

Eyes, Brains, and Autos

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Vision disorders pose a driving safety risk and commonly arise at the level of the eye in cataract, glaucoma, macular degeneration, and diabetic retinopathy and at the level of the brain in advancing age, stroke, and Alzheimer disease and related conditions. These disorders can increase driver safety errors because of reduced visual acuity, contrast sensitivity, and visual fields. Aging and brain lesions, especially, can also reduce the useful field of view in drivers with normal visual fields; increase the attentional blink and change blindness; impair perception of structure and depth from visual motion cues and motion parallax; decrease perception of heading from optical flow and detection of impending collisions; and increase the chance of getting lost. Better tools are needed for detecting and alerting visually impaired drivers who are at greatest risk for a crash. These drivers can be assessed with a state-administered road test, instrumented vehicles, and driving simulators. Emerging safety interventions include optical and electronic visual aids for visually impaired drivers, coupled with new vehicle designs, onboard warning devices, and reflective clothing that highlights the motion of pedestrians.

BACKGROUND AND CURRENT POLICIES

Vision is critically important for safe automobile driving.¹ Drivers must monitor multiple inputs from central and peripheral vision and the other senses, allocate attention among onboard and roadway targets and distracters, and rapidly correct their safety errors while also monitoring personal fatigue or other incapacities that might compromise safety. Drivers with impairments of visual perception, visual cognition, and visual memory are liable to make poor decisions based on faulty inputs, increasing their risk of errors, crashes, and injuries.

In 1968, Burg² reported that impairments of visual acuity, glare recovery, and visual fields were associated with increased numbers of crashes and traffic violations (in 3-year records) of 17 500 California driver's license applicants. Yet, driving safety cutoff scores for common measures such as visual acuity and visual fields remain unclear decades later. Vi-

sual functions such as attention, motion, and object perception and other aspects of visual cognition that may affect driver safety are seldom measured with standard clinical visual assessment tools.

The American Academy of Ophthalmology (AAO), San Francisco, Calif, recognizes that ophthalmologists must often assess visual functions for driving licensure in patients with cataract, diabetic retinopathy, glaucoma, macular degeneration, refractive error, and other visual disorders. Yet AAO policies approved in October 2001 found few reliable visual criteria for discriminating between safe and unsafe drivers.³ Practitioners and patients face arbitrary state policies for driver restriction with visual acuity cutoffs ranging from 20/40 to 20/200. This article reviews current policies, tests, and countermeasures in drivers with visual impairment due to lesion of the eye or brain.

VISUAL ACUITY AND CONTRAST SENSITIVITY

In many states, visual acuity is the only visual criterion used in issuing a driver's li-

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cense. Letter acuity can be easily measured using the Early Treatment Diabetic Retinopathy Study chart.⁴ This common tool for assessing pattern vision has been used in several major clinical trials sponsored by the National Eye Institute, Bethesda, Md. Many practitioners would likely agree that visual impairments of 20/200 should preclude driving, but how should we judge driving fitness in patients with less severe visual impairments? The 20/40 cutoff score in many states may be unfair and is no longer supported by the AAO.

Spatial contrast sensitivity, which is the ability to perceive patterns (such as gratings or letters) presented at different contrasts, may be a better predictor of driving competency than visual acuity. Contrast sensitivity is easy to measure (left eye or right eye or both eyes) using a wall chart⁵ that provides a measure of low to medium spatial frequency sensitivity (ie, near the peak of the human contrast-sensitivity function). Owsley et al⁶ studied police-reported crash rates in treated and untreated patients with cataracts in one or both eyes and a visual acuity of 20/40 or worse. The treated group had slightly less than half the crash rate of the untreated group on 4-year follow-up. Differences in crash rates in treated and untreated patients with cataracts were predicted by contrast sensitivity scores but not visual acuity scores. Surprisingly, contrast sensitivity is not a licensing parameter in any state. Contrast sensitivity can also be measured under standard photopic conditions and under low-visibility conditions by viewing the contrast sensitivity chart through low-transmittance filters. This approach may be useful for screening drivers who have trouble seeing in low-light conditions, but it remains a research issue.

