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# Driving Simulation as a Performance-based Test of Visual Impairment in Glaucoma

**Felipe A. Medeiros, M.D.,Ph.D.**, **Robert N. Weinreb, M.D.**, **Erwin Boer, Ph.D.**, and **Peter N. Rosen, M.D.**
Hamilton Glaucoma Center and Department of Ophthalmology, University of California, San Diego

## Abstract

The fundamental goal of glaucoma management is to prevent patients from developing visual impairment sufficient to produce disability in their daily lives and impair their quality of life. Ultimately, patients are interested in how their vision will impact their ability to perform daily activities, such as driving. Although technological advancements such as automated perimetry and devices for optic nerve imaging have resulted in great improvement in our ability to quantify structural and functional damage in glaucoma, the impact on vision-related quality of life of some of the information acquired from these tests remain elusive. On the other hand, performance-based measures may be better correlated to traditional measures of vision health and, more importantly, they provide a more direct measure of disability. Driving simulators can be used as a performance-based test for evaluation of functional impairment in glaucoma. Their use can potentially help the evaluation of driving safety and performance of diseased subjects and provide insight into the different mechanisms involved in causing driving impairment in this disease. The ability to do this in an experimentally controlled and standardized setting enables testing of a much larger number of hypotheses compared to on-road evaluations. Besides evaluating driver fitness, simulators could also potentially be used as a sophisticated test to evaluate cognitive impairment in the context of an everyday task (driving) that has not been available through traditional neuropsychological assessment.

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Glaucoma is a progressive optic neuropathy that may result in significant visual impairment. The loss of vision affects the quality of life and also has economic consequences to the patient and to society.[1] With an ageing population, it is estimated that over 58 million people will have open angle glaucoma by the year 2020. With approximately 10% of affected individuals being bilaterally blind, glaucoma is a leading cause of irreversible blindness.[2] In the United States, the management of glaucoma costs about $2.5 billion per year and the disease is one of the most frequently reported reasons for a visit to the physician.[3] Furthermore, impaired health, both physical and mental, and decreased vision-related quality of life add significantly to the burden of the disease.

Clinical evaluation of glaucomatous damage is routinely based on visual field testing and assessment of damage to the optic disc and retinal nerve fiber layer (RNFL).[1] Several tests have been introduced into clinical practice to improve functional and structural evaluation in glaucoma, including automated perimeters and devices for imaging of the optic disc and RNFL.[4-10] Although these tests may have improved diagnosis and detection of disease progression, it is still unclear how abnormalities detected in these tests impact the ability to perform activities of daily living, such as driving. Further, although glaucoma has

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Corresponding Author: Felipe A. Medeiros, M.D., Ph.D., Hamilton Glaucoma Center, University of California, San Diego, 9500 Gilman Drive. La Jolla, CA 92093-0946, fmedeiros@glaucoma.ucsd.edu.

traditionally been thought as a disease restricted to the eye, recent studies have suggested that glaucomatous damage may affect cortical and subcortical neuronal populations which may result in further impairment in visual and task performance for diseased patients.[11-15] It is unclear whether conventional tests currently used for glaucoma evaluation can adequately measure and quantify the impairment associated with a broader loss of neuronal activity within the entire visual pathway of glaucomatous patients.

Driving is the primary mode of transportation in many countries including the United States and the ability to drive is intimately associated with health-related quality of life.[16-19] Several eye diseases have been associated with increased risk for motor vehicle accidents, including glaucoma.[20-29] Although it is clear that vision is essential for driving, it is not clear what vision skills and tests are actually more closely related to the ability of driving safely. Despite visual acuity being the most commonly tested visual parameter for licensure by motor vehicle departments, most studies have found no or only a weak association between visual acuity and automobile crash rates. This clearly indicates the need for a more comprehensive evaluation of visual performance as it relates to driving ability.[30-34]

Driving simulators have been increasingly used to evaluate driving safety due to their efficiency, convenience, expense and ability to assess well-controlled and repeatable driving situations that facilitate the identification of cause-effect relationships.[35-42] Because naturalistic driving data provides no experimental control and every event is unique, establishing causality based on records of crashes or from self-reported data will always be challenging. In contrast, driving simulators make it possible to replicate scenarios as often as needed under a variety of controlled settings. Besides assessing driving safety, simulators have also been used as a comprehensive method for the assessment of complex visual functioning in diseases such as Parkinson's and Alzheimer's and may offer an improved method of evaluating cognitive functions in the context of everyday tasks that has not been available through traditional neuropsychological assessment.[43-46]

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In this paper, we review the rationale behind the use of driving simulators for assessment of driving safety and visual disability. In addition, we discuss its potential role as a performance-based test for cognitive impairment in glaucoma.

