HUMAN FACTORS, 1991, 33(5), 507–519

Visual Requirements for Safety and Mobility of Older Drivers

DAVID SHINAR,[1] *Ben Gurion University of the Negev, Beer Sheva, Israel, and*
FRANK SCHIEBER, *Oakland University, Rochester, Michigan*

Efforts to assess visual deterioration with increasing age, coupled with new mechanisms proposed to limit the exposure of visually impaired drivers to driving risks, have emerged in response to the increase in older drivers. Visual functions discussed in this context include static acuity (photopic, mesopic, and in the presence of glare), dynamic visual acuity, visual field, contrast sensitivity, and motion perception. Exposure control mechanisms discussed include alternative periodic vision testing strategies, visual training, and environmental and vehicular modifications to accommodate the older driver. Finally, relevant research needs are addressed.

INTRODUCTION

Models of driver information processing typically consider vision the primary sensory channel, which is responsible for up to 95% of driving-related inputs. This critical role of vision is supported by driving task analysis (e.g., McKnight and Adams, 1970).

If good vision is a necessary condition for safe driving, does it follow that poor vision results in unsafe driving? Studies of the relationship between vision and driving have focused on that issue with mixed results. Some large-scale studies have provided weak but consistent support for the relevance of criterion visual performance levels to safe driving (Burg, 1964; Davison, 1985; Henderson and Burg, 1974; Johnson and Keltner, 1983; Shinar, 1977). All of these studies were correlational, and the only support for a causal link between vision and accident involvement is derived from theoretical considerations rather than empirical data.

Although lower-order visual factors may influence accident involvement directly or indirectly by affecting higher-order cognitive processes, one would expect a weak relationship between visual performance and accident involvement for at least the following reasons:

(1) Accidents most often have multiple causes rather than being attributable to one specific human impairment.
(2) In detailed accident analyses, the most frequently cited human causes of accidents are either attentional or higher-order perceptual failings such as improper lookout, misjudgment, and distraction (Treat et al., 1977).
(3) The statistical phenomenon of a *restricted range* of visual impairments—attributable to the essentially worldwide requirement for driving of at least 20/40 acuity in the better

[1] Requests for reprints should be sent to David Shinar, Department of Industrial Engineering and Management, Ben Gurion University of the Negev, Beer Sheva 84105, Israel.

eye (Charman, 1985)—would act to reduce the strength of a relationship that may in fact exist in the general population.
(4) Many large-scale studies (e.g., Burg, 1964; Council and Allen, 1974; Davison, 1985) rely on relatively unreliable vision data obtained from gross driver screening devices.
(5) Some of the visual requirements with high theoretical construct validity have not been evaluated in large-scale studies (e.g., functional field of view, contrast sensitivity).
(6) The highway traffic system is a very forgiving one, with compensatory mechanisms for human errors and deficiencies.
(7) Drivers with reduced capacities may compensate by restricting their driving to times when there are favorable light conditions and low-density, low-speed traffic.

For these reasons it may be most appropriate to study specific visual impairments and theoretically related driving tasks or accident-causing behaviors. Thus Shinar, McDonald, and Treat (1978) found that improper lookout as an accident cause was almost three times more likely when the driver had reduced vision than when he or she did not. An even more specific relationship has been demonstrated between road sign reading performance and visual skills. McKnight, Shinar, and Hilburn (1985) found that sign-reading distance correlated significantly with depth perception, and Evans and Ginsburg (1985) found a similar relationship between sign-reading accuracy and contrast sensitivity.

AGE-RELATED VISUAL DETERIORATION

Because vision is critical to driving, and because visual skills often deteriorate with advanced age, efforts must be directed to study those driving-related visual skills that are most susceptible to either age-related degeneration or visual diseases most prevalent among the elderly. Examples include loss of light transmissivity, oculomotor impairments, cataracts, glaucoma, and age-related macular degeneration (see Klein, 1991 [this issue]).

Figures 1 and 2 depict the relationship between age and visual performance on a variety of vision tests that have been considered relevant to safe driving. These data (from Shinar, 1977) were all obtained from the same sample of 890 healthy drivers with no known visual diseases. Similar patterns were obtained in an earlier study with a different apparatus (Shinar, 1976, using Henderson and Burg's [1974] vision tester). Several general observations can be made from these data.

