Vision Assessment Technology and Screening Older Drivers: Past Practices and Emerging Techniques

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Three topics related to the visual screening of motor vehicle operators are reviewed. First, procedures used to test driver vision in the United States are examined. The most frequently assessed visual functions and the technology typically used to test these functions are summarized.

The second area of inquiry is research efforts to develop a "scientifically valid" technology for testing driver visual function. Coverage is given to the U.S. Department of Transportation's research initiatives, which led to the development of the MARK I and MARK II series of integrated devices for testing driver vision. Conclusions drawn from the review of these programs were used to formulate objectives and guidelines for future research on such testing.

The third, and major, topic covered in this paper is the description and evaluation of emergent technologies that could affect future developments in mass visual screening programs. This review is focused on recent advances in psychophysical data collection procedures as well as advances in visual imaging hardware and clinical testing devices.

Finally, recommendations for implementation of new assessment approaches and critical research needs for driver vision testing are summarized.

Throughout the paper, special emphasis is placed on the interactive influence of human aging and technology and its applications.

CURRENT VISUAL ASSESSMENT TECHNOLOGY

Many stimuli and environmental factors can exert a systematic influence on performance during a visual screening task. Visual acuity level, for example, changes as a function of target luminance, contrast, spectral composition of the light source, and density of the spacing within multiple target arrays. Subject factors, such as the adaptation state of the eye and whether the target is being viewed monocularly or binocularly, strongly influence visual sensitivity scores *(1)*.

Commercial devices known as industrial vision screeners have been developed to provide a self-contained visual environment that controls the stimulus parameters that can alter vision test performance. These screeners ensure that all individuals are screened under fair and equivalent conditions.

Virtually all of the agencies in the United States that administer driver's license applications and renewals employ such commercial vision screeners in their day-to-day assessment of visual function. The major suppliers of this type of equipment include the American Optical, Bausch and Lomb, Keystone Mass, and Tracor and Titmus corporations. These four vendors supply the vision-testing equipment used by the great majority of driver-licensing agencies. Although they differ in some respects, these devices share many common features of basic design and operation.

In general, vision screeners are electromechanical devices that are compact, portable, and totally self-contained. Perhaps the most important feature of these devices is that they isolate the target stimuli from ambient room illumination by means of functionally light-tight enclosures. Backlighting the targets is done entirely by lamps housed within the device itself. All of the screening devices manufactured by the major ophthalmic vendors can accommodate individuals wearing eyeglasses and require no special optical or medical skills to operate.

These commercial vision screeners can be described as precision stereoscopes with built-in illumination sources. They are capable of delivering independent stimulus images to each eye, which makes possible monocular and binocular testing that fully loads the need for visual fusion. Distance vision is assessed with fixed lenses that effectively place the targets at optical infinity (i.e., 6 m or farther). The visual tests performed by the typical commercial screening device include near (25- to 40-cm) and distance binocular acuity, red-green color blindness, depth perception, lateral and vertical phoria, and horizontal visual field. The field test device is usually optional equipment. This battery of tests can be administered in less than 3 min by an experienced examiner *(2)*.

Binocular Distance Acuity

The procedures used in all of the commercially available vision-screening devices to assess acuity are quite similar. Stimulus targets, the correct identification of which requires varying degrees of visual spatial resolution, are presented via backlighted transparencies. Luminance of the acuity targets varies from approximately 30 to 60 cd/m^2 placing the stimuli firmly within the photopic range of visual sensitivity. Stimulus contrast in all cases exceeds 95 percent. The targets are usually arranged hierarchically from largest in spatial detail (easiest to identify) to smallest in detail (most difficult to identify). Typically, the response criteria are defined in such a manner that an observer has only a 20 to 30 percent chance of "passing" a given level of acuity on the basis of chance (i.e., guessing).

The major difference among the screening devices is the type of target (or optotype) they employ. Several families of optotypes are currently used in the screening of driver's license applicants. They include the familiar Snellen and Sloan letters *(3)*, the illiterate-E or Lazy-E, the Landolt-C, square-wave gratings, checkerboard patterns, and a spatially localized dot pattern used on the Keystone tester. It should be noted that several of the commercial vision screeners support more than one family of optotype.

Figure 1 shows examples of three widely used test stimuli that do not belong to the Snellen or Sloan family of optotypes; namely, a checkerboard, the Landolt-C, and the Keystone stimulus. The crucial detail of each of these optotypes can occur at any of four cardinal orientations: top, bottom, left, or right. Hence, the probability of correctly guessing the critical element of each stimulus level is maintained at 25 percent. Although the critical gap of the Landolt-C could also appear at the four diagonal positions, in practice this is avoided because the report of 8 degrees of freedom becomes awkward and difficult to communicate efficiently (i.e., problems with task instructions arise). The magnitude of the critical spatial detail subtended by each optotype is varied by changing the overall size of the target.

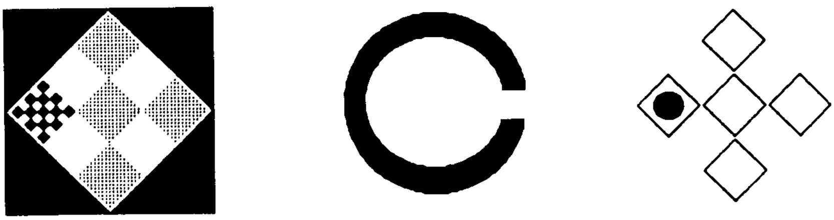

FIGURE 1 Sample optotypes used to assess visual acuity.

Although the acuity measurements yielded by the various vision screeners are highly comparable, small but systematic differences have been noted. For example, the data of Waller et al. *(4)*, which appear in Figure 2, show a systematic difference between acuity measurements made using the Bausch and Lomb Orthorater and the Keystone vision tester. The proportion of license renewal applicants who passed the 20/40 binocular acuity standard was higher when the Orthorater was used. This pattern of results can be attributed to the only major difference between the Orthorater and the Keystone screener, different test targets. The Orthorater unit employs the checkerboard optotype whereas the Keystone tester uses the localized-dot stimulus (Figure 2).

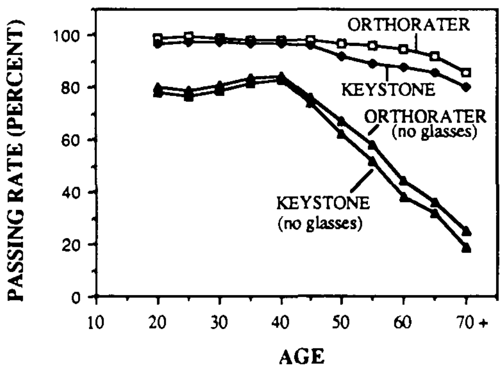

FIGURE 2 Passing rates on the Keystone and Orthorater vision testers as a function of driver age and state of optical correction [after Waller et al. *(4)*].

Hills and Burg *(5)* reported a systematic difference in binocular distance acuity of driver's license renewal applicants who were tested using both the Bausch and Lomb checkerboard optotype and the standard Snellen letters. This investigation was based on a re-analysis of a subsample of 4,753 subjects from Burg's *(6, 7)* earlier studies of driving and vision. It was reported that the correlation between the two acuity measures was only 0.70. Although the acuities generated by the different tests tended to coincide in the normal range of vision (around the 20/20 level), the functions diverged in the range where acuity levels begin to denote suboptimal performance. For example, 20/40 Snellen acuity was found to be equivalent to Orthorater acuity of 20/30. As was the case with the Keystone tester, the Orthorater appeared to be somewhat less conservative (i.e, less stringent). In practical terms, this meant that 46 drivers would have failed the screening test based on the Snellen optotypes whereas only 18 would have failed had the Orthorater standard been applied. Hills and Burg *(5)* explained this difference in terms of the checkerboard optotype's lessened sensitivity to astigmatic (cylinder) error in certain orientations. Provisions for eliminating such differences between tests of visual acuity have been proposed by the National Research Council (NRC) Committee on Vision *(8)*. This NRC report establishes comprehensive guidelines for the assessment of both near and far visual acuity. However, these guidelines are too new to have affected the design of mass vision-screening devices such as those employed in the testing of drivers.

Both the Tracor and Keystone vision testers offer "nighttime" visual acuity options. These tests purportedly simulate nighttime driving conditions by using neutral-density filters to attenuate stimulus luminance down to 10 percent of standard levels (approximately 3 to 10 cd/m^2). This luminance is in the low photopic range and is equivalent to the lighting levels that characterize urban roads at night. Two states, Kansas and Tennessee, have incorporated this form of night vision test into their driver-screening programs. Kansas requires the night vision tests only for drivers aged 65 or older. Persons whose scores are less than 20/50 on this test may have their licenses restricted to daylight driving. Tennessee tests the night vision performance of all applicants. Those who score worse than 20/70 are limited to daytime driving *(9)*.

Changes in the eye that accompany normal aging include a reduction in the size of the pupillary aperture and progressive opacification of the crystalline lens *(10)*. These two factors combine to markedly attenuate the amount of light that ultimately reaches the retina of the older adult. For this reason it is probable that older drivers would be affected by the adoption of low-luminance night vision tests. Two recent investigations confirm this.

Rice and Jones *(11)* examined corrected visual acuity under normal and reduced (i.e., nighttime) illumination using a Tracor integrated vision screener. Of 4,038 drivers who passed the test under standard levels of illuminance, 267 (6.6 percent) were unable to pass the night vision version of the test. Older persons were disproportionately represented in the group that failed the night vision test. The likelihood of failing either the daytime or nighttime version of the acuity test is plotted as a function of age in Figure 3. Reference to this figure reveals that the probability of failing the night vision test remains low for those under age 50. However, the rate of failure for this test climbs to 36 and 68 percent for the 61 to 70 and 81+ age groups, respectively. Similar findings were reported in an earlier study of license renewal applicants using the Keystone vision tester equipped with the night vision option *(4)*. Additional research is warranted before arbitrary cutoffs are established for low-luminance vision.

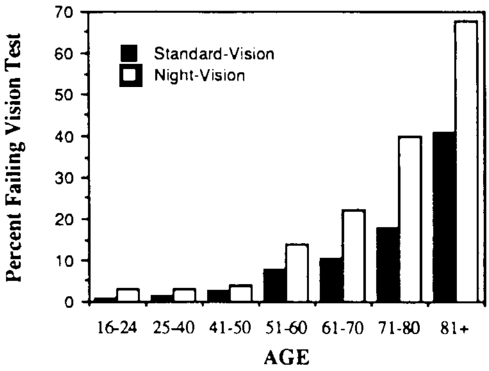

FIGURE 3 Failure rates on regular and night vision screening tests as a function of age of driver [after Rice and Jones *(11)*].

Visual Field Testing

Two basic schemes for assessing the extent of the horizontal visual field have been used in vision-screening devices, a mechanical approach and an electro-optical approach. The mechanical approach, as optionally implemented in the Bausch and Lomb Orthorater, will be discussed first.

The peripheral field test of the Orthorater consists of a small white ball attached to the end of an L-shaped arm. The arm is mounted on the top of the main body of the screening device with a pivoting joint. The arm can be manually rotated to position the target (a white ball) anywhere along a 360-degree arc surrounding the observer's head. The target is maintained at approximately eye height. By having the observers fixate a stationary target straight ahead and instructing them to report the disappearance and appearance of the target as it rotates about their heads, the administrator can determine the extent of observers' peripheral fields of vision.

Validation studies comparing the Orthorater field test with more rigorous clinical assessment of perimetry have indicated that the Orthorater tends to slightly underestimate field size. For example, Allen et al. *(12)* collected monocular temporal field estimates from both eyes using the Orthorater and the Clement-Clarke perimeter. When full-field estimates of peripheral vision were compiled by combining the monocular results, the Orthorater fields were found to be more contracted than those obtained for the same individuals using the clinical perimeter (i.e., 173 versus 188 degrees).

The test-retest reliability and the inter-rater reliability of the Orthorater field test have also been investigated. Neil and Johns *(13)* reported that Orthorater test-retest reliability was good ($r > 0.87$), especially for estimates obtained while the target changed from being invisible (behind the head) to visible. They also found that inter-rater reliability among experienced driver's license examiners was exceedingly high ($r > 0.96$).

The Orthorater's mechanical field tester is relatively accurate and reliable. Another advantage of the device is that the examiner has an unrestricted view of the observer's eyes and therefore has no difficulty in monitoring the maintenance of central fixation. However, an important disadvantage of the Orthorater visual field test is that it is quite time consuming to administer because of the intense instructional demands that result from the relative unfamiliarity of the task to the observer *(14)*.