## Glaucoma and Fitness to Drive

Glaucoma has been associated with an increased risk of motor vehicle accidents.[20-29,47-50] Patients with visual field defects with a bilateral horizontal field width of less than 100 degrees are more than twice as likely to have an automobile accident as those without field defects.[47] McGwin et al[51] found that glaucoma patients had a three-fold increase in the odds of a state-reported accident compared to controls without the disease. In another study, Haymes et al[52] found an even higher association between glaucoma and motor vehicle collisions, although the control group used in the study was generally healthier and had better measures of visual acuity than glaucoma subjects. Alternatively, Owsley et al.[48] showed that people involved in injurious accidents are 3.6 times more likely to have glaucoma than those without any record of accidents. Although glaucoma seems to be associated with increased risk of automobile accidents, no information about stratification of accident risk in relation to the size, shape, location or depth of visual field defects or amount of structural damage is currently available.

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Driving is critically important to most people as they depend on maintaining driving privileges for their independence and mobility. In fact, mobility outside home is cited as one of the two most important visual functions by patients with glaucoma.[53] Elderly subjects who stop driving are nearly five times more likely to move to a long-term care facility[54]. They also have higher rates of depression and report a lower quality of life.[17-19] Patients with glaucoma frequently report cessation of driving activity as they perceive more difficult driving associated with visual field damage. The Salisbury Eye Evaluation Project reported that patients with bilateral glaucoma were almost 3 times more likely to stop driving compared to individuals without the disease.[20] Similar results were found by the Blue Mountains Eye Study.[55] Additionally, some glaucoma patients restrict their driving activities, without completely stopping it, by avoiding driving at night or under foggy conditions, for example.[25] Further, glaucoma is most prevalent in older drivers who may have other coexisting ocular (e.g., cataract, age-related macular degeneration), and neurologic conditions (e.g., Alzheimer's disease, stroke), which may further impair functional vision and driver fitness.

Although some glaucoma patients stop driving due to perceived difficulties, a large number of patients with very advanced visual field loss continue to drive even after a previous collision.[21] This imposes a large risk to themselves and to the society. Further, many unsafe drivers lose insight regarding their driving performance because they have slowly adapted to their declining abilities. Current licensure requirements by Motor Vehicle Departments in most states are mainly based on visual acuity measures and, in some cases, assessment of the visual field. However, mounting evidence suggests that visual acuity is a poor predictor of driving safety and cannot reliably identify high-risk drivers. In a large study of 17,500 California drivers, visual acuity was only weakly correlated with risk of automobile crashes. This lead the authors to conclude that poor visual acuity could not be taken as a causal factor in accidents.[56] In another cohort study of 3158 subjects, a 20/40 or worse visual acuity was not associated with risk for motor vehicle collisions.[33] Although the presence of bilateral visual field defects has been more consistently associated with an increased risk for accidents, some studies have failed to report a clear association between visual field loss and motor vehicle collision rates.[31,57] Further, there is no current agreement on the type and severity of visual field defect that would be associated with an increase in driving risk. In fact, the specific visual field requirements mandated for licensing purposes are highly variable among different states in the United States. It is also interesting to note that glaucoma patients may have a higher risk for motor vehicle collision rates that cannot be completely attributed to visual field defects. This was suggested by a recent study by Hymes and colleagues[52] that found a higher rate of collisions among glaucoma subjects even after adjustment for visual field impairment. This suggests that other factors could be responsible for the increased rates.