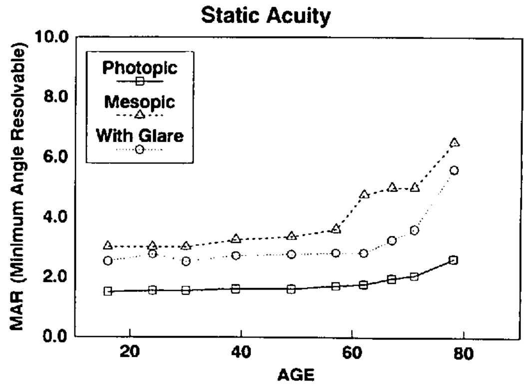

Figure 1. *The relationship between age and performance on three simple visual tasks: photopic static acuity, mesopic static acuity, and static acuity in the presence of glare. The MAR is defined in minutes of arc.*

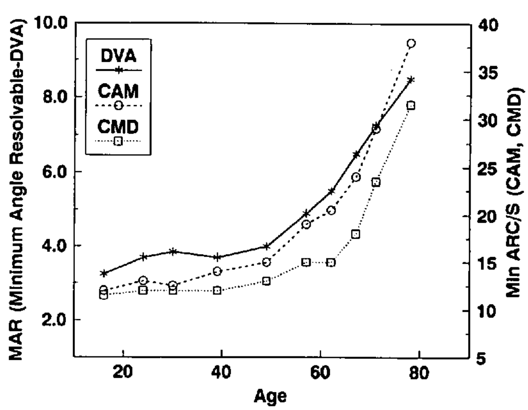

Figure 2. *The relationship between age and performance on three complex visual tasks: dynamic visual acuity (DVA), central angular motion threshold (CAM), and central movement in depth threshold (CMD). The minimum angle resolvable (MAR) is defined in minutes of arc.*

(1) All visual functions deteriorate with increasing age.
(2) The amount, rate, and onset age of deterioration vary widely among the visual functions.
(3) Deterioration in static acuity (under optimal illumination, reduced illumination, and glare) is not significant before the age of 60, whereas deterioration in the more complex tasks—that is, acuity for a moving object (dynamic visual acuity [DVA]), detection of lateral motion (central angular motion [CAM]), and detection of in-and-out movement (central movement in depth [CMD])—begins earlier and accelerates faster with increasing age.
(4) The age-related average deterioration is accompanied by a marked increase in individual differences (not depicted in the figures).

Age-related decreases in mean performance and age-related increases in performance variability have also been reported for contrast sensitivity (Greene and Madden, 1987)—especially for a drifting grating pattern (Owsley, Sekuler, and Siemsen, 1983)—useful field of view (Ball, Owsley, and Beard, 1990; Scialfa, Kline, and Lyman, 1987), stereopsis (Schieber, 1991), and probably overall attentional capacity (Madden, 1986). Nevertheless, a few studies either failed to find a significant age-related effect (e.g., Brown and Bowman, 1987, in sensitivity to size and velocity change) or found such effects to be redundant with other visual performance measures, suggesting that at least in some cases there may be a singular cause for deterioration that is manifest in several different measures (e.g., Greene and Madden, 1987).

The remainder of this section reviews and evaluates current knowledge concerning deterioration of specific visual skills that have been argued, on the basis of theory and/or data, to be relevant to the visual needs for safe driving.

Photopic Static Acuity

Studies (see Shinar, 1977, for a review of earlier studies) typically find a small but consistent correlation between photopic acuity and accident involvement, and this relationship seems to be stronger for older drivers (Davison, 1985). Corrected (with glasses or contact lenses) photopic acuity is the visual function most resistant to deterioration with age. The data in Figure 1 are representative of other studies: though mean acuity declines consistently, the initial significant deterioration in photopic acuity occurs after the age of 60. Between 5% and 10% of the 60- to 65-year-old drivers have corrected acuity worse than 20/40 (Bailey and Sheedy, 1988; Davison and Irving, 1980; Klein, 1991; Sturr, Kline, and Taub, 1990). This is the minimum acuity level (for both eyes with glasses) required by 38 states and the District of Columbia for an unrestricted license.

Scotopic and Mesopic Static Acuity

Acuity under reduced illumination has not been studied as extensively as other types of acuity, but it may be more relevant to the visual requirements of driving. Sivak, Olson, and Pastalan (1981) found that the nighttime legibility distances of highway signs for drivers over 60 years old was 65%–77% of the legibility distance for drivers under 25 years old with equal photopic acuity. In Shinar's (1977) study, mesopic acuity was one of the best predictors of accident involvement among old drivers. As can be seen in Figure 1, the onset of deterioration is somewhat earlier and the magnitude is much larger than that of photopic acuity (see also Sturgis and Osgood, 1982; Sturr et al., 1990; Vola, Cornu, Carruel, Gastaud, and Leid, 1983), which may be attributable, at least in part, to changes in pupil size and age-related increase in lens opacification.