The electro-optical approach to assessing horizontal peripheral vision is the technique most commonly employed by driver-licensing agencies. The Tracor, Keystone, and Titmus screeners all use this approach for field tests. Point sources of colored light are placed in a circular perimeter that extends horizontally from the main viewing aperture of the screening device. The target lights are mounted within this perimeter at varying angular displacements from the principal vertical meridian. The examiner must ensure that the observer fixates a centrally located target and maintains firm pressure against the forehead rest mounted above the viewing aperture. If the observer's forehead is not placed against the headrest, the far peripheral targets effectively move toward the center of the visual field and the validity of the test is compromised. It is primarily for this reason that electro-optical field testers have been reported to be less reliable than mechanical tests such as those employed in the Orthorater *(4)*.

In an attempt to control this problem, some models of the Keystone vision tester have an alarm indicator that warns the examiner when ample pressure is not maintained against the headrest. After the observer is properly positioned in the apparatus, the point sources of light that extend between 50 and 85 degrees into the temporal field are briefly flickered. The observer's task is to report the occurrence of such peripheral stimulations. In the typical test protocol, the temporal fields of both eyes are tested in parallel so that the observer's task is to report when and where (left or right) a peripheral target is presented.

The Titmus sector test is representative of the electro-optical approach. Self-illuminated target discs subtending a visual angle of 1 degree are positioned 55, 70, and 85 degrees into the temporal fields of each eye. A single stimulus point appears at 35 degrees into each nasal field. The test administrator manually selects and delivers the briefly presented peripheral stimuli while monitoring the observer's fixation. In practice, test administrators begin with the most extreme temporal target (i.e., 85 degrees) and terminate testing if that target is detected in both eyes *(14)*. The implementation of the electro-optical field test on the Keystone device is similar to the Titmus test [see Waller et al. *(4)* for a detailed description].

In practice, all of the visual field tests are administered without the use of eyeglasses. This is necessary because spectacle frames can occlude the peripheral field targets. Because the field test is a light detection task and does not require fine spatial resolution, testing without optical correction does not put individuals who suffer from refractive error at a disadvantage.

A final note on electro-optical field tests concerns their apparent insensitivity. Studies involving large numbers of drivers screened with sophisticated clinical perimeters show variability in the extent of individuals' visual fields—especially those of the elderly *(15, 16)*. However, studies of drivers using the more common electro-optical field screeners often fail to detect an age-related decrease in field size. Several large-scale studies could not detect any drivers who failed the field test *(4)*. Rice and Jones *(11)*, for example, screened peripheral vision in 4,544 Oregon drivers and detected only one case with a significant field loss. This pattern of results suggests that apparatus and procedures currently employed to test drivers' visual fields need to be studied further.

Color Blindness

Approximately 4 percent of men and 0.5 percent of women suffer from red-green color blindness *(17)*. The techniques employed by most states to assess this form of color blindness are directly or indirectly based on the Dvorine and Ishihara color plates, the familiar "hidden" color figure test.

The stimuli are composed of multiple dots of varying size and color. They are constructed in such a way that color contours (instead of luminance contours) are used to form alternate pairs of spatial figures.

Typically, the normally sighted individual will report seeing one figure, and the color-deficient individual will report seeing an entirely different figure or object. For example, on one of the Ishihara plates the number 74 is clearly visible to the normally sighted observer; the red-green color-blind observer reports seeing the number 21.

Stereopsis

Binocular depth perception, or stereopsis, is the three-dimensional depth sense mediated through the simultaneous use of both eyes. The most common technique for assessing depth perception in mass screening is the use of stimuli that progressively vary in the degree of retinal disparity that they generate *(18)*. That is, identical images are presented to both eyes through independent optical paths. If properly aligned, these separate retinal images are perceptually "fused" into a single object by the visual system. If a small part of the stimulus presented to one eye is laterally displaced with respect to the stimulus presented to the other eye, a local region of retinal disparity results. This change in retinal alignment across the eyes is the critical stimulus information needed to perceive binocular depth. The less disparity needed to detect a test object as being "closer" than its retinally aligned surround, the better is the subject's stereoscopic vision.

Stereopsis is objectively assessed by presenting the observer with a series of stimuli of progressively diminishing binocular retinal disparity. The minimum disparity, measured in seconds of arc, at which a subject can correctly discriminate the presence of "apparent depth" yields the stereopsis score.

The stimuli for the stereopsis test implemented on the Bausch and Lomb Orthorater are shown schematically in Figure 4. This test is representative of

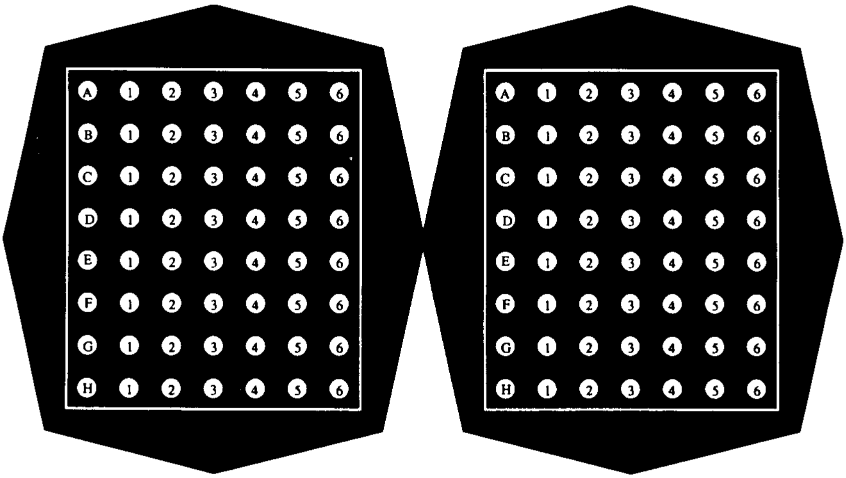

FIGURE 4 A typical "stereo pair" stimulus used to assess binocular depth perception.

the approach used in most mass vision screeners. The two stimuli shown in Figure 4 are presented to the left and right eye, respectively. The two images are identical in all respects except the alignment of a single circular target on each row. The binocular disparity generated by these nonaligned targets provides the information needed to detect depth. The observer's task is to report the stimulus on each row that appears "closer" than the others. The task becomes more difficult as disparity declines from 362 seconds of arc (or 17.8 percent of normal stereopsis on the Fry-Shepard stereopsis scale) on the first row to 9.7 seconds of arc (or 106.5 percent on the Fry-Shepard stereopsis scale) on the bottom row. The discrete test result is applicable to driver screening because depth perception is examined only for advisory purposes and is not used to curtail or limit driving of passenger-car–class vehicles.

SEARCH FOR A SCIENTIFICALLY VALID SCREENING TECHNOLOGY

Throughout the history of driver-licensing programs, it has always been assumed that vision plays an important role in the driving task. The pervasiveness of this assumption is evidenced by the universal requirement of visual screening of driver's license applicants *(19, 20)*. However, before the 1960s there had been no definitive experimental evidence relating visual ability to driving ability or safety. Visual standards adopted by the states had been based on (and for the most part have remained based on) the "expert opinions" of committees of vision specialists. The Federal Highway Safety Act of 1966 mandated that ophthalmologists and other medical professionals take an active role in the development of licensing and screening procedures for driving *(21)*. Because of a lack of scientific data relating vision and driving, visual standards have developed primarily on the basis of input from the clinical community.

Accurate and scientifically derived data were needed to establish more effective visual screening procedures for driver's license applicants. In response to this need, early in 1962 the Institute of Transportation and Traffic Engineering of the University of California at Los Angeles and the California Department of Motor Vehicles initiated a large-scale series of studies that were to form the foundation of a continuing quest to develop a "scientifically valid technology" of driver visual screening *(22)*. In the first phase of these studies, Burg *(6, 7)* examined the relationship among several measures of visual performance, demographic variables (such as age, sex, and annual mileage), and traffic accident and conviction record.

The visual tests used in this study of more than 17,000 California drivers included static visual acuity; dynamic visual acuity; lateral visual field; lateral phoria; low-illumination contrast threshold (i.e., night vision); glare sensitivity and recovery time; and eye dominance.

These visual functions were selected because of their high "logical" likelihood of being associated with certain types of accidents as well as overall rate of accident involvement *(23)*. Special importance was placed on the dynamic visual acuity (DVA) measure because a major visual requirement of driving is the perception of detail in objects that are moving relative to the observer. Previous research had indicated that measures of static visual acuity and DVA were relatively independent, so Burg and Hulbert *(24)* hypothesized that DVA might provide a measure of visual ability that was more directly related to driving demands than static acuity. Hence, DVA would be expected to be a better predictor of driving safety record.

Correlational and multiple-regression analyses of the Burg *(6, 7)* data revealed that driving safety record worsened with increasing mileage, decreasing age, and worsening vision. Mileage and age were the most powerful predictors of traffic accidents and convictions. Increased mileage resulted in more driving incidents because of a concomitant increase in risk exposure. The reciprocal relationship between age and accident involvement was attributable to dual mechanisms: minimal experience and increased risk-taking behavior of the young and markedly reduced mileage (and, hence, reduced risk exposure) for the aged. Indeed, when accident frequency was corrected for mileage driven (e.g., accidents per 100,000 mi), the older drivers were shown to have accident rates approaching or exceeding the high levels of their 20-year-old counterparts.

Although not as powerful as the age and mileage factors, significant predictive relationships were observed between performance on vision tests and involvement in traffic incidents. Dynamic visual acuity was the visual measure most consistently and strongly related to driving. However, the relationship between DVA and traffic safety interacted with age in a complex manner. On the basis of the overall analyses, DVA was positively related to rate of traffic accidents and convictions. That is, good dynamic acuity was significantly associated with a poor driving record.

However, when separate regression analyses were performed on age-stratified subsamples of the drivers, a more interesting pattern of results emerged. First, DVA declined continuously over the life span. Hence, the best dynamic acuity was confined exclusively to the youngest drivers. These same young drivers, for the reasons noted previously, had the highest frequency of accidents and convictions. Thus, a strong "youth factor" accounted for the overall positive correlational relationship between DVA and driving.

Second, the analyses for drivers over the age of 54 revealed a significant DVA-driving relationship that was in the opposite direction: among older drivers, decreases in DVA ability were significantly associated with increased risk of traffic accidents and convictions [see Hills and Burg *(5)* for additional age-related re-analysis of the original Burg *(6)* data].

In addition to DVA, two other visual factors appeared to be systematically related to traffic safety: static visual acuity and glare recovery. Again, decrements in either measure were associated with increased risk of traffic safety incidents for older drivers. Inconclusive results were obtained for the nighttime vision test because of the small number of nighttime accidents encountered in the sample.

Although speculative, the California driving and vision studies *(6, 7)* suggested strongly that new, more ecologically valid vision tests could be developed to predict increased risk of traffic accident involvement—especially where older drivers were concerned. Also, visual screening technology based on scientifically determined procedures appeared to be feasible given the state of the art of engineering. Burg *(6)* recommended that a compact, reliable multipurpose vision tester be developed to enable rapid and reliable assessment of driver dynamic visual acuity, static visual acuity, and low-luminance vision. It was concluded that future research efforts should concentrate on visual tasks that were "perceptual," not merely "sensory," in nature *(22)*.

U.S. DEPARTMENT OF TRANSPORTATION MARK I AND MARK II INTEGRATED VISION TESTER PROGRAMS

On the basis of the pioneering work of Burg *(6, 7)*, the U.S. Department of Transportation (DOT) initiated a series of investigations designed to develop a battery of visual tests that would be more functionally related to driver performance and safety. This initiative was implemented in two phases: the development and testing of the MARK I and the MARK II Integrated Vision Testers. To provide interested scientists and engineers with the mechanical and procedural details of these sophisticated visual work stations, a technical appendix to this paper has been prepared by the author and is available as a separate volume *(25)*. This appendix is a stand-alone document that chronicles the logic behind the development of the MARK I and MARK II systems and offers a critical analysis of the findings of the research programs implemented to assess the reliability and predictive validity of each. Special emphasis has been placed on the role of age-specific factors in the preparation of this auxiliary report. An executive summary of the major contributions of the MARK I and MARK II programs—especially as they relate to future research initiatives—appears in the following paragraphs.

One of the major conclusions to be drawn from the MARK I and MARK II projects was that visual tasks that are dynamic (i.e., temporally modulated) can contribute to the ability to statistically account for group data trends relevant to highway safety indices (i.e., traffic accident and conviction rates). However, this conclusion has been qualified to such an extent that the practical, or applied, significance of this information has been greatly minimized. The relationships found between performance on the innovative MARK II test battery and driving statistics were so weak that they provided less information about the highway safety indices than did knowledge of an individual's age or sex. In other words, the results were significant statistically but not practically.

Regardless of these disappointing results, however, DOT's MARK I and MARK II projects have provided a wealth of information that can serve as an invaluable guide for future research on improved vision-screening techniques. These potential benefits apply to both the theoretical and the practical concerns of any mass vision-screening project.