Driving is a highly complex and often visually and cognitively demanding activity involving simultaneous use of central and peripheral vision, attention switching, kinetic depth perception, gap estimation, dynamically changing spatial orientation and evaluation of hazardous occurrences, all unfolding under the “pressure of time”.[26] Conventional visual sensory tests such as Snellen acuity, contrast sensitivity or visual field assessment seek to minimize distractions and secondary task demands. Therefore, it is not surprising that they may not be strong predictors of driving safety. Additionally, stationary visual acuity test targets may not accurately evaluate the vision skills necessary to perform well in the motion-based driving environment. Previous studies have evaluated the Useful Field of View (UFOV; Visual Awareness, Inc, Chicago, IL) as a test to evaluate driving fitness. UFOV is a computer administered test of visual processing speed and visual attention.[58] UFOV results have been shown to be a powerful predictor of the risk of motor vehicle crashes in longitudinal studies.[31,59] However, although previous studies have evaluated and detected UFOV differences between glaucoma and healthy subjects,[50,52,60,61] no comprehensive evaluation of UFOV and its relationship with different structural and functional tests of glaucomatous damage has been performed.

Eyecare specialists are often asked to assess driver fitness in patients with glaucoma or other diseases who have significant visual field defects and are attempting to renew their driver's licenses. In some situations, they feel ill equipped to make these assessments because it is not clear how to correlate visual field defects to specific driving impairments. Additionally, although they can usually reliably estimate loss of visual acuity due to cataracts, macular degeneration, glaucoma or diabetic retinopathy, they feel ill equipped to assess disorders of vision involving visual memory, visual processing speed, visual attention, and other dimensions of vision at the level of the brain. Dynamic visual, cognitive and information processing skills needed for driver fitness are not usually measured or assessed clinically, despite being recommended by the American Academy of Ophthalmology Driving Assessment Policy Statement and by the American Medical Association Physician's Guide to Assessing and Counseling Older Drivers.[62] However, as no single, perceptual, cognitive or psychomotor test captures all these domains, eyecare practitioners usually simply document the presence of ocular disease, visual acuity and visual field impairment and do not routinely evaluate dynamic perceptual and cognitive abilities associated with driving. It is clear that estimating functional vision for driving goes beyond static measures of vision and structural alterations caused by eye diseases, and involves dynamic cognitive processing of visual information, which controls driving decisions and psychomotor behaviors. These observations highlight the need for more comprehensive tests of driving performance and safety that can be applied in research and clinical settings, such as driving simulators.

## Driving Simulators to Assess Driving Safety and Visual Function Impairment

Driving simulators have become widely used to assess driving safety and performance under a variety of conditions. They have been used to assess general driving behavior in young and old populations[63] and in diseases such as stroke,[64] traumatic brain or spinal injury,[65] Parkinson's,[46,66,67] Alzheimer,[44,45,68] and attention deficit disorders.[69] Also, simulators have been used to study the influence of distracting situations (e.g., cell phone usage),[70] and alcohol or drug use on driving behavior.[71,72] The gain in their popularity stems from the increase in design sophistication which now enables realistic simulations of complex on-road situations with commercially available low-cost systems. Their primary advantage compared to on-road assessment is the ability to perform controlled experiments, that is, different types of driving scenarios can be standardized and tested repeatedly in order to assess a particular task or behavior. Although still considered the “gold-standard”, on-road assessment of driving safety can be technically difficult and may be associated with prohibitive costs, such as those related to liability insurance, track rental or course development. Furthermore, on road assessments correlate poorly with crash involvement and may carry unacceptable risks for the subjects.

Simulators can range in complexity from off-the-shelf desktop computer systems to high-fidelity complex systems with motion platforms. Although the latter would presumably provide the highest level of face or physical validity and be able to replicate most accurately real driving situations, there is evidence that far less complex systems may provide comparable or even better validated measures of driving behavior.[73,74] In fact, decreased computer costs have enabled development of simulators that can largely replicate the most advanced ones in rendering highly representative driving scenes; and this is at a fraction of the cost of simulators used previously. Lower cost driving simulation systems with lower resolution and smaller vertical fields of view have been shown to be sufficient to evaluate various aspects of driver fitness and may reduce unwanted side effects such as simulator sickness. Such capabilities have made it possible for many researchers to benefit from the availability of driving simulators.