Dynamic Visual Acuity

Dynamic visual acuity (DVA) is the ability to resolve details of a moving target. It is typically measured by moving a target, such as a Snellen letter or Landolt ring, at a fixed angular velocity across the horizontal plane in front of the observer. Burg (1964) demonstrated that DVA is more closely associated with accident involvement than is static acuity. Reanalyses of the original California drivers data base and several other studies by Burg and his associates (Burg, 1967, 1968; Henderson and Burg, 1973, 1974; Hills, 1975; Hills and Burg, 1977) replicated the same finding. Shinar (1977) also found that together with mesopic acuity, DVA was the best correlate of accident involvement. Interestingly, in a survey of driving practices of elderly males (mean age 70 years), Retchin, Cox, Fox, and Irwin (1988) found no relationship between frequency of driving and static acuity (photopic or mesopic), but they did find a significant relationship between amount of driving and dynamic visual acuity. DVA is particularly significant for older drivers. Its deterioration, which is probably attributable to the required fine oculomotor control, starts earlier than that of static acuity and accelerates much more rapidly after age 50 (Figure 2). Thus DVA may correlate with accident involvement—especially among aged drivers—because it combines multiple visual sensory and motor skills necessary for safe driving.

Motion Perception

The ability to detect movement—either in-and-out or lateral relative to the observer—is conceptually critical for detecting imminently dangerous situations. Unlike DVA, the perception of angular motion appears to be limited primarily by neural mechanisms, rather than oculomotor ones, which deteriorate with age. However, the oculomotor system is also involved because perceived velocity is affected by the effort in smooth pursuit tracking, which increases with age. Henderson and Burg (1974) found that the detection threshold for lateral movement was slightly but significantly related to accidents, and Shinar (1977) and Hills (1975) found it to be particularly relevant to the older drivers in their samples. Movement detection should also be related to judgments of speed and distance, which are poorer in older drivers (Scialfa, 1987). The deterioration of motion perception with age is shown in Figure 2, and, like DVA, its onset is earlier and more rapid than that of static acuity.

Visual Field

Although the theoretical relevance of a large visual field is compelling, the empirical data relating field to accident involvement are inconsistent. Burg's and Shinar's studies failed to find consistent relationships, and a survey of the visual field of 52 000 North Carolina drivers also failed to find any significant relationship with accident rates (Council and Allen, 1974). A possible significant limitation of these studies was their reliance on simplistic field screening devices rather than on diagnostic clinical tests. Using the latter, Johnson and Keltner (1983) examined 10 000 volunteer California license applicants and found significant deterioration among drivers over 60 years old and that drivers with visual field loss in both eyes had accident and conviction rates more than twice as high as age- and sex-matched drivers with normal fields. The fact that across all ages only 1.1% of the drivers had bilateral visual field loss may explain why studies using gross screening devices, testing field in one eye only, or using small samples are unlikely to find the expected relationship between field and accident involvement. Relative to age, Johnson and Keltner's data indicate almost no deterioration in field until the age of 60, after which there is rapid deterioration. More than 4.0% of the drivers aged 60+ demonstrated severe binocular field loss indicative of glaucoma or retinal pathology.

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 (Hirsh, Nadler, and Miller, 1984). Not only does visual function deteriorate in the presence of a glare source, but prolonged exposure to such effects can result in muscular fatigue and "attitudinal tenseness which degrades driving skill" (Pulling, Wolf, Sturgis, Valliancourt, and Dolliver, 1980, p. 103). The deleterious effects of glare increase with age (LeClaire, Nadler, Weiss, and Miller, 1982; Wolf, 1960). Much of this increase stems from increased intraocular scatter of light by the senescent lens (Allen and Vos, 1967).

Despite the strong association between age and acuity in the presence of a glare source (see Figure 1), little relationship has been found between measures of disability glare and highway safety (Shinar, 1977). The weak relationship may be partly attributable to the use of high-contrast test stimuli by the previous studies that assessed the influence of glare (Schieber, 1988). That is, given that glare changes visual sensitivity by reducing the contrast of the retinal image, it follows that low-contrast stimuli should be more sensitive in detecting the deleterious effects of stray light on visual performance. Indeed, recent evidence supports the notion that the use of low-contrast optotypes (stimulus letters) is better suited for the assessment of glare effects on real-world performance (Hard, Abrahamsson, Beckman, and Sjostrand, 1990).

In addition to static measures of disability glare, the time needed to recover visual function following exposure to a glare source appears to hold potential significance for predicting driving-related performance among the elderly. For example, Burg (1967) found that glare recovery time increased systematically with age and was related to measures of driving safety. However, the relationship to safety was very weak, possibly because of reliability problems inherent in the procedure used to assess glare recovery time. More reliable procedures for measuring glare recovery time are now available (Elliott and Whitaker, 1990; Olson and Sivak, 1989).

Contrast Sensitivity

Contrast sensitivity (CS) and/or acuity for low-contrast targets was theoretically linked to driving requirements as long as 30 years ago (Schmidt, 1961), in that the ability to distinguish large targets against their low-contrast backgrounds is much more relevant to the visual requirements of driving than is the ability to distinguish small details under optimal illumination. Nonetheless, data to test this argument are lacking because of technical difficulties. The introduction of personal computer-based contrast sensitivity tests and wall charts for measuring contrast sensitivity (see Schieber, 1988, for a review), has made assessing this relationship more practical than before. Unfortunately, data on the relationships among contrast sensitivity, visual performance in more complex tasks, and driving performance are still meager and inconclusive. Some studies have shown that CS is a better correlate of the ability to detect complex targets than is acuity (Evans and Ginsburg, 1985; Ginsburg and Easterly, 1983; Ginsburg and Evans, 1982; Owsley and Sloane, 1987; Shinar and Gilad, 1987), whereas others have failed to find a residual effect beyond that of acuity (Kruk and Regan, 1983; O'Neal and Miller, 1987).