One of the major theoretical lessons to be learned from the MARK I and II projects is that it is important to establish the reliability of an assessment technique before attempting to establish its predictive validity as a screening tool. The attempts to develop totally novel assessment techniques and test their reliability and validity in parallel greatly reduced the interpretability of the findings—especially in areas where null findings were obtained. Repeated failures to uncover expected relationships were accompanied by interpretational dilemmas such as: is visual factor-*x* truly unrelated to driving record or was the failure to observe a relationship due to the inability to reliably assess the magnitude of visual factor-*x*? The ambitious attempts to solve all of the problems of developing, verifying, and validating the tests simultaneously necessarily resulted in data that were most difficult, and often impossible, to interpret.

A related problem exposed by the MARK I and II research teams was the inadequacy of traditional correlational and multiple-regression analysis techniques for establishing causal relationships between visual capabilities and highway performance as indexed by accident and traffic violation data. Much of the problem encountered with these techniques stemmed from the highly nonlinear relationship that appeared to characterize the statistical relationship between the vision tests and the highway performance indices.

Nontraditional "graphical analyses" performed on both the MARK I data *(26)* and the MARK II data *(27)* attested to this nonlinear relationship and, consequently, indicated that traditional linear statistical techniques would be insensitive to true relationships within such data sets.

A related problem for establishing a causal relationship between visual capacity and accident experience is the multifactor origin of most traffic accidents *(28)*. That is, because many factors interact to cause the typical accident, any statistical attempts to isolate a specific mechanism (e.g., poor vision) will necessarily suffer from markedly limited sensitivity.

Alternative approaches to correlational and multiple-regression analytic techniques should be considered for application in subsequent research projects. Future investigations should have their research designs optimized for analysis by nonlinear causal modeling techniques *(29, 30)*. The "noisy" results obtained during two decades of correlational research on the relationship between vision and driving demand that future studies employ more rigorous experimental alternatives to correlational research designs. An experimental approach would allow scientific controls to be applied that would greatly increase sensitivity to important factors relating driving performance to visual function. One of the experimental techniques that appears to hold much promise for vision-driving research is the simulation approach. The feasibility and cost-effectiveness of simulation techniques for research on visibility and driving have been expertly reviewed by Burg et al. *(31)*.

The DOT vision-testing initiatives also contributed a substantial volume of information on practical issues that affect the implementation of mass-screening programs. Many of these findings related directly to the unique problems encountered when testing older adult populations. For example, special procedures must be used for testing persons who wear bifocal lenses. Also, luminance levels of the test stimuli must be chosen such that the peak photopic acuity of older observers is not underestimated. Other factors that are critical for efficient administration of tests involving older adults are their diminished response speed and apparently "conservative" response bias, that is, a reluctance to respond when in doubt *(32, 33)*. The potential impact of these and other age-specific population characteristics on the efficiency and reliability of mass-screening systems is noteworthy and discussed more fully elsewhere *(25)*.

Perhaps the most significant outcome of the MARK II vision test program was the demonstrated efficiency that can be attained through the use of computer-controlled vision-screening apparatus. Even though the MARK II tests were implemented using rigid electromechanical stimuli (not the more flexible electro-optic displays available today), they successfully employed computer automation to deliver test instructions, present stimuli, collect responses, and score performance—an outcome that has great implications for future development projects in visual screening. The MARK II project clearly demonstrated that computer automation can be used to implement sophisticated test algorithms (e.g., adaptive psychophysical procedures) in a reliable and efficient manner with little or no manual intervention by department of motor vehicles personnel. Hence, one of the major obstacles to implementing new test programs—the personnel costs associated with administering the tests—could be greatly reduced by the introduction of well-engineered, computer-based automation techniques. Recent improvements in the power and cost-effectiveness of computer and visual display technology offer new opportunities for improving the manner in which driver vision can be evaluated. The emerging visual assessment techniques, which have become realizable through the use of such technological innovation, are the topic of the rest of this paper.

EMERGING VISION ASSESSMENT TECHNIQUES AND THE OLDER DRIVER

Predicting the performance of individuals under adverse viewing conditions represents an important challenge to vision researchers. Traditional assessment techniques have proven to be invaluable for screening and optimizing visual performance under ideal conditions, such as reading high-contrast text or well-illuminated highway signs. However, the predictive validity of these traditional techniques often decreases when visibility conditions are compromised by low levels of illumination (e.g., the highway at night) or inclement weather (rain, fog, etc.). Consequently, individuals who demonstrate "normal" visual capabilities under standard clinical conditions can differ greatly under adverse viewing conditions *(34)*.

There is mounting evidence that this inability to generalize the results of traditional measures of vision to dynamic, nonstandard environments (i.e., the real world) may be exacerbated in the case of older adults. Age-related visual pathologies such as glaucoma, cataract, and retinal disorders (e.g., maculopathy) are often associated with normal scores on standard acuity tests. Yet many of these patients with normal acuity suffer from marked deficits in their ability to function visually under nonstandard conditions such as low illumination, low contrast, and glare.

Laboratory and clinical vision researchers have developed new assessment techniques to bridge the performance gap between high-contrast, optimally illuminated "standard" test environments and the low-contrast, highly variable illumination of the working world. Several of these emerging techniques are potentially useful in the assessment of driver's license applicants. These assessment paradigms and techniques are explored in the subsections that follow and include contrast sensitivity testing, functional glare assessment, use of low-contrast optotypes, and automated peripheral vision testing. These emergent visual assessment techniques were chosen for discussion because they meet the following evaluation criteria: (a) they offer strong potential for identifying correctable vision problems of the aged; (b) the technology for implementing the technique is currently available; (c) sufficient data are available to assess the potential for implementing the techniques in a mass-screening environment; and (d) life-cycle cost (i.e., total costs of development, acquisition, maintenance, training, and personnel and administrative overhead) of the technology needed to implement the technique is not prohibitive.

Contrast Sensitivity

Standard measures of visual acuity assess the spatial resolving power of the visual system in terms of the smallest high-contrast detail that can be perceived at a given distance. Because small amounts of refractive error in the eye yield reliable decrements in acuity, the acuity test has been widely adopted as the basis for correcting optical errors of the eye with spectacle lenses *(35)*. However, the traditional measures of spatial acuity do not fully describe the visual capabilities of an individual. Laboratory and clinical research has revealed that visual sensitivity varies as a function of target size, contrast, and illumination *(36, 37)*. Acuity provides an index of visibility that pertains to only a very narrow band of the size-*x* luminance-*x* contrast permutations that characterize the driving environment.

Contrast sensitivity testing techniques have been developed to augment acuity measures in the assessment of visual function. At the cost of more sophisticated and time-consuming procedures, currently available clinical contrast sensitivity measurements yield information about an individual's ability to see low-contrast targets over an extensive range of target size and orientation. Contrast sensitivity tests use sine-wave gratings as targets instead of the letter and checkerboard optotypes used in acuity tests. Sine-wave gratings are used because they are relatively simple to generate and have certain useful mathematical properties *(38)*. Researchers have discovered that early stages of visual processing are optimally sensitive to sine-wave grating targets *(39, 40)*.

Sine-wave gratings can be characterized by three clinically important attributes: spatial frequency, contrast, and orientation. Figures 5 and 6 show

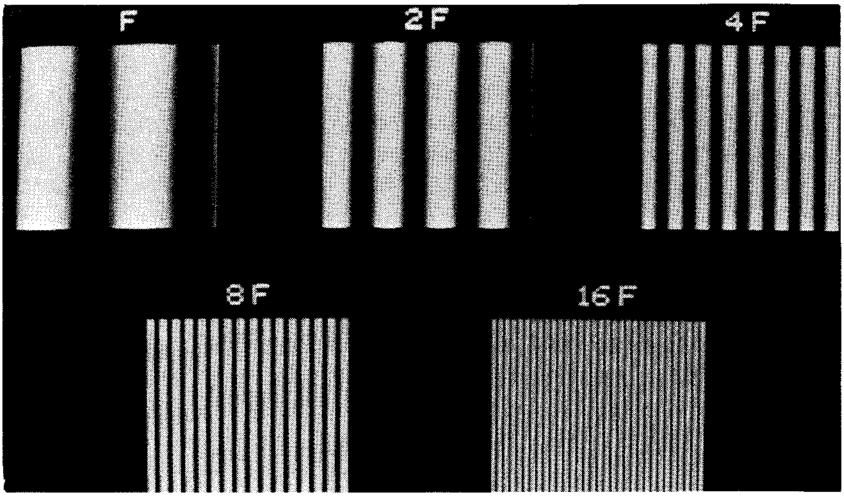

FIGURE 5 Sinusoidal luminance gratings of progressively higher levels of spatial frequency.

some typical sine-wave gratings. When oriented in the vertical position, they appear to consist of a series of fuzzy, alternating light and dark bars of light. In actuality, the luminance of the gratings repeatedly increases and decreases as a sinusoidal function across their horizontal axes. The number of light-dark cycles delineated by a degree of visual angle (or cycles per degree) defines the spatial frequency of a grating. Spatial frequency is an index of the size or width of a grating target: as the width of the bars decreases the spatial frequency of the grating increases. Test gratings varying in spatial frequency are shown in Figure 5.

The contrast of a sine-wave grating is defined by the ratio of the minimum (L_{min}) and maximum (L_{max}) luminance values along the sinusoidally varying axis $[(L_{max} - L_{min})/(L_{min} + L_{max})]$. Contrast of a grating target can be varied from 0.0 to 1.0 without changing the space-average luminance of the stimuli. Hence, a constant state of light adaptation can be maintained during testing. Figure 6 shows a series of sine-wave gratings of constant spatial frequency but progressively diminished contrast.

The final parameter of clinical interest is the orientation or tilt of a grating. Although contrast sensitivity varies as a function of orientation *(41)*, large-scale normative data on the effects of orientation are not available.

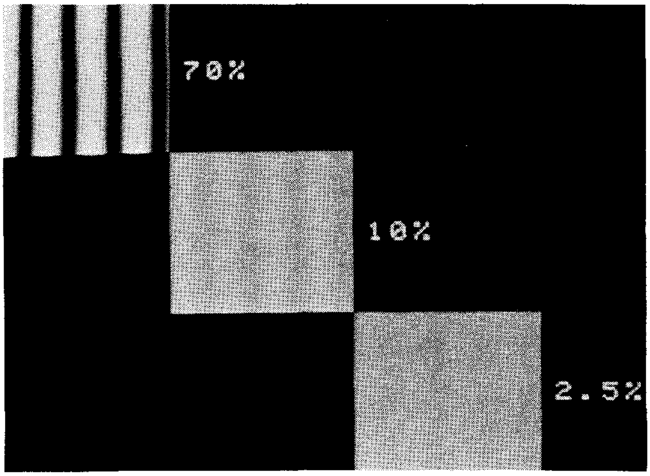

FIGURE 6 Sinusoidal luminance gratings of progressively diminished contrast.

A typical contrast sensitivity assessment procedure is as follows: A vertical sine-wave grating of a given spatial frequency is presented to an observer. The contrast of the grating is reduced until it reaches the threshold of visibility. (The contrast threshold, simply stated, is the minimum contrast at which a sine-wave grating can be distinguished from a uniform field of luminance with some criterion level of accuracy.) The less contrast needed to detect the grating, the more visually sensitive is the observer. Contrast thresholds of this sort are collected for a series of vertically oriented gratings that vary in spatial frequency from 0.5 cycle per degree (c/deg) to approximately 32.0 c/deg, the lower and upper limits of normal spatial vision. Because high levels of visual sensitivity are associated with low contrast thresholds, a reciprocal measure (1/threshold), termed the contrast sensitivity score, is computed. The contrast sensitivity scores collected across the range of spatial frequencies examined during the assessment procedure yield an individual's contrast sensitivity function (CSF).

A typical CSF for a normal, young adult is shown in Figure 7. Spatial frequency is plotted on a logarithmic scale along the horizontal axis of the figure. A logarithmic scale of contrast sensitivity occupies the vertical axis. For normal observers, the CSF (and hence visual sensitivity) peaks in the region between 2.0 and 4.0 c/deg. Visual sensitivity declines rapidly at both higher and lower spatial frequencies.

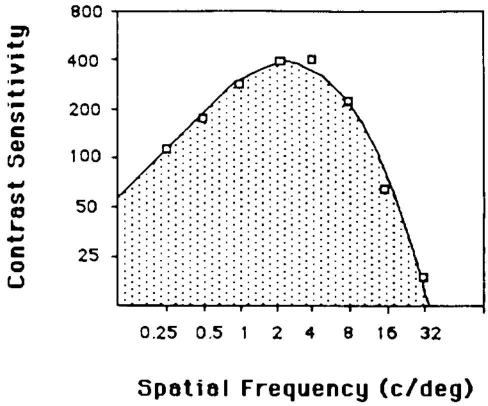

FIGURE 7 A typical contrast sensitivity function.