Several driving scenarios may be replicated in a driving simulator in order to test different tasks such as regulation of vehicle speed and direction, lane positioning, obeying traffic signs and signals, negotiating curves, merging into traffic, passing into oncoming traffic, maintaining safe following distance, and response to errors by others, such as sudden appearance of pedestrians or cars in the central or peripheral field of view. These scenarios may be customized depending on the driving behavior that is under investigation. Additionally, changing weather and lighting conditions may impose additional difficulties that can be more sensitive for detection of driving impairment.[75,76]

When used as a tool to evaluate driving safety, it is essential that the performance data obtained from a driving simulator can be demonstrated to have predictive ability for driving behavior on the road. Several studies have compared the performance measured on driving simulators to that obtained on on-road tests.[63,74,77-85] Lee[63] conducted a study of 129 elderly subjects that underwent evaluation by a low-cost driving simulator and subsequent on-road performance tests. A high correlation ($r = 0.72$) was found between overall measures of performance in the driving simulator and the on-road assessment. In another study, Boydstun and colleagues[83] also found a strong correlation ($r = 0.88$) between performance on a simulator and driving tests on the road in a group of healthy subjects and individuals with motor handicap. Blaauw[82] found that performance measured on a driving simulator was able to discriminate experienced from inexperienced drivers better than an assessment conducted on the road. Schechtman et al[81] found that the types of errors most commonly made by drivers in a driving simulator were very similar to those made during on-road testing when performing complex driving maneuvers. Lew et al[39] concluded that automatic assessment of simulator performance in patients with traumatic brain injury provided valid measures that could be more sensitive predictors of future driving performance than traditional on-road assessments with a human judge. The authors suggested that this was because the simulator exposed the driver to a wider range of demands than it is safely possible on the road.

Driving simulators have also been validated using surrogate safety measures and self-reported data about motor vehicle accidents. Reimer et al[86] showed that measures of performance obtained in a driving simulator correlated well with self-reported driving history. For example, history of total speeding tickets showed a significant correlation to speeding during the driving simulator test. Also, five-year accident history was correlated with number of crashes during the simulation.[86]

## Driving Simulation as a Performance-based Test in Glaucoma

The fundamental goal of glaucoma management is to prevent patients from developing visual impairment sufficient to produce disability in their daily lives and impair their quality of life. Ultimately, patients are interested in how their vision will impact their ability to read, write, eat, dress, use a computer, interact socially or drive a car, for example. This has led to the application of so-called performance-based measures for evaluation of visual impairment in glaucoma in which the individual is asked to perform a specific task commonly encountered in daily living while being evaluated using standardized criteria.[87-90] Although technological advancements such as automated perimetry and devices for optic nerve imaging have resulted in great improvement in our ability to quantify structural and functional damage in glaucoma, the clinical significance and impact on vision-related quality of life of some of this information remain elusive. On the other hand, performance-based measures are, in general, better correlated to traditional measures of vision health and, more important, seem to directly measure disability.

Driving simulators can be used as a performance-based test for evaluation of functional impairment in glaucoma. Their use can potentially help the evaluation of driving safety and performance of diseased subjects and provide insight into the different mechanisms involved in causing driving impairment in this disease. The ability to do this in an experimentally controlled and standardized setting enables testing of a much larger number of hypotheses compared to on-road evaluations. For example, a large number of glaucoma patients with different degrees of disease severity and types of visual field defect could be evaluated using driving simulators to help elucidate risk factors for unsafe driving in this population. Studies of the association between patterns and rates of progressive visual field loss and simulator measures may help us understand the impact of adaptations to visual impairment in the ability to drive. Also, investigations of the relationships between driving simulator measures and other clinically performed tests, such as optic disc and retinal nerve fiber layer imaging assessment and function-specific perimetry, could help validate these tests as predictive measures for development of disability from glaucoma.