Numerous studies have demonstrated an age-related deterioration in CS (see Owsley and Sloane, 1990). These losses are most pronounced at the higher spatial frequencies—that is, four or more cycles per degree (Owsley et al., 1983; Scialfa et al., 1988). When illumination is reduced to mesopic levels, there is a synergistic interaction among the three variables (age, luminance, and frequency) so that the age-related deterioration is even more pronounced at lower luminance and higher frequencies (Sloane, Owsley, and Alvarez, 1988). Also, as with DVA, when dynamic targets are employed (such as gratings that move across the screen), the deterioration in CS is much greater for old (mean age 69) subjects than for young (mean age 24) ones (Scialfa, Garvey, Tyrrell, Leibowitz, and Goebel, 1989).

Low-contrast acuity charts may provide the same potential for screening a wide variety of age-related visual defects without incurring many of the costs and disadvantages of CS procedures (Adams, Wong, Wong, and Gould, 1988; Schieber, 1988). Preliminary research with the Pelli-Robson charts suggests that they may provide much of the same additional information (relative to standard acuity measures) as do contrast sensitivity assessments (Pelli, Robson, and Wilkins, 1988).

Higher-Order Perceptual Functions

The importance of complex or higher-order functions is that (a) they are conceptually more relevant to the driving demands and (b) they manifest a much faster rate of age-related deterioration (see studies on effective visual field: Ball et al., 1990; Scialfa et al., 1987; Sekuler, 1986).

In two recent comprehensive assessments of vision-related testing needs, Schieber (1988) and Bailey and Sheedy (1988) concluded that there is enough evidence to focus research on some higher-order visually related functions such as visual search, effective visual field, and divided attention among visual and other tasks. These tasks reveal a central limit in information processing that is likely to affect performance on realistic visual tasks but not necessarily on simple clinical vision tests that isolate specific functions. Thus based on a series of experiments requiring subjects to divide their attention between a visual search task and tone detection, Madden (1986) concluded that there is "an age-related reduction in a processing resource, such as attentional capacity or effort . . . evident in the encoding and response selection processes required by the visual-search task, and in the use of advance information for improving search performance" (p. 335). In the driving environment, Mourant (1979) and Rackoff (1975) found significant differences between young and old drivers in their visual search efficiency.

COPING WITH AGE-RELATED VISUAL DETERIORATION

Three general approaches to dealing with the visually deficient older driver are driver licensing (retesting, followed by training and/or restrictions), environmental modifications, and vehicle modifications.

Licensing

The low frequency of accidents with elderly drivers coupled with their high rate relative to exposure suggests that there is an imposed or self-selection process that governs the amount and type of driving of elderly people. This self-selection hypothesis is supported by most people's personal knowledge of some elderly people who have a valid license but refrain from driving under certain circumstances—for example, at night, for long distances, or on high-speed expressways. Some empirical evidence supports this notion.

Kline et al. (in press) conducted a survey that examined self-assessments of visual and driving problems across the adult life span. They found that older adults not only recognized their limited visual capacity but also reported a large number of compensatory self-limiting behaviors such as avoiding rush hour traffic and not driving at night. However, several other studies that surveyed older adults about their driving habits and visual problems concluded that this process of self-selection is quite inadequate. Flint, Smith, and Rossi (1988) found no correlation between the amount of self-reported driving by the elderly and their performance on the driving simulator and no correlation between performance on the vision test and their self-assessed quality of vision. Others have also found that many elderly drivers with poor vision are unaware of their problem and continue to drive with reduced vision (Bengtsson and Krakau, 1979; Harms, Kroner, and Dannheim, 1984; Humphriss, 1983; Johnson and Keltner, 1983; Shinar, 1977). Consequently the extent to which older adults can monitor and assess their own visual capacity and then compensate for these deficits in their driving remains to be established.

If individuals cannot be assumed to restrict their driving as warranted, can they be effectively monitored and/or controlled through the licensing system? Meeting this challenge depends on at least three actions: increasing the validity of vision tests and standards for driving; developing valid vision criteria for different types of restricted licenses; and developing screening measures to detect early signs of pathology and age-related visual deterioration.

If the validity of vision scores as predictors of accident involvement can be improved at all, it is most likely to be reflected in the elderly population because individual differences in driving and visual/perceptual-motor skills are greatest for this age group, and because variations attributable to other factors, such as youth-related risk taking and alcohol use, are probably greatly reduced.

