addition, evidence of dementia, cognitive impairment or neurologically impairing disease, current residence in a nursing home or assisted living, ocular disease that results in visual impairment that does not meet the legal standard for driving, other significant ocular disease including but not limited to: diabetic retinopathy, significant cataracts, high myopia, etc., all resulted in exclusion from our study. Participants were also excluded if they were currently taking miotic glaucoma medications, or had recent laser or incisional eye surgery within 1 and 3 months of the study, respectively.

Measurements of Off-road Functional Abilities

Participants were clinically assessed for visual function, cognitive function, motor skills, and mental health disorders through the combination of clinician examination and surveys. The cumulative process took approximately 2 hours for completion. Since safe driving is a complex task that involves the interaction of many different factors, tests in the above categories were chosen for their conceptual or empirical contribution to driving skills. Driving questionnaires were also conducted to assess knowledge of traffic safety, driving habits and amount of driving exposure.
**Vision Measures**

Participants were clinically evaluated for a variety of visual sensory functions that may be linked to driving, through a series of tests and common screening tools. All vision tests were performed under photopic conditions. Sensitivity of visual field (VF, the total area in which objects can be seen in the peripheral vision while one or both eyes focus on a central point) was measured using the industry standard 24-2 Humphrey Visual Field Analyzer, an automated perimetry threshold test for the central 24 degrees of vision, which maps out areas of limited optic nerve fiber sensitivity at the back of the eye. The “better” eye (eye with the smaller depth defect) was used in all subsequent data analysis and evaluated through mean deviation (MD) and decibels (dB), the unit of measurement of VF. Data was analyzed through the better eye because studies have shown that visual function is more strongly correlated to visual field in the better eye, as opposed to the worse eye.45

Visual acuity (VA, sharpness or clearness of vision) was measured using the Early Treatment of Diabetic Retinopathy Study (ETDRS) chart (a standardized method used in most clinical studies) and expressed as log minimum angle resolvable (logMAR). Sloan Near Visual Acuity (an assessment of near, or reading vision) was also recorded. In accordance with the legal limit for licensure in many states, impaired visual acuity was defined as worse than 20/40.

Contrast sensitivity (CS, visual ability to distinguish between object and its background) was measured using the Pelli-Robson chart and expressed as log10 contrast sensitivity. Impaired contrast sensitivity was defined as a score of 1.5 or
lower. Glare Sensitivity (GS, ability to see clearly upon exposure to reflected or very bright light) was measured using the MCT-8000 (VisTech Consultants, Dayton, Ohio) and calculated as the difference in visual acuity (logMAR) under glare versus no glare conditions. Values greater than 0 defined glare impairment.

All visual testing followed standard protocols as stipulated by the manufacturers’ manuals. All tests except for the visual field test (in which each eye was tested separately) were administered binocularly. Since everyday visual function was of primary interest, participants wore their habitual corrections (such as glasses or contacts) for all tests except the visual field test (appropriate corrective lenses are provided during this test).

Cognition Measures

The following tests were administered to all participants to assess cognitive skills likely needed and interacting during the complex task of driving: the Short Blessed Test\textsuperscript{48} briefly screened for mental status (cut-off for an abnormal screen was typically set at a score of 9 or higher, corresponding to a Mini-Mental State Score (MMSE) score of 24); the Clock Drawing Task\textsuperscript{49} (using the Freund scoring method) tested executive function and visual spatial abilities; the Trail Making Tests\textsuperscript{50} A and B tested attention and alternating attention respectively, as well as psychomotor speed, visual scanning (only Test B assessed executive function; the Forwards and Backwards Digit Span Tests\textsuperscript{51} gauged immediate and working memory respectively). Participants were also tested on two aspects from the Driving Health\textregistered Inventory\textsuperscript{52} (DHI) to assess divided visual attention, visual
memory and speed of processing. Other cognitive tests administered include the Motor Free Visual Perceptual Test for visual closure and the Snellgrove Maze Task\textsuperscript{53} (SMT)\textsuperscript{®} for attention, visuoconstructional ability, and the executive functions encompassing planning and foresight. For all of the above cognitive tests except for the Clock Drawing Task, higher scores indicated a greater degree of impairment.