Drivers with macular degeneration have visual field loss primarily in areas of high-detail vision around fixation and may be included in discussions of drivers with abnormal visual acuity and contrast sensitivity. A study of drivers with Stargardt disease and cone-rod dystrophy affecting their central vision showed an increased crash risk only for night driving when compared with control subjects.⁷ Drivers who are aware

of their visual defect may compensate well enough to drive safely during the daytime. Some states allow such drivers with reduced visual acuity the chance to demonstrate driving competency in a road test.

GLARE

Glare can impair road visibility on sunny days in the summer, in the winter from reflections off the snow, and at night from the headlights of oncoming cars. Glare discomfort is a complex measure that may or may not be related to driver performance impairment. Glare disability is tied to performance impairment and is more directly relevant to driver safety. Laser assisted in situ keratomileusis surgery and radial keratotomy may increase glare discomfort and disability. Older drivers with cataracts may report rings of glare around glowing objects like lamps and headlights. Whether these phenomena affect driver safety is a research question. These drivers may already have impaired low-luminance vision, independent of glare. We recently found that glare disability correlated with visual attention impairments in older individuals, suggesting a decreased ability to separate visual signals from noise created by extraneous glare.⁸ Glare disability can be tested using a commercially available instrument, the Mentor Brightness Acuity Tester (Marco Inc, Jacksonville, Fla),⁹ which floods a viewer's eye with light as the viewer tries to read a visual acuity chart.

COLOR

Color cues allow us to parse information in scenes from chromatic boundaries. These cues increase the recognition of targets in natural scenes amid glare, shadows, and camouflage, which reduce conspicuity and mask object borders.^{10,11} While these roles would seem to be highly relevant to the driving task, the AAO does not recommend color-vision testing in driver assessments. This is because studies to date show no association between color-vision impairment and reduced driving performance and color-impaired drivers can use cues other than color. Note that traffic signals are often mounted in a standard vertical order so that a

knowledgeable driver can infer stop (red on top), go (green on bottom), and caution (yellow in the middle) despite color-vision loss.¹² However, in some places, traffic lights are arranged horizontally. Future traffic devices may use single, large, energy-saving LED lamps that show yellow, red, or green and eliminate position cues. Color-vision testing might then assume greater importance.

VISUAL FIELD LOSS AND DRIVING

Visual field defects, which may arise at the level of the eye or the brain, are a common reason for considering whether a patient is fit to drive. The effects on automobile driving depend on the location of the defect within the visual fields and the specific types of processes affected within the abnormal region. The many possible degrees of visual field loss correspond to different lesions in the visual pathways.

Some individuals with acquired visual field defects may experience a "hole" in their vision.¹³ The added task of having to remember to search for critical information in the areas of impaired vision might create an extra cognitive load or interference, tantamount to the burden of multitasking.

Briefly, the binocular visual fields normally subtend more than 180° across. The fovea subtends about 3° and has the highest visual acuity. The macula or parafovea spans about 10° and also participates in visual tasks that demand fine visual resolution such as reading maps, road signs, dials, and gauges. The peripheral visual fields extend beyond this and have low visual acuity but good temporal resolution and motion detection. Few would argue that keyhole or tunnel vision with fields spanning 20° would be a contraindication to licensure, but there is a vast gap between this and full monocular or binocular fields.

Wood and Troutbeck^{14,15} found that young adult drivers whose binocular visual fields were acutely constricted to 40° or less by wearing goggles had trouble identifying road signs and navigating and needed more time to complete a test-track drive. It is unclear how these acute

findings apply to real patients with chronic visual defects. Council and Allen¹⁶ found no increased overall crash risk in drivers with binocular visual field restrictions lower than 140°, yet less than 1% of the drivers had restrictions lower than 120°. Field-restricted drivers had a higher proportion of side collisions. The study did not include formal field mapping or correlation to the shape of the field restriction. North¹⁷ thought that lack of correlation between visual field loss and driving problems reflected methodological flaws in previous studies or neural recovery and compensatory strategies by drivers with an acquired field loss.