Visual Training Effects and the Older Driver

Although our sensory system and cognitive capabilities may deteriorate somewhat with age, it appears that some of these skills can be improved through training. Ball and Sekuler (1986) found that motion discrimination in the elderly improved significantly following practice. Sekuler and Ball (1986) also found that age-related deteriorations in search and localization performance within a cluttered visual field were reduced by task-specific training. Ball, Beard, Roenker, Miller, and Griggs (1988) extended these findings and showed that performance increments obtained through training sessions were maintained when experimental participants were reexamined six months later. Hennessy and Newton (1977) demonstrated that some training effects could be generalized to the driving situation.

However, the existence of such task-specific training effects also represents a problem in the development of assessment tools for dynamic or complex visual skills, which may be more highly predictive of driving performance: improvements in test performance that occur as a result of experience strongly compromise reliability and, hence, limit the potential utility of screening instruments.

Figures 3 and 4 illustrate the problematic learning effects that can occur as the complexity of one's screening procedures increases. These data are based on eight older female licensed drivers (median age 68) whose initial dynamic visual acuity was poorer than 20/50 on the Honeywell Mark II Integrated Vision Tester. Their training con-

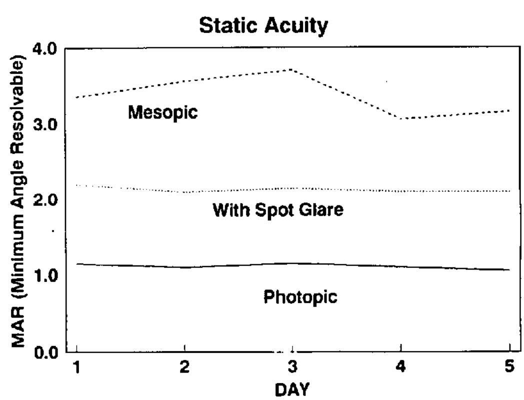

Figure 3. *The effects of practice on three simple visual tasks: mesopic static acuity, static acuity with spot glare, and photopic static acuity. The MAR is defined in minutes of arc.*

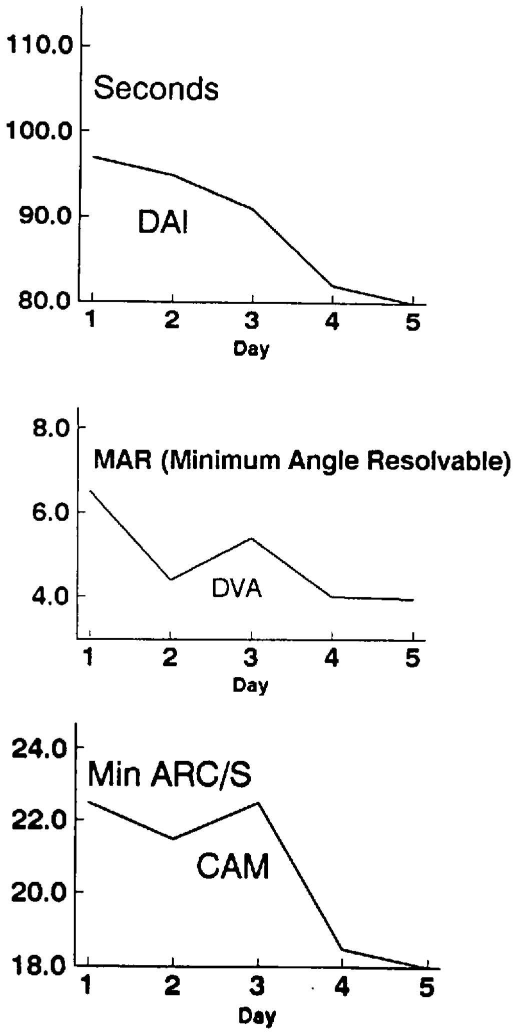

Figure 4. *The effects of practice on three complex visual tasks: visual search (detection-acquisition-identification [DAI]), dynamic visual acuity (DVA), and central angular motion threshold (CAM). The MAR is defined in minutes of arc.*

sisted of five days of four repetitions for each of the following tests: photopic acuity, static acuity in the presence of spot glare (simulating car headlights), mesopic acuity, dynamic visual acuity, visual search (speed of detecting, acquiring, and identifying a target appearing at a random location in the peripheral visual field), and movement detection. Significant improvement occurred across days for the three more complex tasks (Figure 4) but not for the simple acuity tests (Figure 3).

Improving the Visual Environment through Vehicular and Roadway Modifications

There is concern that as cars and trucks become more sophisticated, their display and control panels require a level of sophistication and quick responses that may be outside the range of older drivers. One possible reason for that trend is that most design engineers are young and do not empathize with, or are not aware of, the difficulties of older drivers (Yanik, 1990). Vehicle modifications that would help elderly drivers are those that would reduce glare, such as nonglare panels and day/night rearview and side mirrors (the current standard does not require different day/night settings even in the rearview mirror; S. P. Wood, personal communication, July 13, 1989). Other potential increases in visibility may be achieved through improved headlight configurations (Mortimer, 1988), such as midbeam headlights that would increase visibility distance without increasing glare from oncoming cars, and near-obstacle detection radar systems (Rogers, 1989).