Origin and Significance of the CSF

The inverted U-shape of the CSF is due to the interacting influences of the optical and neural properties of the eye and the higher-order visual system *(42)*. The progressive loss of visual sensitivity at the higher spatial frequencies (>4.0 c/deg) is a function of the optical quality of the eye. Contrast sensitivity for high spatial frequency gratings is strongly influenced by optical factors such as the refractive state of the eye, the accommodation and clarity of the lens, and the size of the pupil. Contrast sensitivity for low spatial frequency gratings, on the other hand, is not significantly influenced by such optical factors. Instead, the limits of low spatial frequency sensitivity are set by the density and range of the receptive fields of the processing units that compose the visual nervous system; that is, limitations at the level of the retina and primary visual cortex *(43)*.

Extensive laboratory research has revealed that contrast sensitivity is mediated by a series of parallel and independent processors or "channels" in the visual system. Each of these channels is "tuned" to a relatively narrow band of stimulus spatial frequency *(44, 39)*. It is the independent nature of these multiple channels of the visual system that is of particular significance for visual screening and diagnosis. That is, contrast thresholds for spatial frequencies separated by a factor of two are statistically unrelated to one another. Therefore contrast sensitivity measurements for a 0.5-c/deg grating do not necessarily predict an individual's visual sensitivity at 2.0 c/deg. Likewise, contrast sensitivity measurements taken at 4.0 c/deg fail to predict sensitivity at either 1.0 or 16.0 c/deg *(45, 46)*.

Given the independence of these spatial frequency–specific channels, it should not be surprising that visual acuity measurements (which are related primarily to high spatial frequency sensitivity) cannot predict contrast sensitivity for gratings of low and intermediate spatial frequencies. The clinical literature is replete with cases in which patients with normal visual acuity suffered from losses in contrast sensitivity at low-to-intermediate spatial frequencies and a consequent deficit in the ability to function. The evidence clearly indicates that visual acuity reflects but a small range of spatial visual ability. The contrast sensitivity function offers a much more comprehensive assessment of overall visual capacity.

Temporal modulation of a stimulus grating—whether by drifting at a constant velocity or discrete counterphase flicker—can alter an observer's contrast sensitivity to that grating *(47, 36)*. Again, the difference in contrast sensitivity between a stationary and a temporally modulated grating varies as a function of spatial frequency. Contrast sensitivity is much improved for lower spatial frequencies (<3 c/deg) when temporal modulation is present, but at high spatial frequencies contrast sensitivity is markedly attenuated for temporally modulated gratings. Such spatiotemporal interactions, first systematically demonstrated by Kulikowski and Tolhurst *(48)*, have been attributed to a further specialization of the visual nervous system into sustained and transient processing channels *(49)*. Kline and Schieber (*50*, p. 181) describe the properties of these sustained and transient channels as follows:

> Sustained channels respond primarily to finely patterned targets (that is, those of high spatial frequency) which have been presented for prolonged intervals. The sustained channels are responsible for the mediation of pattern or form perception. As implied by their name, these channels respond slowly and have a relatively long response persistence or integration time. Transient channels, however, are most sensitive to targets of low spatial frequency and respond optimally to rapid stimulus change such as motion or flicker. These transient channels also have very brief response latencies.

The apparent organization of the visual system into sustained and transient channels further constrains the ability to generalize the results of vision tests across targets and environmental conditions experienced while driving an automobile. Just as contrast sensitivity for high spatial frequency targets cannot predict the visibility of low spatial frequency stimuli, it appears that visual sensitivity to stationary targets cannot account for individual differences in visual sensitivity to temporally modulated (i.e., moving) objects.

Moving and stationary stimuli are processed in fundamentally different ways by at least two functionally distinct subdivisions of the visual system: the transient and the sustained channels. Currently implemented driver-screening tests assess only the high spatial frequency, sustained-channel mechanisms that mediate the perception of small, high-contrast optotypes.

Clinical Applications of Contrast Sensitivity Testing

As has the laboratory research reviewed previously, clinical studies have shown that people with identical contrast sensitivities for high spatial frequency targets may have quite different sensitivities at low spatial frequencies *(51, 52)*. Indeed, the dissociation between visual acuity measures and the CSF was first demonstrated in patients with cerebral lesions. For example, Bodis-Wollner and Diamond *(53)* examined brain-damaged patients who had good acuity (2.0 minarc or better) but complained about severely blurred vision. Contrast sensitivity measures revealed a selective deficit for intermediate spatial frequencies, whereas visibility for higher spatial frequencies remained unimpaired.

Studies of other clinical pathologies (e.g., multiple sclerosis and optic neuritis) have revealed that changes in contrast sensitivity can be confined to narrow bands of spatial frequency. Such selective loss of function in the visual channels responsible for the perception of low and intermediate spatial frequencies often is not detected by traditional acuity-based screening procedures *(54)*. The contrast sensitivity function may also be useful in screening hidden low spatial frequency losses in persons with developing cataract (a pathological clouding of the eye's crystalline lens). Many persons with insidious (undiagnosed) cataract may suffer from blurred vision yet present with normal visual acuity *(55)*. The CSF provides a new means of detecting (screening) and quantifying the diminished visual functioning associated with such cases of insidious cataract *(34)*.

Individuals who wear contact lenses, especially the hydrophilic ("soft") variety, frequently report problems associated with blurred vision even though they retain the ability to resolve the high-contrast, high spatial frequency targets on conventional acuity charts *(56)*. Simple measurements of visual acuity are not sufficient to assess the quality of vision through contact lenses *(57)*. The mechanism of this loss of function, reported as "blurred" vision, appears to be the contrast reduction effects of light scatter introduced by the contact lenses themselves or complications of their use. That is, the lens may become scratched or cloudy, or both, or stimulate deleterious changes in the eye (e.g., corneal edema) that can scatter light and reduce effective retinal contrast. Clinical assessment of the CSF has been found to be useful in detecting heretofore insidious reductions in visual function that result from wearing contact lenses *(58)*.

There is growing evidence that low spatial frequency contrast sensitivity measures may also be useful for detecting insidious age-related diseases of the retina such as glaucoma and maculopathy (a degeneration of the central region of the retina). Glaucoma patients show a 50 percent loss in contrast sensitivity across the whole spatial frequency spectrum. However, the visual loss below 2.0 c/deg is particularly specific to retinal dysfunction because contrast sensitivity in this frequency range is relatively independent of errors in the refractive state of the eye *(59)*.

Comerford *(58)* describes the CSF as a measure of the integrity of both central and peripheral vision. A loss of function in the visual field resulting from a retinal lesion that is of sufficient magnitude to interfere with visual tasks such as driving will be associated with a general decline in the CSF—especially for low spatial frequency stimuli. This view of low spatial frequency contrast sensitivity as an index of the visual system's ability to integrate spatial information across the entire visual field is consistent with recent clinical findings. For example, contrast sensitivity changes often precede losses in standard visual acuity in cases of age-related maculopathy and glaucoma *(60–62)*.

Contrast Sensitivity and Vehicular Performance

Individual differences in the contrast sensitivity function may potentially serve as the basis for predicting individual differences in performance of complex visual tasks. The research initiative to develop such applications of the CSF has been spearheaded by the U.S. Air Force. Many of the available research results pertain to the piloting of aircraft. Fortunately, however, some of these research findings can be generalized in straightforward fashion to the task of automobile driving.

Ginsburg et al. *(63)* examined the relationship between the CSF and the ability of Air Force pilots to detect simulated air-to-ground targets (such as another aircraft on a runway). Although all pilots had good visual acuity (i.e., high spatial frequency sensitivity), they varied widely in terms of their peak contrast sensitivity scores. These individual differences in the amplitude (and, perhaps, the spatial frequency) of the CSF peak sensitivity correlated well with individual differences in maximum distance at which target stimuli could be detected. High peak sensitivity predicted high levels of real-world visual detection performance.

In another study of Air Force pilots *(64)*, the relationship between CSF and the ability to detect an approaching aircraft was investigated. Pilots searched for approaching targets under a variety of viewing conditions ranging from clear sky to overcast, rain, and fog. Again, good contrast sensitivity was found to be significantly related to good performance of the detection task. The pattern of results underscored the need to assess visual function under a variety of stimulus conditions. Contrast sensitivity for high spatial frequencies (>8 c/deg) predicted detection performance under optimal viewing conditions. However, under suboptimal viewing conditions (where the atmosphere would be expected to attenuate the high spatial frequency components of a target) it was found that contrast sensitivity for low (<8 c/deg) rather than high spatial frequencies was capable of predicting detection performance. These results suggest that, unlike acuity measurements, the CSF sampled over a range of spatial frequencies has the potential for predicting real-world detection performance under a variety of visibility conditions. Such a capability would be invaluable in the assessment of driver visual function.

A recent study by Evans and Ginsburg *(65)* demonstrated a more direct link between contrast sensitivity and the visual skills required for driving. The relationship between the CSF and the ability to discriminate highway traffic signs was examined in young and old observers with good visual acuity (1.0 minarc or better). Age-related declines in the ability to discriminate between highway signs were demonstrated. Furthermore, these declines were predicted by concomitant age-related decreases in contrast sensitivity. The significance of this finding is augmented by the finding of previous studies that age differences in highway sign discrimination could not be accounted for by age differences in standard visual acuity *(66)*.

Aging and Contrast Sensitivity

A number of studies have examined age-related trends in the nature of the CSF. However, the small sample sizes and varying techniques employed in the studies have precluded the accumulation of sufficient data on which age-related CSF norms could be based. The studies employing the two largest sample sizes *(37, 67)* both used the same assessment technique (the contrast-tracking procedure implemented on the Optronix CS vision tester) and reported similar age-related changes in the CSF: contrast sensitivity for stationary sine-wave gratings above 2.0 c/deg begins to decline after 40 years of age. By age 60, functionally significant attenuation of contrast sensitivity occurs at 8.0 and 16.0 c/deg. Neither study observed an age-related decline in contrast sensitivity for sine-wave gratings below 4.0 c/deg. Figure 8 shows this age difference in contrast sensitivity by superimposing the CSFs typically obtained for groups of young and old observers. Similar age-related increases in the magnitude of the roll-off of contrast sensitivity at high spatial frequencies have been reported in a number of smaller-scale studies *(62, 68–70)*. The agreement in the findings, despite wide variations in the procedures and stimulus parameters employed, indicates that the age-related loss in contrast sensitivity at intermediate and high spatial frequencies is a robust and clearly replicable phenomenon.

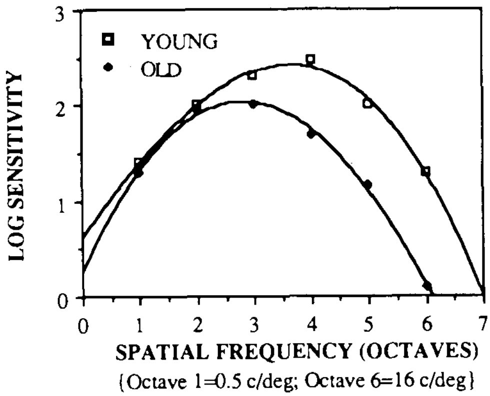

FIGURE 8 Differential contrast sensitivity functions typically demonstrated by young versus old observers [after Kline et al. *(69)*].

Several studies have noted a progressive downward shift in the spatial frequency of the CSF peak with advancing age *(71, 69)*. Given a standard set of viewing conditions, peak sensitivity appears to shift from approximately 4.0 c/deg at age 20 down to 2.0 c/deg by age 65. This age-related change may be of great functional significance given the predictive role of peak sensitivity for real-world visual performance discussed previously *(63)*.

Several investigators have sought to uncover the specific mechanisms that underlie age-related changes in CSF. The converging evidence generated by these studies suggests that only about one-half of the age-related loss in contrast sensitivity can be attributed to optical factors such as lenticular opacification, refractive error, or restricted pupillary diameter *(72–74)*. Owsley et al. *(37)* found that age differences in contrast sensitivity at intermediate and high spatial frequencies were not eliminated when young subjects viewed the stimuli under conditions of simulated optical aging (markedly reduced retinal illumination and refractive error induced via a "plus" spherical defocusing lens). These results indicated that the residual age difference in contrast sensitivity most probably was the result of age-related changes in the visual nervous system (i.e., the retina or brain, or both). When Morrison and McGrath *(75)* bypassed the optics of the eye and directly imaged visual stimuli on the retina using a nonrefractive laser technique, marked age-related losses in contrast sensitivity at intermediate and high spatial frequencies continued to be observed. Taken together, this evidence indicates that both neural and optical mechanisms contribute to the age-related loss in contrast sensitivity.

Finally, there is laboratory evidence that advanced age may also be accompanied by an insidious loss of visual sensitivity to large, moving objects.

When Owsley et al. *(37)* measured contrast sensitivity with a stationary, low spatial frequency (1.0-c/deg) grating, they observed no age-related differences. However, when this same grating was temporally modulated (i.e., drifted from left to right at a velocity of 4.3 deg/sec) a marked age-related decrement in contrast sensitivity was found. Older subjects failed to demonstrate the motion enhancement of contrast sensitivity for low spatial frequency targets typically observed in younger observers. Similar results were reported by Abusamra et al. *(76)*. Although speculative, these results suggest that visual aging may be accompanied by a diminished capacity to process and detect "transient channel" stimuli (such as large, moving objects like automobiles and pedestrians viewed in motion while driving). Such a loss would not be detected by traditional vision-screening techniques *(50)*.