The Useful Field of View (UFOV\textsuperscript{®}; Visual Awareness, Inc)\textsuperscript{54} test was also administered to measure the speed with which participants could rapidly process (at a brief glance not involving eye or head movements\textsuperscript{55}) stimuli under differing degrees of distraction. Despite the misleading name, the UFOV is a test of cognitive processing, and not visual field, since it probes only the central 30° of the VF.\textsuperscript{56} The UFOV test consisted of three subtests of increasing difficulty, in which stimuli was presented on a touch-driven monitor, and viewed binocularly as white targets against a black background.\textsuperscript{57} The first subtest evaluated speed of processing (identification of central target), the second addressed divided attention (simultaneous identification of central target and localization of peripheral target), and the third tested selective attention (similar to the second subtest, but peripheral target was embedded among distractors).\textsuperscript{57} Three scores were derived from each subtest, recording the time in milliseconds (16 to 500 ms range) at which participants could correctly perform each test.\textsuperscript{57}

The UFOV test is an important analytical tool because it informs us on the critical intersections of cognition and vision, and has also been found in prospective and retrospective studies to be predictive of driving safety when measured in terms of crash rates.\textsuperscript{58} Owsley et al\textsuperscript{59} found that glaucoma diagnosis and UFOV were the
only significant independent predictors of involvement in an injurious crash, while UFOV was the only independent variable associated with involvement in a non-injurious crash. Therefore, it is important to evaluate vision, cognitive, and other non-vision factors in order to gain a complete understanding of all of the comprehensive skills involved in the complex task of driving, and how they may interact in glaucoma patients.

Motor Skills Measures

Standard physical examination techniques were used to evaluate the upper and lower extremities for active range of motion and strength. Standard goniometric techniques were used to determine cervical range of motion. Grip strength for each hand was assessed using an average sum from the Jamar grip dynamometer.\textsuperscript{60} As part of gait and balance assessments, motor speed and agility were evaluated using the Rapid Pace Walk,\textsuperscript{61} motor coordination was analyzed with 9-Hole Peg test\textsuperscript{62} and lower extremity coordination and speed were tested through the Delta Braking Response Time Monitor.\textsuperscript{63}

Other Questionnaires

A Driving Habits Questionnaire (DHQ)\textsuperscript{64} was administered to assess participants’ driving exposure and driving difficulty level, the National Eye Institute Visual Function 25-item Questionnaire\textsuperscript{65} was used to establish a driving subscale, and a traffic safety knowledge test was conducted to assess subjects’ road sign recognition. The Geriatric Depression Scale\textsuperscript{66} and Epworth Sleepiness Scale\textsuperscript{67} for
daytime sleepiness were also administered to collect data on factors that could affect driving.

**Outcome Measures of On-Road Driving Test**

The main outcome measures of this cross-sectional study were: overall driving performance score of either pass, marginal pass or fail, as explained in the Rating Method section, and the number of at-fault critical interventions, namely braking or steering intervention required by the driving instructor. The specifications of these outcome measures will be explained in further detail in the Rating Method section.

**Study Design**

Testing of driving ability was conducted at the DrivingConnections outpatient clinic of The Rehabilitation Institute of St. Louis (TRISL, affiliated with the Washington University Medical Center and Barnes-Jewish Hospital). Driving performance and major outcome variables were evaluated using the *modified Washington University Road Test* (mWURT), a 14-mile course running through residential and business areas in St. Louis, Missouri, designed to take each participant 1 hour to complete. The driving test (reconstructed using common traffic situations and road maneuvers from the previous WURT) is representative of various general driving maneuvers, including maneuvers expected to be difficult for people with limited visual fields.
The mWURT consists of two components: a closed course and an open-road course, both conducted between the daylight hours of 9:00 AM and 4:00 PM. The participant begins the test in the closed course, a large parking lot they can drive around in, to familiar themselves with the car and surroundings. If the subject can demonstrate proficiency with the basic operations of the automobile and follow instructions, they then proceed to the second portion of the test: open course traffic. From there, the difficulty of the test gradually increases, with more challenging tasks required in the later portion of the route. The course involves many unprotected left hand turns, along with complex merges and intersections towards the end. The test includes unprotected left hand turns because older adults are over represented in crashes while performing this specific driving task. In addition, a minor aspect of the route requires self-navigation (i.e., being able to find way out of a parking lot independently and then a return to the correct road).

**Rating Method**

The participant drives a standard 4-door sedan with a dual braking system. An occupational therapist and driving rehabilitation specialist (OTR/DRS) sits in the front passenger seat and acts as the driving instructor, monitoring safety of the car and its occupants. Another OTR/DRS directly observes driving performance in the rear seat of the vehicle and performs driving assessments in a standardized manner as trained for this study. The observing occupational therapist was blind to any information regarding which group the participant was in and their level of vision. However, the front-seat driving instructor was informed of key information.
pertaining to key safety concerns relevant for individual and public safety reasons (i.e. driver with advanced glaucoma or highly restricted visual field that might impair safe driving).