Innovative designs should consider novel possibilities such as better positioning of critical displays and the use of collimated images (head-up displays projected at infinity). These modifications would simplify visual search and reduce the need to change the state of accommodation (a more difficult process for older drivers; see Bailey and Sheedy, 1988) when shifting the gaze between the road scene and the displays. However, the same modifications are likely to introduce glare and increase clutter in the visual field and create problems of divided attention and slowed visual search. Some current design trends may also create visual problems for the older driver. For example, the light transmission standard for windshields is 70% for a perpendicular line of sight, but increasing vehicle aerodynamic design leads to sloping windshields at ever-increasing angles and, correspondingly, ever-decreasing transmission for the driver's line of sight.

Enhancing the visual scene outside the vehicle seems to be more straightforward. To allow for reduced visual capabilities (poorer mesopic acuity, lower contrast sensitivity, higher dark adaptation levels, slower reading times, and slower reactions to a changing environment), the highway designer can employ larger signs, advance warnings, redundant signs and signals, and enhanced brightness and contrast (especially all-weather) of roadway signs, lane markers, and delineators (Michael, 1989).

The Limits of Vision Testing for the Elderly

The relative independence of different visual functions such as contrast sensitivity, acuity, and field of view implies that visual screening for the elderly cannot be done by simply adding one or two quick tests to the battery already in use at state licensing stations. One consideration is that each minute of testing for all U.S. drivers is estimated to cost approximately $11 million per year (National Research Council, Transportation Research Board, 1988).

Two approaches offer more promise than does periodic retesting with the current vision tests at the license renewal station after the age of 60 (or 50). The first is a two-tiered vision-testing process. The first tier would consist of a small number of screening tests conducted at licensing stations using current standards (e.g., visual acuity) and emerging techniques that would be better suited for detecting visual problems associated with advancing age. Candidate tests for augmenting traditional screening procedures include contrast sensitivity, effective visual fields, and mesopic and dynamic visual acuity. In the second tier, drivers who fail would be referred to a centralized testing center or a private practitioner for a comprehensive clinical evaluation of those measures as well as other measures, such as motion detection, effective field of view, and performance under conditions of divided attention.

As new data from research initiatives accumulate, the individual tests at the two tiers would be expected to change. This approach is already in operation in a rudimentary way: applicants who fail the states' screening tests are referred to state-licensed vision specialists. However, the cost-effectiveness of periodic gross vision screening at the state licensing stations needs to be reexamined given that two large-scale evaluations in California failed to demonstrate its safety benefits relative to mail-in license renewal (Kelsey and Janke, 1983; Kelsey, Janke, Peck, and Ratz, 1985).

The second approach is to require older drivers to present a certificate of good vision from a licensed ophthalmologist or optometrist. Added cost should not be excessive, considering that most aged drivers see or should see vision specialists from time to time. The inclusion of state-specified vision tests would then become part of a standard evaluation. This approach would ensure better screening of elderly drivers and provide them with professional help to improve their vision. Such a program exists in Israel, where every driver 65 years old or older must undergo a biannual medical examination and test of visual acuity and visual field to retain his or her license. In an evaluation of 11 000 elderly drivers who underwent this process, Zaidel and Hocherman (1986) found that not a single operator's license was revoked, and 18% of those tested had vision problems that were corrected with glasses. Also, 39% reported that they first became aware of their vision problems as a result of the license renewal test. Thus improved vision screening can improve the well-being and mobility of older drivers beyond the hoped-for small reduction in accident involvement.

DIRECTIONS FOR FUTURE RESEARCH AND DEVELOPMENT

To improve safety and mobility of older drivers, society must ensure that they have the necessary visual capabilities and skills to perform the driving task. Simply introducing new vision test requirements is not practical because (1) there is insufficient agreement on which visual skills are most critical, (2) for all but photopic acuity, there are no pass/fail criteria that can be scientifically defended, and (3) the complex visual skills that seem to be more relevant to driving are susceptible to practice effects, which complicates setting the criteria.

The following are research issues that must be addressed before new vision testing procedures can be implemented.

(1) Understanding of the relationship between eye pathology and specific visual performance deficiencies must be improved. Clinicians could apply this information to help drivers with reduced vision. One approach to the problem would be to conduct an in-depth analysis of the visual diseases of people failing the present standard screening tests and to relate these diseases to functional impairments on the more complex measures of driving-related visual skills.

(2) Methods must be suggested for improving vision through training and/or optical aids. Training on complex visual skills still needs to be validated.