Potential Significance of Contrast Sensitivity for Driver Screening

The research findings discussed here clearly indicate that the CSF provides information about the quality of vision not generated by standard measures of visual acuity. An important question that remains unanswered is whether the implementation of CSF screening of driver's license applicants would have a significant impact on the safety and mobility of the U.S. population. Given the current state of the art of CSF testing, no definitive scientific answer can be offered to the question. However, the case for the efficiency of CSF screening is strong if the population under consideration is aged drivers.

The CSF has been shown to be useful in the early screening and detection of several visual disorders that often remain "invisible" to standard acuity assessment techniques now universally used on driver's license applicants. These visual disorders include cataract, glaucoma, retinal degeneration (maculopathy), and the insidious loss of visual function under conditions of low contrast or bright illumination that can develop as a consequence of extended contact lens wear. The younger driver population is at risk only with respect to the contact lens syndrome, but the older population is at risk with respect to all of these vision problems that elude detection by mere visual acuity screening.

Epidemiological data *(77, 78)* indicate that a significant percentage of the older driver population could potentially benefit from the implementation of routine CSF vision screening. These data indicate, for example, that 5 to 7 percent of those aged 65 and older suffer from cataract. On the basis of 1980 census data this figure translates into nearly 2 million individuals. Most of these individuals continue to drive despite markedly diminished visual capacity. Indeed, cataract is often not detected and diagnosed until it has progressed to such an advanced state that even high-contrast acuity is impaired. As a result, the typical older driver with cataract could be expected to experience several years on the road with significantly impaired vision before diagnosis. Early detection and management of cataracts could result in significant improvements in driver safety, efficiency, and mobility.

It has been estimated that 3 to 5 percent of those aged 65 and older (more than 1.25 million older adults) are afflicted with glaucoma. Glaucoma causes a progressive loss of peripheral vision resulting from the destruction of the optic nerve by the buildup of excessively high pressure within the eye. This loss of vision is permanent and ultimately even central vision is consumed. Total blindness can result if glaucoma is left untreated. Fortunately, the progress of glaucoma can be arrested by medication or surgical intervention, or both. Unfortunately, glaucoma typically develops insidiously. The individual feels no pain and often fails to note the diminished peripheral field of vision until tremendous amounts of visual function have been permanently lost. Early detection of glaucoma could prevent the loss of visual function in many individuals and result in improved highway safety and continued mobility and productivity for high-risk members of the adult population.

The development of debilitating retinal disorders such as maculopathy can be expected to occur in 1 to 3 percent of those over age 65, or 0.75 million persons. Many more older adults suffer from retinal pathology if the complications of diabetes are included in this assessment *(79)*. Until recently, diabetic and age-related maculopathy were entirely untreatable. However, recent developments in laser photocoagulation techniques have been demonstrated to arrest the progress of the disorder in many cases *(80)*. Again, early detection aided by CSF screening procedures could be instrumental in the maintenance of mobility in the population of older adults.

The potential benefit of CSF screening for improved safety and mobility extends beyond the older adult population in the case of detecting diminished visual capacity associated with contact lens wear. The "fogginess" of vision associated with the contact lens syndrome results from accumulated damage to the lenses themselves or to changes in the underlying corneal tissue. Such problems could be quickly reversed if they were detected by contrast sensitivity measurements at low or intermediate, or both, spatial frequencies.

It appears, therefore, that contrast sensitivity measures have a potentially significant role to play in attempts to improve the safety and mobility of the older population. Additional research is required to ascertain the extent to which young and middle-aged drivers could benefit from CSF screening. Work remains to be done on standardizing CSF assessment techniques and generating age-specific performance norms.

Implementation of Contrast Sensitivity Testing for Mass Screening of Drivers

At this time, several systems for assessing contrast sensitivity are commercially available. These include the Arden grating test, the Vistech VCTS 6500 chart, and the Nicolet Optronix CS 2000 vision tester. An analysis of the critical features of these tests reveals many of the important issues that need to be addressed if contrast sensitivity assessments are to be implemented in a mass-screening application such as the testing of millions of driver's license applicants.

The Arden grating test *(81)* was developed for clinical assessment of patients with anomalous vision and is currently marketed as the American Optical Contrast Sensitivity System. The test consists of a series of five photographic test plates. Each plate depicts a sine-wave grating of a different spatial frequency (0.2, 0.8, 1.6, 3.2, and 6.4 c/deg). The contrast of each stimulus plate varies in a continuous, logarithmic fashion across its vertical extent. That is, the contrast of the grating decreases logarithmically until it reaches zero at the bottom of the plate. The edge of each plate is marked with a scale, each unit of which is equal to a contrast change of 0.08 log unit.

The examiner administers the test by first familiarizing the observer with the target and then covering it completely with a gray occluder card. The occluder is slid upward, exposing the lowest contrast portion of the stimulus first, until the observer reports that a striped rather than a blank pattern can be detected. At this point, the contrast sensitivity score is obtained by reading the value at which the occluder card intersects the contrast scale printed along the vertical margin of the plate. The entire test can be administered in less than 5 min by an experienced technician *(59)*.

The Vistech VCTS 6500 is a wall-mounted chart that consists of a matrix of circular sine-wave grating test patches of variable spatial frequency and contrast. The chart is approximately 100 cm high by 120 cm wide and is viewed from a distance of 200 cm. The chart is organized as a set of six rows of eight stimulus gratings each. Spatial frequency varies across rows and contrast varies across the columns in each row. The first grating in each row is a high-contrast stimulus meant to provide the observer with an unambiguous example of the target spatial frequency for that row. The gratings progressively decrease in contrast as the observer scans left to right across the row. The stimuli in a given row have the same spatial frequency but vary randomly in orientation (75, 90, or 105 degrees). The observer's task is to read across each row and report the orientation of the grating at each position. The contrast of the last correctly identified stimulus in a row yields the contrast sensitivity score for the spatial frequency represented within that row. Experienced administrators can collect a CSF of six data points in less than 6 min—inclusive of instruction time *(82)*. The spatial frequencies sampled by the chart include 1, 2, 4, 8, 16, and 24 c/deg.

The Nicolet Optronix CS 2000 is a computer-controlled, video-based contrast sensitivity tester. Electronically generated sine-wave gratings are presented on a television monitor. The spatial frequency of the target gratings can be varied continuously. The resolution of the display screen is limited, and, as a result, it must be viewed from a considerable distance (3 m) in order to test spatial frequencies above 12 c/deg. Target contrast can be varied continuously in small, approximately equal steps. In addition to its wide range of spatial frequency and contrast configurations, this television display system is also capable of generating temporally modulated stimuli. The sine-wave gratings can be made to drift from left to right or flicker in counterphase at frequencies of up to 15 Hz.

Because the Optronix tester is controlled by a microprocessor, it has a modest degree of automation for stimulus presentation and test scoring. However, instructions must be given by a trained technician, who must also control session start-up and termination. The device supports several types of psychophysical procedures that take limited advantage of the microcomputer's ability to implement advanced assessment techniques. The procedures for collecting CSF data include continuous contrast tracking, a two-alternative forced-choice task, and a modified ascending method of limits.

The Arden grating test is inexpensive (less than $200) but entails considerable costs for test time and administration. However, even if these costs were within acceptable limits, other factors preclude its use in a mass-screening application such as the assessment of driver's license applicants. Because of great variations in stimulus conditions (e.g., viewing distance, luminance, rate of stimulus presentation) both the precision and the reliability of the test fall below operational levels necessary to meet the objectives of a mass-screening program.

The Vistech VCTS 6500 system, on the other hand, has several advantages for the mass-screening environment. It is relatively inexpensive (less than $400) and can be administered with low overhead for instructions and test time. The system samples a wide range of spatial frequencies and requires the observer to make a forced-choice response (when administered properly). This last feature is critical for testing older individuals because of their tendency to adopt a conservative response criterion that tends to decrease the reliability of their contrast sensitivity scores when assessed by techniques that do not implement the forced-choice strategy *(59, 83)*.

The large size of the Vistech CS 6500 chart, however, presents several difficulties for mass screening. Its physical size and large viewing distance limit the ability to test many individuals at the same time. In addition, the charts would have to be mounted in a specially prepared room to adequately control display luminance. Perhaps the most important problem with the Vistech chart is that it comes in only one variety and would be easy to memorize given the public display at the test area.

Vistech has recently introduced alternative implementations of the test that preclude these problems. These tests present the grating targets via slides in a self-illuminated viewing device. The problem of cheating can thus be controlled through randomization of stimuli across multiple slides. The use of removable stimulus slides also provides the potential for using the same device to test other visual functions such as acuity and color vision. In addition, the self-contained display device eliminates the problems associated with excessive space requirements and controls target luminance more precisely.

The Optronix video tester offers unique advantages such as the ability to temporally modulate the grating display and a degree of automation. However, the poor resolution of its display and the limited processing power of its 6502 8-bit processor do not make it a good choice for mass screening of drivers. The video electronics only display one-dimensional grating stimuli. Hence, alphanumeric optotypes and video-based instructions cannot be generated; this reduces the advantages of a computer-controlled, video-based visual test station, namely, flexibility of stimulus configuration and the ability to incorporate multiple, general-purpose functions. It appears that a much more powerful and sophisticated system could be developed and marketed if the demand existed. A computer-controlled, video-based vision tester that expands on the single-function implementation of the Optronix system offers great promise for test administration and development in a mass-screening environment. In particular, a computer-based system could be designed to fully automate the heretofore labor-intensive process of collecting reliable CSF data. The functional requirements and candidate hardware technologies for implementing such a system are specified in a subsequent section of this paper.

Finally, in addition to stimulus presentation problems, several more basic issues impede the implementation of contrast sensitivity testing as a general-purpose tool for evaluating driver visual function. Legge and Rubin (*84*, p. 269) have offered an insightful analysis of these problems and have concluded that before the CSF test can be recommended as a practical screening technique the following questions need to be answered:

1. How accurately does the CSF test distinguish subjects with abnormal vision from those with normal vision, either on its own or in conjunction with conventional test measures?
2. How are CSFs to be scored? What criteria are to be used to separate abnormal from normal CSFs?
3. How many measures of contrast sensitivity are necessary to make the test accurate enough to be of use in screening? At what spatial frequencies should these measurements be taken?
4. How robust are measurements of contrast sensitivity to the types of unavoidable variability in testing conditions typical of screening contexts? What sort of repeat reliability is expected of the CSF?

Disability Glare

Disability glare is a reduction in visual efficiency caused by a veiling luminance superimposed on the retinal image. The resulting reduction in the quality of the retinal image is often accompanied by significant decrements in visual performance *(85)*. Not only does visual function per se deteriorate in the presence of glare, prolonged exposure to such effects can result in muscular fatigue and "attitudinal tenseness which can degrade driving skill" (*86*, p. 103).

The cause of disability glare can be either external or internal in origin. The effective contrast of the retinal image can be decreased by extraneous external luminance sources such as the scattering of light by the dirty windshield of an automobile. Of greater clinical interest, however, are the internal sources of glare that result from the light-scattering properties of opacities within the optic media of the eye. For example, patients with cataract, corneal edema, or cloudiness of the vitreous body can experience excessive reductions in visual function in the presence of unshaded light sources and reflections that are commonly found throughout the driving environment *(87)*. Because standard measures of visual acuity are performed using high-contrast, optimally illuminated stimuli they fail to detect persons who suffer from excessive sensitivity to glare *(88, 86)*.

Laboratory and clinical studies have clearly revealed two driver populations characterized by significant risk of excessive sensitivity to glare: individuals who wear contact lenses and older adults. The light-scattering effects of contact lenses stem from damage to the lenses themselves or changes in the cornea resulting from prolonged contact lens wear. Excessive glare sensitivity resulting from such problems with contact lenses eludes detection by standard clinical tests of acuity *(57)*.

Aging and Disability Glare

All older adults, even those who do not wear contact lenses, are at risk of developing glare sensitivity problems by virtue of the normative age-related decrease in the clarity of the optic media. Between the ages of 10 and 40 there is a steady increase in the amount of light scatter that occurs within the optics of the eye. After age 40, this increase in intraocular light scatter accelerates significantly *(89, 90)*. Numerous studies have shown that such age-related increases in the optical density of the eye are clearly associated with decreased visual performance in the presence of a bright, glare-inducing light source *(91–93)*. This age-related increase in glare susceptibility accelerates after age 40, paralleling the trends observed in objective measures of the optical quality of the eye *(88)*. The finding that the vitreous body remains relatively intact during old age *(94)* and the observation that sensitivity to glare is markedly reduced after cataract surgery *(92)* point to the crystalline lens as the dominant mechanism mediating age-related increases in susceptibility to disability glare.