Johnson and Keltner¹⁸ screened the visual fields of 10 000 volunteers (20 000 eyes). Drivers with binocular visual field loss had up to twice the crash and traffic violation rates of those with normal visual fields. Drivers with monocular visual loss had crash and conviction rates equivalent to those of a control group. Most subjects with visual field defects had glaucoma, retinal disorders, or cataracts (and the number who had homonymous hemianopia was not specified).

Drivers with retinitis pigmentosa may have marked constriction of the peripheral visual fields causing them to be unable to detect objects approaching from the side. Fishman et al¹⁹ found a greater likelihood of crashes in 42 patients with progressive constriction of the visual fields due to retinitis pigmentosa than in 87 control subjects of similar age. Szlyk et al²⁰ found more crashes both in driving simulator tasks and state records during the preceding 5 years in 21 drivers with retinitis pigmentosa than in 31 healthy control subjects. Visual field size was the best predictor of real-world and simulator crashes.

In short, when it comes to visual field loss and driving, size matters. Severe binocular visual field loss elevates driver crash risk, but subtle visual field impairment alone is unlikely to play a significant role.²¹

EFFECTS OF CEREBRAL LESIONS ON VISION

There is a paucity of research on driving performance and crash risk due to

cerebral visual field loss. Lesions of the primary visual cortex (located in Brodmann area 17, aka striate cortex or area V1) or white matter produce defects in the visual fields opposite the side of the lesion. These defects are *homonymous* (they occupy the same hemifield in each eye because of the reversal of real-world images by the lens and crossing of nasal fibers of the optic nerve) and *congruent* (meaning the defects in the 2 eyes are nearly identical when superimposed).

Hemianopia refers to loss of half of the visual field. Drivers with hemianopia cannot see objects on one side of fixation. A visual field defect that is restricted to the upper or lower quadrant of a hemifield is known as a quadrantanopia. A lesion below the calcarine fissure results in an upper quadrantanopia. A lesion above the calcarine fissure causes a lower quadrantanopia and may have a greater effect on automobile driving because the lower visual quadrants normally possess better attentional resolution than the upper²² and are better positioned for searching the roadway panorama, vehicle controls, and displays. Damage to the macular representation in V1 is troublesome because it may interfere with ocular fixation, visual scanning, and the ability to process visual spatial details (see “Visual Acuity and Contrast Sensitivity” subsection).

Because of a lack of evidence on driving performance in patients with hemianopia, some US states are unable to disclose the criteria they use for licensing these drivers. Under many Australian and European rules, the diagnosis of hemianopia precludes holding any driver's license. Belgium has relied on medical experts to decide on the licensure of drivers with cerebral visual loss.²³ Under such policies, a driver may come under scrutiny for reasons unrelated to a visual defect and face license loss despite having driven safely for years or individuals with hemianopia since childhood may be denied a driving learner's permit despite having developed adequate compensatory mechanisms.

Paris et al²⁴ reviewed the records of 60 Canadian drivers with homonymous hemianopia. At first, 57% did not meet the minimum field requirements for an unrestricted li-

cense in any province or territory. Forty percent had some functional recovery, mostly during the first 6 months after initial diagnosis. Paris et al emphasized that various types of homonymous hemianopia may have different driving risks and that health care personnel should advise the driver of the potential risks. The problem is that there are no consistent performance-based safety standards to guide this advice.

Tant et al²⁵ studied driving performance in 28 drivers with chronic homonymous hemianopia (15 left, 13 right). Of these 28 drivers, 21 had quit driving. Driving evaluators rated reduced steering control as the most noticeable effect of hemianopia, but some individuals with hemianopia appeared to be safe drivers. Patients with hemianopia may adopt visual search strategies to successfully compensate for their defects. Hemianopia with macular involvement would seem to pose the greatest driver safety risk, but this remains a research issue.