(3) Efforts should be focused on the vision tests that are most relevant to driving needs: contrast sensitivity, dynamic visual acuity, photopic and mesopic acuity, movement sensitivity, effective visual field, and possibly glare resistance. Direct efforts toward the following goals. (a) Develop test standards that would pertain to the driving task requirements. (b) Improve test reliability and stability, particularly with respect to pass/fail criteria. This is difficult because with visual skills that are susceptible to learning effects, high test-retest correlations are not necessarily accompanied by stable criteria. (c) Identify key parameters that affect test scores. Although the standards for licensing specify only the visual function that must be tested, different tests measuring the same visual function (e.g., contrast sensitivity) often yield consistent differences in absolute levels (e.g., Scialfa et al., 1988). Therefore, conditions that contribute to differences among testing devices need to be examined (e.g., luminance levels, to which older drivers are very sensitive, in acuity tests).

(4) Two types of studies are needed to assess comprehensively the interaction among vision, age, and driving safety: (a) a large-scale study of the relationship between visual and performance measures and accident involvement by accident characteristics that may be related to vision, such as the vehicle(s)' relative heading, traffic density and complexity, and ambient illumination; and (b) small, focused studies that would relate the new driving-related measures of visual performance to everyday visual tasks that are critical for safe driving, such as visual search in the real world, redirecting of visual attention, and low-contrast real-world target detection.

(5) In the area of improved vehicle design, we need to (a) identify the relative eyes-off-the-road time the aged driver can sustain safely under different driving conditions, and (b) study alternative headlight configurations and beam patterns that would increase visibility and/or reduce glare.

(6) With regard to improving the highway environment, research should focus on the night driving environment given that, it is visually the most demanding for the older driver and, hence, the one that would benefit

the most from changes. The importance of different visual cues of guidance (from delineation) and navigation (from signs) should be assessed, and efforts should then focus on ways of improving their visibility. To maximize cost-effectiveness, the different approaches to enhancing visibility should be evaluated with particular attention to the needs of the older driver (Deacon, 1988).

(7) The research reviewed here indicates that some older individuals are aware of some of their cognitive and/or visual deficiencies and adjust their driving habits accordingly, whereas others are not aware of their deteriorated capacities and hence do not adjust for them. Research should investigate the visual domains that are likely to be accompanied by self-awareness and the ones that are not; the utility of self-awareness when it exists; the possibility of devising practical tests to enhance self-awareness (e.g., in England it is reading license plate numbers from a fixed distance); and the efficiency of self-limiting behavior that is based on it.

(8) Finally, the relevance of measures of complex visual skills warrants more research on the relationship between vision and cognition. Research should attempt to relate specific visual functions and specific behaviors that in turn determine the mobility and safety of the older driver.

ACKNOWLEDGMENTS

This paper is based in part on presentations made by the authors at a workshop jointly sponsored by the National Institutes of Health and the National Highway Traffic Safety Administration on the Safety and Mobility of Older Drivers (August 23–24, 1989). Work on this paper was supported in part by Grant No. DTNH22-89-Z-05182 to the first author. Some of the views we present here were influenced by comments and research presented by the other participants, in particular Ray Briggs, Ron Klein, Herschel Leibowitz, and Cynthia Owsley. We also thank John Eberhard for his insightful editorial comments on earlier drafts.

REFERENCES

Adams, J. A., Wong, L. S., Wong, L., and Gould, B. (1988). Visual acuity changes with age: Some new perspectives. *American Journal of Optometry and Physiological Optics, 65*, 403–406.

Allen, M. J., and Vos, J. J. (1967). Ocular scattered light and visual performance as a function of age. *American Journal of Optometry and Archives of the American Academy of Optometry, 44*, 717–727.

Bailey, I. L., and Sheedy, J. E. (1988). Vision screening for driver licensure. In *Transportation in an aging society: Improving mobility and safety for older persons* (Special Report 218; pp. 294–324). Washington, DC: National Research Council, Transportation Research Board.

Ball, K., Beard, B. L., Roenker, D. L., Miller, R. L., and Griggs, D. S. (1988). Age and visual search: Expanding the useful field of view. *Journal of the Optical Society of America, 5*, 2210–2219.

Ball, K., Owsley, C., and Beard, B. (1990). Clinical visual perimetry underestimates peripheral field problems in older adults. *Clinical Vision Sciences, 5*, 113–125.

Ball, K., and Sekuler, R. (1986). Improving visual perception in older observers. *Journal of Gerontology, 41*, 176–182.

Bengtsson, B., and Krakau, C. E. T. (1979). Automated perimetry in a population survey. *Acta Ophthalmologica, 57*, 929–937.

Brown, B., and Bowman, K. J. (1987). Sensitivity to changes in size and velocity in young and elderly observers. *Perception, 16*, 41–47.

Burg, A. (1964). *An investigation of some relationships between dynamic visual acuity, static visual acuity, and driving record* (Report 64-18). Los Angeles: University of California, Los Angeles, Department of Engineering.

Burg, A. (1967). *The relationship between vision test scores and driving record: General findings* (Report 67-24). Los Angeles: University of California, Los Angeles, Department of Engineering.