Excessive sensitivity to the deleterious effects of glare is often one of the criteria used to justify cataract surgery *(85)*. However, surgical removal of the lens does not necessarily eliminate the risk of redeveloping problems with disability glare. Modern cataract surgery is often associated with the implant of a replacement or prosthetic lens. This procedure typically involves anchoring the new lens within the capsule of tissue that formed the exterior layer of the original lens structure. In approximately 10 percent of surgery cases, a clouding of this capsule subsequently develops, which leads to a condition known as "secondary cataract" *(87)*. This condition is associated with a clouding of vision and an increased susceptibility to the effects of disability glare. Finally, the refractive state of the eye after cataract surgery often needs to be corrected with contact lenses. Unfortunately, older adults may be more susceptible to developing the corneal complications of contact lens wear that have been associated with decreased contrast sensitivity and elevated problems with disability glare *(95)*.

Benefits of Driver Glare Sensitivity Testing

Glare sensitivity testing has definite potential for detecting significant but correctable vision problems among two large subpopulations of drivers in the United States: older persons and individuals who wear contact lenses. The aged are increasingly likely to develop cataractous or precataractous ocular opacities that cause marked deficits in the ability to see under transient-illumination or high-illumination conditions (e.g., opposing headlamps during nighttime driving, high-mast roadway lighting, driving toward the brightly illuminated sky at dawn or dusk). Persons suffering from severe lenticular opacities could be routinely screened and treated. Precataractous individuals could potentially benefit from optical aids such as spectacles with special antireflective lens coatings that can attenuate the contrast-reducing effects of glare by a factor of 1.5 to 5 *(96)*. Likewise, persons found to suffer from excessive sensitivity to glare resulting from the complications of contact lens wear could be referred to a vision specialist. The glare problem could then be corrected by replacing the worn or damaged contact lenses or treating corneal inflammation, as appropriate. The potential number of drivers who could benefit from such intervention is undoubtedly large. This potential pool of individuals can only be expected to grow as both the frequency of contact lens use and the number of older persons continue to grow.

Glare Sensitivity Testing in Driver Screening

Few commercial glare sensitivity tests were available at the time of this writing. Of these systems only the Miller-Nadler tester and the newly introduced Vistech MCT 8000 appear compatible with a mass-screening application for older individuals.. Although the MCT 8000 doubles as a contrast sensitivity tester, not enough data are currently available to assess its reliability and operational efficiency.

Several experimental systems that use television-based sine-wave grating targets to test susceptibility to glare using contrast sensitivity techniques have been successfully demonstrated *(97, 98)*. The limitations and potential usefulness of these techniques for mass screening of driver's license applicants are discussed in this subsection.

The Miller-Nadler apparatus consists of a table-top slide projector system with a rear surface viewing screen. The test stimuli are 17 slides of black Landolt-C optotypes centered within a gray circular surround. These stimuli have a Snellen-equivalent critical detail of 20/400 (20 minarc) and vary in contrast from a high of 80 percent to a low of 2.5 percent. The stimuli are presented against an illuminated surround of approximately 6800 cd/m^2, which serves as a constant glare source. To measure disability glare, the observer is positioned in a forehead and chin rest at a distance of 36 cm from the screen. The stimuli are presented in sequential fashion beginning with the highest contrast slide. The stimulus contrast is reduced until the observer can no longer correctly identify the position of the critical gap in the Landolt-C. The lowest contrast correctly identified provides the glare sensitivity index. The test is conducted separately for each eye.

Studies of normal and cataractous older adults indicate that a glare score of 15 percent contrast or lower is within normal range and that a score of 20 percent contrast or higher is indicative of significant visual loss in the presence of a source of glare *(87, 85)*. The Miller-Nadler test is reliable and yields easy-to-interpret results. However, it possesses several characteristics that limit its usefulness in a mass-screening environment. First, the device is totally manual, requiring the full attention of an administrator to update the stimuli, collect responses, and calculate a final performance score. More problematic, the test assesses only glare sensitivity. Additional equipment and training would be required to implement other measures such as sine-wave contrast sensitivity or standard visual acuity. Finally, the apparatus is not readily amenable to automated administration, which would allow it to be life-cycle cost competitive with a multipurpose, computer-based system.

Prototypes of television-based contrast sensitivity testers of glare sensitivity have seen limited application in the laboratory and clinic. These systems use sine-wave gratings of variable spatial frequency and contrast generated on a computer cathode ray tube (CRT) display or monitor. The display is then viewed through light from a bright (e.g., 25 000 cd/m^2) circular fluorescent lamp that surrounds the stimulus area. Comparisons of contrast sensitivity measures collected with the glare source illuminated and extinguished are used to formulate a glare attenuation ratio at each spatial frequency. Significant reductions of contrast sensitivity in the presence of glare have been found to correlate well with patient reports of glare problems *(97, 98)* and objective ophthalmic estimates of lens opacification in older precataractous and cataractous patients *(98)*. Paulsson and Sjostrand *(97)* have presented clinical evidence that contrast sensitivity assessment techniques are both more sensitive and more specific to the detection of cataract when a glare stressor accompanies the sine-wave grating target.

The efficacy of the prototypical CRT-based glare testers strongly suggests that glare sensitivity testing could be incorporated as part of a general-purpose computer-controlled video tester. Such a tester would benefit from advanced automation capabilities and off-load the personnel requirements for administering sophisticated assessments of visual function. The stimulus parameters and procedures required to develop such a video-based glare sensitivity test are reviewed in an exhaustive experimental analysis by Miller et al. *(99)*.

Low-Contrast Acuity Testing

Recent evidence suggests that a new type of vision test may yield much of the same information about visual disability that is provided by the CSF but without many of the costs associated with CSF assessment. This new technique is similar to the familiar Snellen acuity test except that low-contrast optotypes are substituted for the high-contrast letters typically employed in such tests. Clinical data from tests using the Regan contrast sensitivity letter chart *(100)*, a commercially available implementation of the low-contrast acuity test, have indicated extremely promising results. Proponents of the low-contrast acuity test have claimed that it rivals CSF measures in its power to make clinical diagnoses of visual disorders such as cataract, glaucoma, diabetic retinopathy, age-related retinopathy, diffusive visual blur associated with contact lens syndrome, ocular hypertension, glaucoma, and various neurologically mediated losses of visual function *(101–104, 83)*.

The manner in which low-contrast acuity charts can discriminate anomalies in the CSF can be understood by referring to Figure 9. The upper line represents the normal CSF and the lower, more attenuated, line represents an abnormal CSF that might characterize the visual sensitivity of an individual with cataract or corneal edema suffered as a consequence of the contact lens syndrome described previously. Note that the highest spatial frequency that can be resolved by both individuals occurs at 100 percent contrast (as indicated by the dashed lines in the figure). Also note that the two CSF curves

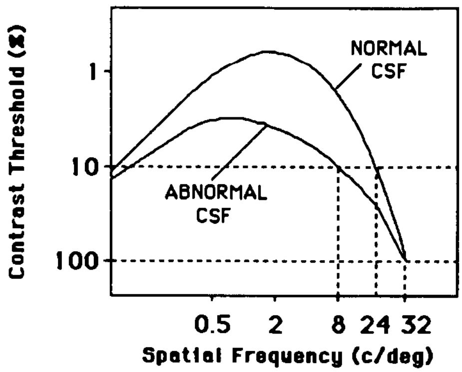

FIGURE 9 Variation in individual differences in spatial sensitivity as a function of stimulus contrast.

virtually overlap at this level of contrast. Both observers could resolve a 32.0-c/deg (1.0-minarc) target presented at 100 percent contrast. That is, both individuals would be able to read the 20/20 line on a high-contrast Snellen chart (ignoring constraints imposed by luminance and viewing distance). These observers could not be discriminated by their scores on a standard acuity test. The situation changes dramatically, however, when visual sensitivity is compared with a 10 percent contrast target instead of one presented at full contrast. At this low level of contrast, the highest spatial frequency that can be resolved drops to approximately 24 c/deg (1.25 minarc) for the person with the normal CSF and all the way down to 8.0 c/deg (3.75 minarc) for the individual with the anomalous CSF. That is, the performance of these two individuals would be markedly different if they were tested using a Snellen acuity chart composed of low-contrast (10 percent) optotypes. The CSF-normal individual would lose one line of Snellen acuity (20/25) on the reduced contrast chart whereas the CSF-abnormal individual could be expected to lose as much as five lines of acuity (20/70) under the low-contrast conditions.

The potential advantages of the low-contrast acuity paradigm for screening drivers are numerous: (a) The technique would be less expensive to implement in terms of the complexity of the instructions to the observer and ease of administration; (b) the scoring criteria would be easier to develop and interpret than in the case of the CSF, largely because of the familiarity of the standard Snellen acuity test; (c) low-contrast optotypes could be easily retrofitted into many of the vision screeners already in use by driver-licensing authorities; and (d) the test is essentially a forced-choice task that would minimize the effects of age-related changes in observer response bias.

The major disadvantages of the low-contrast acuity test include the inability to temporally modulate the stimuli (i.e., add a motion component) and the difficulty of automating a task that has 26 response alternatives (i.e., the letters of the alphabet). However, neither of these problems is insurmountable. The use of Landolt-C optotypes would make the low-contrast acuity test more amenable to automation because only four response categories are needed to code the position of the critical gap (i.e., top, bottom, left, and right). In addition, the production of temporal modulation needed to test the dynamic properties of the visual system would not be precluded if the low-contrast optotypes were presented using a high-resolution, video-based system.

The simplicity of the low-contrast acuity paradigm and its apparent sensitivity in detecting many of the visual anomalies associated with old age suggest that it holds great potential as a technique for routinely screening driver's license applicants. Although low-contrast acuity testing has been known to have relevance for real-world visual performance for many years *(105, 38)*, it has only recently become an area of active research interest. Additional work is required before the full benefits of this emerging technique can be assessed.

Automated Visual Field Testing

The field of vision of an eye is the total area over which effective sight is maintained relative to a constant, straight-ahead fixation point. The extent of the visual field has consequences for everyday activity, such as driving a car. Assessment of the visual field also provides information that is important for the detection and diagnosis of certain visual dysfunctions such as glaucoma, the cortical varieties of cataract, and degenerative retinal disorders *(106)*. The incidence of all of these visual disorders increases markedly with advancing adult age *(10)*. Unfortunately, these disorders typically have insidious onsets and, with the exception of cataract, lead to permanent loss of visual function and mobility if not detected and treated in a timely fashion.

The apparent validity of a causal relationship between the extent of the visual field and driving safety has prompted many state licensing agencies to initiate field testing as part of their routine driver-screening battery. However, as already discussed in the introductory section of this paper, the field testers currently available for mass-screening applications are highly insensitive and often pose severe problems of reliability. Mass field screeners typically test only a few points in the visual field, and these few points fall only along the main horizontal axis of vision. Unfortunately, severe field losses are not confined to the principal horizontal meridian.

Full-field perimetry has been a mainstay of clinical assessment for 50 years. Procedures exist for evaluating the full peripheral extent of the visual field along many axes of orientation (kinetic perimetry) as well as evaluating functions at representative locations within the bounds of extreme peripheral vision (static perimetry). These techniques provide sensitive tests for glaucoma or the existence of local retinal dysfunctions (scotomas), or both, associated with age-related maculopathy and senescent diabetic retinopathy. Unfortunately, traditional field assessment techniques are labor intensive; it takes at least 15 to 20 min for a highly qualified medical technician to administer them. Recently, however, a host of computerized, highly reliable automated static perimeters have been introduced (e.g., the Humphrey field analyzer, and the Octopus and Fieldmaster automated perimeters). These devices, although expensive at present, point the way to new approaches that could ultimately enable full-field perimetry to be performed in a mass-screening application such as driver vision assessment.

Extensive laboratory and clinical field testing with these automated perimeters indicates that they have high diagnostic sensitivity for glaucoma and localized retinopathy *(107, 108)*, especially when adaptable psychophysical procedures that automatically detect and retest suspicious data points are incorporated into the computer algorithms of the devices *(109)*.

The typical automated perimeter consists of a large, table-mounted hemispheric projection screen at which the observer must gaze. A fixation point and a chin rest and headrest are provided to help maintain fixational stability. Some of the more portable devices require optical aids (i.e., a spherical lens) to allow the short-distance test spots to be optimally focused by presbyopic middle-aged and older adults. The devices use a computer-controlled projector or a two-dimensional array of light-emitting diodes to deliver the test targets at various positions within the field. Fixation maintenance is automatically monitored by dummy probes to the blind spot (which should fail to be detected if the observer is properly fixated) or by monitoring the alignment of an infrared beam reflected off the surface of the cornea.