PARALLEL PROCESSING

Stroke, trauma, and tumor commonly cause the cerebral lesions that produce visual field defects. These lesions often extend into the prestriate cortex (Brodmann areas 18 and 19 or area V2/V3) and adjacent temporal lobe and parietal lobe. The resulting defects tend to be incomplete and less well localized than those caused by V1 lesions. These defects have been explained using the simple heuristic device of parallel processing in 2 visual systems originating in V1: a “what” pathway and a “where” pathway. Lesions in these pathways can impair visual processes important to automobile driving independent of V1-type visual field defects.²⁶

Briefly, damage in the ventral occipital lobe and adjacent temporal regions along a “what” pathway is associated with defects of visual recognition (visual agnosia), color perception (cerebral achromatopsia), and reading (acquired alexia). These conditions can impair driving performance, even in the absence of a visual field defect. For example, drivers with visual agnosia may have driving safety problems

due to the inability to recognize the meaning of hazardous objects, and drivers with alexia may have difficulty reading road signs and maps.

Damage along the occipital-parietal “where” pathway is associated with defects of visually guided eye and hand control and disordered visuospatial attention and impaired motion processing (cerebral akinetopsia). Patients with Bálint syndrome, often associated with bilateral parietal lobe lesions (due to stroke or a visual variant of Alzheimer disease), have severe reductions of visual attention²⁷ and cannot drive safely. Some of these patients are looking but not seeing²⁸ (Figure). Patients with hemineglect, a neurological syndrome most often associated with a lesion of the right parietal lobe, often fail to attend to stimuli in the left hemifield, whether they have a left homonymous hemianopia, and also should not drive (see “Visual Attention and Driving” subsection).

Information from parallel pathways is also processed outside of the visual cortex. Damage to the prefrontal cortex may impair mechanisms for “executive attention” and working memory (see “Visual Attention and Driving” subsection) that briefly maintain visual information (such as the location and identity of other vehicles near the

driver’s car) so that it is available for use.²⁹ Damage to the cerebellum may impair neural mechanisms that distinguish between image movement across the retina and self-movement,³⁰⁻³² which are important for perception of heading, collision detection, and related abilities.

VISUAL ATTENTION AND DRIVING

Visual attention is of key importance to automobile driving. Standard perimetry tasks (such as Goldmann and Humphrey perimetry) minimize attention demands to gain maximal estimates of sensory ability, leading to overestimates of functional ability in elderly individuals and persons with brain damage engaging in real-world tasks that demand peripheral vision.^{33,34} Reduction in the useful field of view, the visual area from which information can be acquired without moving the eyes or head, correlates with increased vehicle crash risk.^{35,36} Useful field of view task performance depends on speed of processing, divided attention, and selective attention. The attended field of view is similar to the useful field of view except drivers are allowed to move their eyes and head.³⁷ The efficiency with which drivers can extract information from a cluttered scene (such as a busy traffic intersec-

tion) begins to deteriorate by 20 years of age.³⁸

Change blindness is an example of a type of blindness that occurs even in persons with normal vision and is the inability to detect critical changes in a scene because of a brief visual disruption. The disruptions can include saccades, flickers, blinks, camera cuts,³⁹ or gradual image changes.⁴⁰ Change blindness probably depends on visual working memory and spatial attention.⁴¹ Change blindness is more likely when working memory is occupied by other information or working memory capacity or duration is impaired (eg, because of aging, neurological disease, drugs, or fatigue), and it reduces the ability to perceive salient changes in traffic-related scenes.^{42,43}

The attentional blink is another type of blindness that can occur in people with normal vision. When we identify a visual object, our ability to perceive a second object is impaired for several hundred milliseconds (because visual working memory is still occupied by the first object when the second arrives). This period, known as the attentional blink, is not due to an eye blink and can be measured in a laboratory setting using a rapid, serial visual presentation of visual targets (often a sequence of letters) on a computer monitor. The attentional blink can increase pathologically because of reduced temporal processing speed and working memory in patients with a variety of brain lesions.⁴⁴ Increased attentional blink may impair a driver’s ability to perceive information from a continuous stream of signs, lights, roadway obstacles, and other vehicles.