At the end of the drive, the back-seat evaluator grades the participant's overall traffic performance based on the qualitative scale of pass, marginal pass (e.g. rolling through a stop sign, a low to moderate safety concern), and fail (e.g. failure to yield to a pedestrian, constant lane drifting, and other collision-risky maneuvers). The evaluator also reports the number of at-fault critical interventions, defined as instructor-directed braking and steering, required during the course.

RESULTS

Recruitment of Glaucoma Patients

Through the process of participant recruitment, 135 moderate or advanced glaucoma patients met criteria. Of these patients, 86 were eligible, while 49 (36%) were not currently driving during time of study. The vast majority of eligible glaucoma patients: 64 (74%) of the 86, either declined or eventually withdrew from the study. Out of the 52 (81%) patients who provided specific reasons for not completing the study, 13 (25%) noted concern of driving environment and 7 (14%) noted fear of losing driving license as primary reasons for dropout. This cumulates in 20 (39%) patients who gave reasons, withdrawing from the study out of concern for external conditions that could potentially limit their personal freedoms. Scheduling issues, lack of interest, and testing center distance from home were also
listed by 15, 9, and 8 patients respectively as main reasons for opting out of the study.

**Participant Characteristics**

The final study cohort consisted of 22 patients with moderate or advanced glaucoma and 38 age-matched control subjects with normal vision. Differences in age, education, mental status, and number of vision or health comorbidities between the glaucoma and control groups were not statistically significant (Fisher’s exact test, p>0.05). Characteristics of participants by group are presented in Table 1. Median age of the entire cohort was 70.5 years, and participants had a median of 2 comorbidities; 50% of cohort was also Caucasian. The only significant difference in participant demographics was sex: more males enrolled in the study for both the normal group (20 males, 53%) and the glaucoma group (18 males, 73%).

**Statistical Analysis of Outcome Measures**

For the purpose of statistical analysis, main outcome variables were classified as a dichotomous measure: marginal pass and fail were combined and compared against the pass rating; participants were analyzed as having no critical interventions or ≥ 1 critical intervention. Results are depicted in Figures 2 and 3. Eleven (50%) of the 22 glaucoma patients scored a marginal pass or fail for the on-road driving test, compared to 8 (21%) of the normal controls (P = .04). Thus, patients with moderate to advanced glaucoma were 3.8 times more likely to receive a marginal pass or fail the than normal controls (95% CI, 1.20 – 11.76). In addition,
7 (32%) glaucoma patients required 1 or more at-fault critical interventions compared to 6 (16%) normal participants. However, these results are not significant likely due to the small sample size.

Participants in the glaucoma group who received a marginal pass or fail score were significantly older and performed significantly worse (p<0.05 by Fisher’s exact test) than the glaucoma group receiving a pass score on the following: Trails A and Maze cognition tests, the Rapid Pace Walk and Brake Reaction Time motor tests, and Traffic Knowledge of signs and functions. Scores of bilateral VA based on the ETDRS test, the Trails B cognition test, and Written Driving test were approaching significance (p<0.10 by Kruskal-Wallis test) in their correlation to pass and marginal pass or fail driving performance scores. Glaucoma group measures of off-road functionalities are summarized in Table 2.

**DISCUSSION**

The ability to drive is undoubtedly an invaluable societal necessity and privilege. As the primary mode of transportation in many countries, driving is also connected to mobility, autonomy, self-esteem, and quality of life. Glaucoma is linked to driving difficulties, driving avoidance under certain conditions, cessation of nighttime driving, and increased risk for MVCs. However, little is understood about the specific effect glaucoma has on actual driving performance and how exactly it induces unsafe driving behavior. Existing studies on this topic are either lacking in the vigor of the driving test (not real life on-road conditions) or limited to a cohort with only mild to moderate glaucoma. In this
study, we address these limitations by comparing driving performance in patients with moderate to advanced glaucoma to that of subjects with normal vision in a gold standard ORDT.

In this cohort, older drivers with moderate to advanced glaucoma performed worse on overall driving performance than normal age-matched controls. Specifically, the glaucoma cohort incurred a substantially higher proportion of marginal pass or fail scores on the ORDT and required more than one at-fault critical intervention compared to normal vision participants. Examining the glaucoma sample as a whole (collapsing marginal pass scores into the “fail” category) 50% of 22 patients failed the ORDT; in other words, 50% also passed. Since the number of safe versus unsafe driving outcomes were split evenly among the glaucoma group who were expected to perform poorly due to their severe visual impairment, these findings provoke ambivalence as to what population of older drivers should legally be driving. It remains to be answered: can public road safety be maintained without impinging on the rights of those who, despite moderate or advanced glaucoma, still retain the capability of safe, responsible driving? And to what extent is driving ability derived from a multitude of factors outside of vision – or do these factors intersect and interact?