The observer's task is to maintain rigid central fixation while small illuminated disk targets are randomly presented at strategic points throughout the visual field. The observer presses a button to signal the detection of a test probe. Consistent failure to detect targets at specific locations is indicative of a local loss of retinal sensitivity. Preprogrammed computer algorithms administer the entire testing sequence as well as provide a scored output.

Keltner and Johnson *(110)* modified the standard clinical test procedure implemented on the Fieldmaster automated perimeter (Model 101-PR) to assess its reliability for mass screening of drivers. The modifications consisted of employing suprathreshold stimulus levels determined by previously established age-norm data instead of trying to determine the increment threshold at each point. Also, because the majority of observers, regardless of age, tends to miss targets presented in the extreme periphery, these targets were dropped from the test procedure. Because these points yield highly variable results, the overall reliability and sensitivity of the field test were not significantly altered. After making these two changes, Keltner and Johnson *(110)* found that they could reduce the total testing time for a full-field static assessment to 1.5 to 2.0 min per eye. Data collected from 778 volunteers (1,027 eyes) recruited from driver's license renewal applicants revealed that the test was efficient and reliable.

On the basis of these findings, a follow-up validation study of the technique was conducted on 10,000 driver's license applicants at two California Department of Motor Vehicles branch offices. The average total test time, based on an assessment of approximately 20,000 eyes, was 1 min 54 sec per eye. Results of this mass screening indicated significant field loss in 3.0 to 3.5 percent of all age groups between 16 and 60 years. Frequency of field loss began to accelerate thereafter, reaching a rate of approximately 12 percent for the 65+ age group. More than 4 percent of those aged 65 and older suffered from severe binocular visual field loss indicative of glaucoma or related pathology. These incidence figures were consistent with the results of the preliminary study of more than 1,000 eyes *(110)* and a second mass-screening study by Bengtsson and Krakau *(111)*.

More than one-half of the subjects with abnormal visual fields (57.6 percent) in the Johnson and Keltner *(15)* study were previously unaware of any visual problems. This figure was quite similar to the findings of an automated mass visual field testing study by Bengtsson and Krakau *(111)*, which showed that 48 percent of subjects with visual field loss were previously unaware of any visual problem. Follow-up letters to subjects with visual field deficits revealed that the most commonly diagnosed sources of significant field loss were glaucoma, cortical cataracts, and retinopathy. These data are a grim reminder of the insidious nature of glaucoma and retinal disorders and their potential deleterious impact on the mobility and visual functioning of the older population.

Another significant outcome of the application of automated perimetry to the mass screening of drivers was the demonstration of a functional link between visual field deficits and driving accident and conviction rates. Johnson and Keltner *(15)* found that drivers with visual field loss in both eyes exhibited a traffic accident and conviction rate that was twice as high as that of age- and sex-matched observers with normal vision. This outcome is consistent with previous studies of monocular drivers *(112)* and patients with visual fields constricted as the result of retinitis pigmentosa *(113)*. The difference between these positive findings and previous studies that failed to demonstrate a relationship between visual field and driving performance *(6, 26, 27)* was attributed to the use of nonvalidated field test procedures in prior research efforts.

The potential benefits of screening older drivers for visual field deficits are apparent. Because of the insidious nature of visual field losses, hundreds of thousands of persons could be detected and treated in the early stages of dysfunction, thereby preventing permanent loss of visual function and markedly limited mobility. Even age-related maculopathy can be "slowed down" by treatment.

Numerous impediments prohibit immediate implementation of automated field-testing technology, however. Currently available equipment is expensive, and even mass production would not reduce the cost to sufficiently low levels because these devices cannot be used to administer other tests of visual function. Instead, the basic components of automated field assessment need to be translated to a general-purpose visual testing apparatus such as a high-resolution, television-based technology. Such a translation would require substantial effort because of the size of the visual field that must be stimulated. However, this problem could be circumvented through the use of multiple CRT screens deployed at different orientations. Television-based perimetry is not without precedent *(114)*. Additional research on the development of such an automated "glass" (i.e., CRT) perimeter could yield great advances in the safety and mobility of older drivers.

COMPUTERS, IMAGING TECHNOLOGY, AND THE FUTURE OF VISUAL ASSESSMENT

Most of the apparatus currently used for visual testing is based on electromechanical technology and simple display optics. This equipment tends to be rigidly inflexible and quite limited in function. It is often difficult or impossible to upgrade these systems to accommodate advances in visual assessment procedures. Electromechanical systems are labor intensive and not easily converted to automated operation. Recent advances in digital electronics and video-imaging technology have resulted in the availability of computer and display systems capable of presenting traditional and new-generation visual test optotypes in a cost-effective manner.

Computer Technology

During the past several years extremely powerful 16/32-bit microprocessors or central processing units (CPUs) have been developed. Microcomputer systems built around these CPUs have become so powerful that the distinction between "microcomputer" and "computer" has become somewhat of an anachronism. The CPUs that currently dominate the technological niche that has direct implications for new developments in vision testing include the Intel 80286/80386, the Motorola 68000/68020, the Digital Equipment Corporation LSI 11/73, and the National Semiconductor 32000 series. Most of the currently available graphic workstations, which meet the processing needs of a computerized vision tester, are based on the 80286/80386 and 68000/68020 processors. As a consequence of the resulting economies of scale, these two architectures currently hold the lead in cost-effectiveness in terms of original equipment manufacturer (OEM), hardware pricing, and availability of software development tools such as compilers, graphics support libraries, and operating systems *(115)*.

Modern computer systems built around these new generations of CPUs are powerful and inexpensive. Off-the-shelf systems such as the IBM PC/AT (80286 CPU) and the Apple Macintosh II (68020 CPU) are capable of rapidly accessing and processing millions of pieces of information per second and searching through vast archival records in just a fraction of a minute. This class of small computers can also inexpensively generate high-resolution graphic displays that rival the quality of those produced by workstations costing tens of thousands of dollars.

The advent of special-purpose, very-large-scale integration (VLSI) devices has made it possible to manufacture high-resolution monochrome or color graphic display systems (exclusive of the display monitor) for costs below $1,000 *(116)*. These low-cost systems are capable of generating the types of stimuli needed to implement emerging visual assessment techniques such as those employing sine-wave gratings, low-contrast optotypes, and temporally modulated figures *(117)*. These systems possess the general-purpose processing functions needed to fully automate test administration and scoring. The strategies and benefits of test automation are described further in a subsequent section of this paper.

Display Technology

The factor that limits the cost and quality of state-of-the-art visual graphics is not computational constraints. Currently available CPUs and VLSI graphics processors are more than powerful enough to exceed the spatial-processing limits of the human visual system. Instead, the major constraint on graphics quality is the imaging technology that ultimately translates the computer's electronic signals into visible light energy—for example, the familiar CRT found in video monitors.

Several display characteristics emerge as critical criteria for the selection of an imaging technology for an application such as a multipurpose vision-testing apparatus: spatial resolution, brightness, gray scale, maximum size, contrast, color capability, and cost *(118)*. The minimum spatial resolution, brightness contrast, and cost requirements of a vision tester are self-evident. The need to consider gray scale, maximum size, and color capability, however, is not so obvious. Gray scale refers to the ability of a display to vary the brightness of each of its picture elements (pixels). The contrast modulation of sine-wave luminance gratings required by CSF assessment paradigms mandates a minimum gray scale of 256 levels (8 bits); a 1,024 gray scale range (10 bits) is optimal *(119, 120)*. General-purpose vision testing would be best served by large, bright displays—especially if assessment of peripheral vision were desired. However, many of the newest technologies can be economically implemented only in small sizes (e.g., electroluminescent and vacuum fluorescent displays). The role of color in driver vision testing is marginal. However, a general-purpose vision tester would need to have the capacity to assess color blindness. Color capacity would enable the display to faithfully depict real-world stimuli in a manner consistent with the requirements of a first-order computer simulation facility.

Given these criteria, the CRT monitor is the unambiguous technological choice for a general-purpose visual screening apparatus. CRTs are capable of the highest resolution, gray scale, contrast, and color capacity at the lowest cost. They can produce brightnesses well above those required by clinical vision assessment (>100 cd/m^2) and are available in a variety of sizes ranging from 2 to 100 cm (diagonal). No other technology can match the CRT, in a cost/function trade-off analysis, for visual assessment. Liquid crystal displays (LCDs) lack the contrast, brightness, and resolution of CRTs and are available in a limited range of sizes. Electroluminescent panels have limited gray scale and are available only in small-sized configurations. Gas plasma displays suffer from limitations in spatial resolution, gray scale, and color capability. Vacuum fluorescent panels have the same limitations as gas plasma displays and are economically realizable only in relatively small sizes.

Several factors must be considered in the selection of the best CRT configuration for general-purpose vision testing. The principal decisions center on the size-versus-brightness and the color-versus-resolution trade-offs. That is, as the size of a CRT display increases, its maximum usable brightness level decreases. When color is added to a CRT display, its spatial resolution drops to approximately 25 percent of a monochrome equivalent. Finally, increased size and the addition of color affect the cost of a CRT. Fortunately, the computer applications market has created an economy of scale that has reduced the OEM cost of bright, medium-sized, high-resolution (1,000 × 768 pixels) color monitors to under $500. This price is almost low enough to render such a trade-off analysis moot. The only limitation of the new generation of color displays is that they may be too small (13- to 14-in. diagonal) to be used in visual field testing. Large-scale (19-in. diagonal), high-resolution (2,000 × 1,700 pixels) displays that allow comprehensive assessment of the visual field are currently quite expensive (OEM cost approximately $1,500). The electronics needed to drive these displays are also more costly and incompatible with standard video disk technology.

Monochrome monitors of comparable size and resolution are available at much lower cost (<$500). It would appear that, given present economies of scale, a size-versus-color trade-off is unavoidable. Adopting a display that is both large and supports color will be expensive. A large, monochrome display may have the potential for visual field testing but sacrifices color capability. A medium-sized, high-resolution color display can be used to assess color blindness and depict realistic simulations of many targets at the cost of constraining the potential for visual field assessment.

Video Disk Technology

The video disk is an optical storage device specifically developed to record and play back pictorial and graphic information. Full-length feature films can be stored and played back as up to 10,000 or more individual picture fields or frames. The unique advantages of this technology compared with standard film media are that (a) video disks can be easily interfaced and controlled by a computer and (b) video disk frames can be accessed randomly, not just sequentially. Hence, a properly interfaced computer can display, on demand and in real time, any frame or sequence of frames stored on the video disk.

The potential significance of video disk media for driver vision-testing applications is that highly realistic simulations could be supported at a relatively low cost *(121, 122)*. That is, first-order approximations of typical driving scenes could be presented and potentially used in the testing and training of driver's license applicants. For example, because of the realism of the video disk medium, actual video representations of new highway signs could be used in general-knowledge assessment and instruction. Similarly, the technology could be used to show video sequences depicting proper driving procedures or special techniques to compensate for poor weather conditions or diminished sensory capacity, or both. Video disks typically support two audio channels that could be used to provide auditory accompaniment and hearing assessments. Finally, video disks could be used to store and present stimuli needed to implement visual assessments of standard acuity, contrast sensitivity, and low-contrast acuity without incurring the cost of a graphics processor in the host computer controller.

Several manufacturers currently supply video disk players (e.g., Panasonic, Phillips, Pioneer, and Sony). The OEM cost of the units varies from around $400 to $1,200, depending on specifications *(123)*. The upper end of this range ($1,000 to $1,200) is a good estimate of the cost of a unit with the minimum resolution and picture quality needed to test driver vision (exclusive of the cost of the CRT display and control computer system). The hidden costs of implementing video disk-based stimuli would be incurred in the production of any active materials such as those demonstrating proper driving behavior and techniques. Such scenes must be thoroughly planned and filmed with the support of a professional video studio. These costs can become quite high if much training footage is to be produced *(124)*.

APPLYING THE NEW TECHNOLOGY

All of the tests currently used to assess driver vision as well as all of the emerging techniques discussed previously could potentially be implemented on a computer-controlled, video-based system. For the purposes of exposition, two prototypical advanced-technology visual assessment systems (ATVAS) are shown in Figure 10. System Configuration A, in the top half of Figure 10, consists of a disk-based (30 meg) control computer ($1,000), a video graphics controller ($300), a high-resolution display monitor ($500), and a four-position response console ($100). The total estimated cost of this system is $1,900 based on OEM quantity pricing. System Configuration B, at the bottom of Figure 10, is similar to Configuration A except that the graphics controller is replaced with a high-quality interactive video disk player ($1,000). The estimated OEM cost of this system is $2,600. The potential applications and benefits of such video-based vision testing systems are described next.

Automation

The first advantage of computer-controlled video testing systems would be highly automated test administration. Because of the inherent flexibility of the general-purpose computer controller and the programmable video display, the system would be capable of automating standard pencil-and-paper knowledge tests of traffic laws, signs, and procedures that are currently administered and scored by hand. Hence, in addition to providing a gateway for new visual assessment techniques with minimum impact on personnel costs, an automated general-purpose vision tester could off-load current personnel demands by assuming test administration functions.