Safe driving also requires executive attention to switch the focus of attention among critical tasks such as tracking the road terrain; monitoring the changing locations of neighboring vehicles; reading signs, maps, traffic signals, and dashboard displays; and checking the mirrors.⁴⁵ This involves switching attention between disparate spatial locations, local and global object details, and different visual tasks and is thought to rely on mechanisms in the prefrontal areas.⁴⁶ Note that cell-phone conversation diverts the



Intersection incursion crash in a patient with homonymous hemianopia. The crash occurred during a simulated intersection incursion. The driver, who has a dense right homonymous hemianopia, fails to detect an illegally incurring vehicle from the right side and broadsides the vehicle at highway speeds.

brain's attention to an engaging cognitive context and interferes with visual demands of driving.⁴⁷ A multitude of gauges, dials, radio controls, and "infotainment" displays in modern vehicles provide similar interference.

VISUAL OBJECT STRUCTURE, MOTION, AND DEPTH

There is little evidence that impairments of binocular stereopsis, which may affect up to 10% of the general population, affect driving safety. This is probably because information on object structure and depth is so critical for interacting with objects and obstacles that our brains use multiple redundant cues.⁴⁸ These cues include accommodation, convergence, binocular disparity, motion parallax, texture accretion/deletion, convergence of parallels, position relative to the horizon, relative size, familiar size, texture gradients, edge interpretation, shading and shadows, and aerial perspective.⁴⁹ Understanding the role of these redundant cues in the driving task is an active research topic.

Briefly, perception of structure-from-motion or kinetic depth is a real-world use of motion perception that may fail in patients with visual cortex lesions due to stroke⁵⁰ or early Alzheimer disease.⁵¹ Structure-from-motion deficits in drivers with brain lesions are associated with increased relative risk for safety errors and car crashes in driving simulation scenarios.⁵²

Recovery of depth from motion relies on relative movements of retinal images. For motion parallax, relative movement of objects is produced by moving the head along the interaural axis. Impairments of motion parallax may be a factor in vehicle crashes involving drivers with cerebral impairments, when the drivers must make quick judgments with inaccurate or missing perceptual information regarding the location of surrounding obstacles, and may contribute to crashes involving alcohol intoxication.⁵³

Displacement of images across the retina during self-motion (egomotion) produces optic flow patterns that can specify the trajectory of self-motion with high accu-

racy.⁵⁴⁻⁵⁶ Perception of heading from optical flow patterns can decline because of aging and drugs such as marijuana (THC) and ecstasy (MDMA), presumably because of chronic effects on cholinergic receptors (with THC) and serotonergic/5-hydroxytryptamine-2 receptors (with MDMA).⁵⁷ Processing of visual motion cues also may be impaired in patients taking antidepressants, such as nefazodone hydrochloride, that block serotonin reuptake.⁵⁸

Detecting and acting to avoid impending collision events require information on the driver's vehicle and approaching objects. Objects on collision paths with the driver maintain a fixed location in the driver's field of view, whereas safe objects will translate to the left or right side. Time to contact is estimated from the expanding retinal image of the approaching object. Older drivers are less accurate than younger drivers at detecting an impending collision during braking^{59,60} and at determining if an approaching object in a driving scene will crash into them.⁶¹ Performance is worse for longer time-to-contact conditions, possibly because of a greater difficulty in detecting the motion of small objects in the driver's field of view.⁶¹ Judgments on time to contact can be measured in real life using radar detectors.⁶²

NAVIGATION

Navigating a route relies on visual perception, attention, spatial abilities, and memory. Drivers with topographical disorientation have navigation problems despite normal or near-normal visual sensory abilities.^{63,64} Patients with topographical disorientation may have lesions in inferotemporal regions, posterior parahippocampal regions, and the hippocampus, especially in the right hemisphere. Causes of topographical disorientation include stroke, trauma, and neurodegenerative diseases including Alzheimer disease.⁶⁵ Associated problems include visual agnosia and other memory-related disturbances. Aspects of complex disorders of visual processing associated with driver navigation impairments can

be tested with the Trail-Making Test, Benton Visual Retention Test, and the Complex Figure Test.^{45,66,67}