A few studies have conducted driving simulation in relatively small samples of patients with glaucoma. Szlyk et al[24] found that glaucoma patients had a higher number of accidents during driving simulation compared to normal control subjects and that these measures were related to self-reported history of higher number of real life accidents. Additionally, they showed that the number of accidents was correlated to the horizontal extension of visual field measured by Goldmann kinetic perimetry. In another study of glaucoma patients with mild or no visual field loss, only contrast sensitivity measures were related to driving simulator performance.[91] In a study of subjects with central and peripheral visual field loss, including patients with glaucoma, age-related macular degeneration and retinitis pigmentosa, Coeckelbergh and colleagues[92] showed that patients with different types of defect showed differential performance on several driving simulator measures. For example, subjects with peripheral field loss made more lane boundary crossings than subjects with central or mild visual field defects. Further, some of the driving simulator measures were predictive of performance during on-road test driving, such as minimum time to collision and driving speed.

Glaucoma may affect several other aspects of visual function besides those related to the presence of peripheral field loss on perimetric tests. Deficits in contrast sensitivity,[93] color and shape detection,[94,95] visual processing speed,[50,52,61] motion detection,[96-98] divided and selective attention, spatial orientation and visual search[23] can result in reduced task performance on activities of daily living, even when visual acuity is still good. The mechanism for image quality degradation and reduced task performance in glaucoma could be related to neural under-sampling as a result of retinal ganglion cell death or dysfunction.[99] Retinal ganglion cell death results in loss of neurons in the lateral geniculate nucleus and in cortical and subcortical areas of the brain which may result in further degradation of image quality and impairment in complex visual tasks.[12] Visual and task performance measures that go beyond high contrast acuity and include dimensions of vision that tap into the neural transfer function may provide new insights into glaucoma early detection, progression and task performance.

Besides evaluating driver fitness, simulators could also be used as a sophisticated test to evaluate cognitive impairment. According to Lengenfelder et al[43], virtual reality technologies such as driving simulators potentially offer an improved method of evaluating cognitive functioning in the context of everyday tasks that has not been available through traditional neuropsychological assessment. In fact, the driving simulator can be thought of as an treadmill-based exercise tolerance test for the brain[65] integrating component level visual functions (color, shape, contrast, motion, visual processing speed, divided attention, kinetic depth perception, reaction time, peripheral motion detection, spatial orientation and others) into a coordinated, system level performance task. Component level visual functions (visual performance) are tested in the context of dynamically changing task performance (driving). Like the treadmill-based exercise tolerance test that evaluates cardiac function under increasing exercise difficulty, the driving simulator evaluates visual function under increasing task performance demands. This may uncover impairments that would otherwise go undetected if the patient is only tested using conventional measures. For example, increasingly challenging visual tasks on the simulator, under low contrast, low luminance conditions and performed under the pressure of time, could potentially reveal functional impairments that would not be detected by standard visual field assessment. This hypothesis remains to be investigated.

Driving simulators have several potential limitations. They evaluate only a representation of the reality. The driving environment is simpler in a simulator than in the real world and the amount of overall information processing required by the driver is less in the simulator. However, this relative simplicity is essential in order to enable testing of specific associations or hypothesis of cause-effect relationship. Driving simulators have also been associated with simulator adaptation syndrome (SAS), characterized by autonomic symptoms such as drowsiness, vertigo or nausea during testing.[100,101] The discomfort is thought to occur due to a mismatch between visual cues of movement and imperfect or non-existing inertial cues. SAS has been reported to occur in 5% to 15% of subjects undergoing testing, although the prevalence varies according to certain risk factors such as age and type of simulator.[101,102] Questionnaires have been proposed to evaluate propensity to SAS and may help identify patients who are not suitable for testing.[100]

## Conclusion

Glaucoma is a progressive optic neuropathy that may significantly impair visual function and the ability to perform activities of daily living, such as driving. However, little is currently known about the relationship between the different measures of structural and functional damage in the disease and the risk of vision-related disability. Driving simulation can play a significant role in linking visual performance to task performance, providing a standardized way to assess driver fitness and safety, and an improved method for evaluating cognitive functioning in the context of everyday tasks. As a performance-based test, driving simulators can provide data concerning the risk of functional disability and can potentially serve as endpoints that have direct clinical impact in glaucoma clinical trials.

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