The potential operational cost savings of automated testing should not be underestimated. Commenting on the personnel demands that would be placed on the Pennsylvania Department of Motor Vehicles if just 1.5 min of test time were needed to assess visual function in each eye, Keeney (*125*, p. 791) writes:

> In Pennsylvania this would require over 8 million examinations. At . . . a minimum test time of 1.5 minutes per eye, this would require 10,000 work weeks or 200 man-years to accomplish. If another 1.5 minutes were required (for preliminary test preparation), Pennsylvania would require 600,000 hours, or 300 man-years to process its drivers once.

Fully automated test stations would not only allow new visual assessment techniques to be implemented in a cost-effective manner but could potentially pay for themselves by taking over the current test administration duties of motor vehicle bureau personnel.

Development of an automated test facility for the mass screening of driver vision would need to carefully incorporate the special needs and characteristics of the older population. Many of these special requirements have been discussed by Schieber *(25)*. Several other age-specific constraints on automated testing were not covered by the DOT studies and are discussed elsewhere *(25)*: general age-related slowing in motor response and information processing *(126)* and a recent finding that older adults have considerable difficulty recognizing computer-synthesized speech *(127)*. The MARK II *(27)* Integrated Vision Tester employed prerecorded audio instructions in its successful attempt to apply the principles of automation to visual assessment of drivers. Because of the limited reliability and flexibility of sequential audio tape, more recent attempts at system automation have employed computer-synthesized speech to deliver test instructions and response feedback. Benefits of using computer-generated audio include the more rapid speed at which instructions can be delivered and understood, the ability to implement automation with illiterate populations, and the ease of support for bilingual test administration. However, the "unnatural" quality of low-cost speech synthesizers represents a real obstacle to speech intelligibility in older adults. The reasons for this difficulty with synthesized speech on the part of the aged are not understood but may involve diminished short-term memory processing capacity, lack of previous exposure to and practice with synthesized speech, or changes in the auditory nervous system *(128)*. This problem must be avoided in automated testing of older adults. Fortunately, inexpensive digital-to-audio peripherals that are capable of high-fidelity, random-access replication of the human voice have been introduced recently (e.g., Antex Model VP-600 digital audio interface). The approximate OEM cost of adding digital audio playback capability to the disk-based computer controller shown in Figure 10 is estimated to be less than $200.

The second age-specific problem with automated test administration is the increased time required by older adults to process and respond to sensory information. As a result, a stimulus delivery rate that would be optimal for young populations would place undue "pacing stress" on older respondents. On the other hand, a more relaxed stimulus presentation rate suitable for older adults would result in diminished efficiency of testing of the young and middle-aged population. Fortunately, the solution to this stimulus pacing problem is straightforward and simple to implement. Despite the simplicity of this solution, however, it is often overlooked by system designers. Pacing stress can be avoided and optimal test time efficiency maintained by programming the automated test system to deliver stimuli at a rate dependent on the

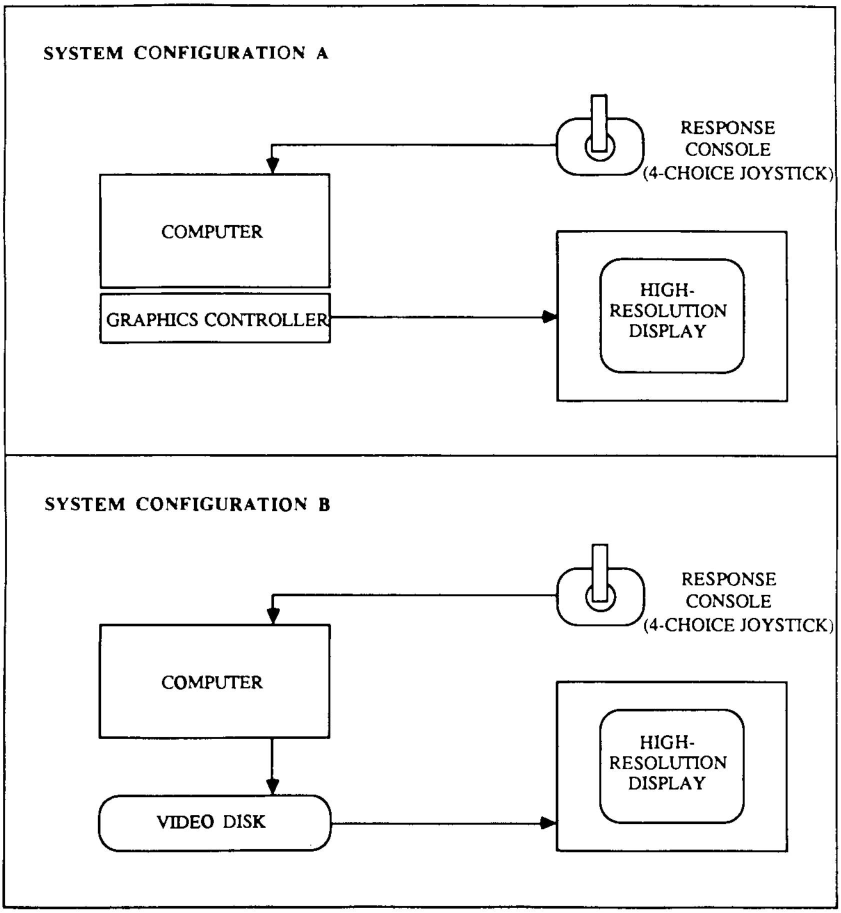

FIGURE 10 Schematic representation of some prototypical electronic visual assessment systems.

observer's response latency. That is, the next stimulus is not presented until the observer signals that he or she is ready to respond. Such self-pacing strategies have been successfully employed for many years by laboratory researchers to reduce response error and variability in older adults.

There is ample precedent for reliable assessment of visual function through the use of automated screening apparatus *(129–131)*. More recently, the efficient use of CRT displays for the administration of basic acuity testing has also been successfully demonstrated *(57, 132)*. Automated visual acuity testing via CRT displays is best performed using Landolt-C optotypes instead of standard Snellen-like letters. The Landolt-C response can be easily communicated to the control computer (unlike the 26 choices available in the alphabet) and adheres to the recommendations of the National Research Council Committee on Vision *(8)* standards for acuity assessment.

The use of CRT displays for computer-generated sine-wave gratings and automated collection of the CSF has already been documented. Although many procedures have been used to rapidly assess contrast sensitivity *(133)*, it has been clearly demonstrated that forced-choice methods must be used with older observers *(59)*. Otherwise, their responses tend to be excessively variable and conservatively biased *(10)*. Administration of such forced-choice contrast sensitivity assessment procedures, using pairs of sine-wave grating targets, could be automated quite readily by either of the prototypical systems shown in Figure 10.

A computer-controlled, video-based vision tester could also be used to implement low-contrast acuity testing. As described previously, such assessments would be most easily implemented through the use of Landolt-C optotypes instead of the more familiar Snellen and Sloan letters. Other tests, such as those employing a glare stressor, would require hardware extensions to the prototypical systems shown in Figure 10. The glare test, for example, would require the addition of an external luminaire that could be illuminated and extinguished under computer control. Additional revisions to the basic design might also include a viewing hood to isolate the video display from extraneous light sources and simple optics to allow multiple distance testing (e.g., near versus far acuity).

Finally, the computer control incorporated into the design of the prototypical vision tester could be used to implement state-of-the-art developments in psychophysical procedures that mathematically optimize test efficiency and reliability *(134, 135)*. New "adaptive" techniques based on the maximum likelihood principle and more sophisticated Bayesian estimation approaches are computationally intensive and, hence, are not amenable to manually administered applications. However, the insertion of powerful, high-speed computers into the test administration loop now makes these advanced mathematical procedures practical and readily realizable *(136–138)*.

Research and Development Gateway

A less obvious, yet significant, benefit of implementing an advanced-technology vision testing system is its potential role as a gateway for future research and development. A general-purpose, computer-based video assessment system could be easily reprogrammed to add new visual tests or modify current ones. As a result, researchers could quickly and inexpensively develop and test novel techniques in the field. New techniques and procedures could be developed and improved within a stable, evolutionary context rather than through "fits and starts" characteristic of approaches that have employed traditional "hard-wired" test instruments. Automation of such experimental procedures would minimize the need to involve field personnel already busy with other duties.

The visual assessment approaches that are more perceptual than sensory in nature could benefit the most from such flexible test hardware. Assessment of visual search abilities and related higher-order "information processing" skills has potential for developing into preliminary screening tools for the determination of "cognitive competency." With sufficient development and testing, it is feasible that computer-based video techniques could be used to identify persons suffering from significant "developmental disability" or age-related dementing illness that could seriously impair driving safety. Such individuals could be subsequently referred to medical personnel for more rigorous physiological and psychological assessment.

Other research issues that could be readily addressed through a flexible, video-based assessment system include the use of nighttime-level luminance and motion in stimulus displays (e.g., the dynamic visual acuity debate). Luminance levels of visual optotypes could be easily reconfigured and tested in the field. The kinetic visual acuity *(139, 140)* and rotary DVA *(141)* techniques appear to provide tests of essentially the same functions as traditional DVA but in a manner amenable to implementation on a video display device.

A computerized, video-based test system could be deployed in several phases. First, it could be introduced to automate existing visual and informational testing programs. In a second phase, newly developed visual assessment techniques, such as those based on contrast sensitivity measures or low-contrast optotypes, could be deployed. After these are in place, a third phase that implemented computer-based instruction (CBI) for driving laws, signs, and procedures could be developed. In this manner "continuing education" of the driving population could be assured. Finally, a fourth, much more speculative, phase could be developed in which cognitive competence assessments were performed. In summary, the development and sequential deployment of an advanced-technology visual assessment system hold much potential for cost-effective improvements in the testing and delivery of services to the driving population.

SUMMARY OF RECOMMENDATIONS AND FUTURE RESEARCH REQUIREMENTS

The objective of visual screening for older drivers should be optimization rather than prohibition or restriction. Special tests that are sensitive to the frequent ocular pathologies of old age are emerging. When detected, most of these age-related visual disorders can be corrected by prompt medical intervention. Hence, successful optimization screening of the elderly would not result in significant increases in the loss of driving privileges; instead, it would yield improved visual functioning with an accompanying increase in driving safety, mobility, and efficiency.

Studies should be conducted to quantify the effectiveness of contrast sensitivity techniques and low-contrast acuity testing for improving the mobility and productivity of the older driver population. Laboratory and clinical evidence clearly demonstrates that contrast sensitivity provides screening sensitivity for age-related visual pathologies that most often elude detection by traditional acuity measures. The modes of contrast sensitivity measurement that yield the most information on age-related ocular pathologies (e.g., cataract, glaucoma, and retinal disorders) are expensive to administer because of the apparatus and testing time required. In addition, standardized procedures for collecting and scoring CSF data remain to be developed. Recent findings have indicated that low-contrast acuity tests may yield a large subset of the information made available by CSF procedures. Unlike the contrast sensitivity techniques, low-contrast acuity tests are simple to administer and interpret. The costs and benefits of these two emerging techniques need to be carefully examined before either is implemented in a mass-screening application such as driver vision testing. The potential for employing a glare stressor for increasing the diagnostic selectivity of these methods needs to be explored. Both the contrast sensitivity paradigm and the low-contrast acuity technique hold promise for improving the level of visual functioning of older drivers.

Advanced technology should be applied to automate driver-screening tasks. The emergence of low-cost computers and high-resolution displays has made it possible to develop a general-purpose vision test station for mass-screening applications. Such a system could be used to implement fully automated administration of existing vision and driving knowledge and information tests. Computerized, video-based vision testers possess the characteristics required to implement emerging visual assessment techniques, such as contrast sensitivity and low-contrast acuity testing, and have the design flexibility to support anticipated future developments in vision testing, such as those incorporating motion and higher-order information-processing skills.

Mandatory periodic retesting of older drivers should be initiated by all driver-licensing agencies. All of the data collected to date clearly indicate that visual function is prone to dramatic changes during the latter part of the human life span. These data need to be carefully analyzed to show changes in the incidence rates of various visual disorders as a function of age. These quantitative data should then serve as the basis for scientifically determining the age at and frequency with which visual retesting is to be conducted. Such a process would ensure that subsequently determined retest selection criteria would be based on facts rather than arbitrary conventions. The development of advanced automated vision-testing systems would make it possible to administer an ambitious retesting program in a cost-effective manner.

The following three steps need to be taken:

- Establish a photopic acuity illumination standard that is free of potential age bias.
- Transfer automated full-field perimetry technology to one amenable to mass screening.
- Explore the costs and benefits of employing CBI for continuing driver education.

Future attempts to establish causal relationships between measures of visual function and driving performance should employ simulation studies rather than rely entirely on correlational designs.

The feasibility and desirability of cognitive competence screening of driver's license and renewal applicants also need to be studied.

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