RECOMMENDATIONS AND COUNTERMEASURES

The AAO recommends that drivers with vision loss of "intermediate" severity be allowed to take a road test to assess if they can compensate for the measured loss. Road tests assess driver performance under the supervision of trained experts and are often assumed to be the "gold standard" of driver fitness. The licensing authority may then grant an unrestricted license; restrict driving to certain conditions, destinations, areas, or equipment; or deny licensure. Yet road tests were developed to test if novice drivers had learned to apply the rules of the road, not to test experienced drivers who may have become impaired. Road testing carries the risk inherent in the real-world road environment. Test conditions vary depending on the weather, daylight, traffic, and driving course. Driving experts may have different biases and scoring criteria, and there are few data to show that road-test scores predict crash involvement. The use of driving simulation (Figure) and instrumented vehicles offer more controlled and less biased assessments of driver performance.^{45,68}

The AAO recommends testing visual sensory, motor, and cognitive abilities in at-risk drivers. If possible, training and interventions should be offered to mitigate deficiencies. Drivers may wear glasses or contact lenses as needed to optimize visual acuity. Drivers with reduced contrast sensitivity may benefit by avoiding dawn, dusk, and nighttime driving and by wearing yellow-filter lenses. Some drivers find that glare is reduced by wearing yellow filters and polarized lenses. The effect of reduced visual acuity and contrast sensitivity on driving safety may be decreased by restricting travel to familiar low-speed roads and avoiding rush hour, nighttime, and poor weather conditions like rain, snow, and ice.

Bioptic lenses are sometimes prescribed to allow drivers with low vision to see magnified images of

traffic signals and signs through telescopes mounted on glasses.⁶⁹ Efficacy should be demonstrated case by case. Safety benefits and drawbacks of these devices are research issues. Overlap of the expanded image onto the background produces a ring scotoma; whether this actually increases risk for crashes is a research question. Other issues with optical and electronic techniques that inlay images of areas of interest in traffic scenes are user acceptance, training, adaptation, and cost. Some of the older drivers who might use these devices have difficulty dividing attention between 2 sources of information and do not even check the gauges and mirrors. Because it takes several hundred milliseconds to direct attention from the natural scene to the high-resolution inlay, sudden traffic conflicts might catch the driver unaware.

Reductions in the useful field of view can be partially reversed by training effects that can be maintained for at least 1 year⁷⁰; the transfer of this training to driving performance is under investigation. Rehabilitation strategies in homonymous hemianopia include compensation, adaptation, and restoration.²⁵ Enlarged side and rearview mirrors may aid some drivers with peripheral visual field defects. Dangers arising in the vehicle's blind spot can be detected with modern sensors that trigger devices to warn the driver of the impending danger by haptic, voice, or visual cues.

Of note, while people have poor vision, cars have blind spots. The pillars between the doors produce wedge-shaped areas of blindness trailing off obliquely from the mid-section of the vehicle. The posts at the end of the windshield create blind spots going obliquely off the front part of the car. There are industry efforts to mitigate these blind spots with the use of mirrors and cameras, although added displays may offer more interference and distraction from the road. Night driving uses photopic vision, made possible under the illumination provided by streetlights and a car's headlights. Modern cars (eg, some Cadillacs since 2000) have "night vision" systems to allow cars to "see" beyond the headlights in the dark.

These displays are not meant to supplant other driver cues but to augment these cues and to add information that can help the driver. Such a system is not a prosthetic or aid for the night vision-impaired driver, and a night vision-impaired driver should not expect to benefit from a car equipped with night vision.

Finally, about 78 000 pedestrians are struck and injured by cars each year in the United States; nearly 5000 of those struck are killed, and more than 60% of these injuries occur at night.⁷¹ Use of reflectors around joints producing motion cues may be a wise prevention strategy at night for pedestrians. Drivers are much better able to recognize pedestrians at night who wear reflective tape around the joint areas of clothing (wrists, elbows, shoulders, knees, ankles) as opposed to a reflective vest or white clothing.⁷² By the time an older driver detects a pedestrian in black clothing, it is often too late.

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