Our results indicate that a combination of both vision and non-vision factors are involved in the complex task of driving. These findings support the increasing awareness that vision screening exams for driving licensure are inadequate and require more than just VA and VF testing. We hypothesized that driving performance would be most strongly correlated to visual defect for the moderate or
advanced glaucoma sample. However, only bilateral distance VA had a relationship to pass and marginal pass/fail scores that approached statistical significance (p<0.10). In the glaucoma group, being significantly older, female, and having comparatively lower scores for distance VA were risk factors significantly associated with poor driving performance (P<0.05).

Cognitive status, which included a component of visual scanning, was another significant risk factor for poor driving performance. Future research could explore the role of cognition in vision and driving, as previous studies have been able to predict road-test performance in drivers with dementia, and link findings with vision deficit. The group of glaucoma patients receiving a marginal pass or fail also had significantly worse motor skills, namely lower-body coordination measured from Braking Response Time, and motor speed and agility assessed through the Rapid Pace Walk. The relationship of motor coordination to vision and driving could be another topic worthy of further investigation: Haymes et al show a correlation between MVCs and the risk of falls for older glaucoma patients, which relates to our association between poor motor skills and poor driving performance.

The significant correlation we found between poor traffic knowledge and unsafe driving opens up the potential for older-driver education and training programs. These developments could enhance rather than limit independence and on-road freedom of older drivers, since traffic knowledge is easier to control and restore than functional impairment factors. Glaucoma patients may be aware of their limitations and learn to restrict their driving exposure as necessary.
Researchers have observed patients with more severe ocular impairment voluntarily limiting their driving to daytime only, choosing local over highway routes, and other compensatory mechanisms. These self-motivated measures could be implemented into new driver training programs that would allow vision-impaired patients to increase their driving safety, yet stay mobile and independent. Overall, our results illustrate that safe and responsible driving is a multifactorial process that involves not only vision, but many other crucial interactive components. Definitive fitness to drive in an individual with glaucoma is more complex than a visual screening test or road test can predict.

Further studies using similar evaluation methods and a larger sample of patients with moderate to advanced glaucoma are essential for determining better parameters for safe driving. Moderate and advanced glaucoma patients are highly prevalent in the older and vision-impaired sector, yet greatly under-studied in regards to driving performance and safety. The stark irony is that the clinical subset that could most enhance the limited literature is also the most challenging to recruit for on-road studies. According to eligibility and recruitment analysis, unease with driving environment and fear of losing licensure were major concerns and factors in refusal to participate. Naturally, older adults are cautious and hold tightly to their freedom to drive since it is extension of their mobility, independence and happiness. This highlights the difficulty of successfully incorporating the ORDT gold standard in more severely vision-impaired populations. Because an ORDT is by nature conducted on public roads in real-time, offering little control over traffic density and
other external unforeseen events, there are inevitably safety concerns for any
driver, let alone a functionally impaired driver.

Accordingly, a major limitation in our study was our small sample size, which
may contribute to some lack of statistical significance. The evidence may even
underestimate the severity of driving difficulty for patients with moderate and
advanced glaucoma, due to a volunteer selection bias. Since 74% (64) of eligible
patients refused to participate, one might anticipate that the remaining 26% (22)
who elected to complete the driving test under this research setting had either
better vision, more advanced driving skills, or a higher level of confidence in their
driving ability. Fostering a safe and controlled driving environment where patients
are not deterred to participate is necessary to prevent selection bias and obtain a
larger sample size in a follow-up investigation.

More comprehensive evaluations are needed to better understand the
interplay of driving factors like vision, cognition, motor skills, and knowledgeability.
These insights could inform public policy decisions for licensure, enhance driving
ability screening tools, and aid in the development of training or intervention
programs for improving driver performance and public road safety. Increased
vigilance for patients with glaucoma who drive does not necessarily restrict driving
privileges and independence. Proper medical care and monitoring can in fact
maintain a level of vision in glaucoma patients that enables safe driving.71 This
stresses the importance of finding a balance between public safety and personal
freedom. Given their high crash rate per distance travelled and believed high risk to
road safety,59 the fitness-to-drive of the elderly is an ever-present and hotly
contested issue. Therefore, the question of whether moderate and advanced glaucoma patients can safely be allowed on the road, and whether action is required on part of the DMV should be an urgent concern for all parties: for the public, as it has major implications for public road safety and traffic policy, as well as for the elderly, especially the visual-field impaired, because it could directly affect their daily mobility, independence, daily lifestyle, and quality of life.
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