Burg, A. (1968). *The relationship between vision test scores and driving record: Additional findings* (Report 68-27). Los Angeles: University of California, Los Angeles, Department of Engineering.

Charman, W. N. (1985). Visual standards for driving. *Ophthalmic and Physiological Optics, 5*, 211–220.

Council, F. M., and Allen, J. A. (1974). *Visual fields of North Carolina drivers and their relationship to accidents.* Chapel Hill: University of North Carolina, Highway Safety Research Center.

Davison, P. A. (1985). Inter-relationships between British drivers' visual abilities, age and road accident histories. *Ophthalmic and Physiological Optics 5*, 195–204.

Davison, P. A., and Irving, A. (1980). *Survey of visual acuity of drivers* (Transport and Road Research Laboratory Report LR945). Crowthorne, England: UK Government Departments of the Environment and Transport.

Deacon, J. A. (1988). Potential improvements in roadway delineation for older drivers. In *Transportation in an aging society.* (Special Report 218; pp. 253–269). Washington, DC: National Research Council, Transportation Research Board.

Elliott, D. B., and Whitaker, D. (1990). Decline in retinal function with age. *Investigative Ophthalmology and Visual Science, 31*(4) (Suppl.), 357.

Evans, D. W., and Ginsburg, A. P. (1985). Contrast sensitivity predicts age-related differences in highway sign discriminability. *Human Factors, 27*, 637–642.

Flint, S. J., Smith, K. W., and Rossi, D. G. (1988, July). *An evaluation of mature driver performance* (Tech. Report). Santa Fe: Traffic Safety Bureau, Transportation Pro-

grams Division. New Mexico Highway and Transportation Department.
Ginsburg, A. P., and Easterly, J. (1983). Contrast sensitivity predicts target detection and field performance of pilots. In *Proceedings of the Human Factors Society 27th Annual Meeting* (pp. 269–273). Santa Monica, CA: Human Factors Society.
Ginsburg, A. P., and Evans, D. W. (1982). Contrast sensitivity predicts pilot performance in air-craft simulators. *American Journal of Optometry, 59*, 105–109.
Green, H. A., and Madden, D. J. (1987). Adult age differences in visual acuity, stereopsis, and contrast sensitivity. *American Journal of Optometry and Physiological Optics, 64*, 749–753.
Hard, A. L., Abrahamsson, M., Beckman, C., and Sjostrand, J. (1990). A new glare test based on low contrast letters for the evaluation of cataract patients pre- and post-operatively. *Investigative Ophthalmology and Visual Science, 31*(4) (Suppl.), 185.
Harms, H., Kroner, B., and Dannheim, R. (1984). Ophthalmological experiences with automobile drivers with inadequate vision [German; English abstract]. *Klinische Monatsblatter fur Augenheilkunde* (*Stuttgart*), *185*, 77–85.
Henderson, R. L., and Burg, A. (1973, December). *The role of vision and audition in truck and bus driving* (Report TM-[L]-5260/000/00). Santa Monica, CA: Systems Development Corp.
Henderson, R. L., and Burg, A. (1974, April). *Vision and audition in driving* (Final Report DOT-HS-009-1-009). Santa Monica, CA: Systems Development Corp.
Hennessy, R. T., and Newton, R. E. (1977, June). *Peripheral vision training for motor vehicle drivers* (Final Report DOT-HS-5-01204). Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.
Hills, B. (1975). Some studies of movements, perception, age, and accidents. In *Proceedings of the First International Congress on Vision and Road Safety* (pp. 65–80). Paris: Routiere Internationale.
Hills, B. L., and Burg, A. (1977). *A re-analysis of the California driver vision data: General findings* (Report 768). Crowthorne, England: Transport and Road Research Laboratory.
Hirsh, R. P., Nadler, M. P., and Miller, D. (1984). Clinical performance of a disability glare tester. *Archives of Ophthalmology, 102*, 1633–1636.
Humphriss, D. (1983, March). A survey of research projects into the relation of drivers' vision to road accidents in overseas countries and South Africa. *South African Optometrist*, pp. 11–17.
Johnson, C. A., and Keltner, J. L. (1983). Incidence of visual field loss in 20,000 eyes and its relationship to driving performance. *Archives of Ophthalmology, 101*, 371–375.
Kelsey, S. L., and Janke, M. K. (1983). Driver license renewal by mail in California. *Journal of Safety Research, 14*, 65–82.
Kelsey, S. L., Janke, M. K., Peck, R. C., and Ratz, M. (1985). License extension for clean-record drivers: A 4-year followup. *Journal of Safety Research, 16*, 149–167.
Klein, R. (1991). Age-related eye disease, visual impairment, and driving in the elderly. *Human Factors, 33*, 521–525.
Kline, D. W., Kline, T., Fozard, J. L., Kosnick, W., Schieber, F., and Sekuler, R. (in press). Vision, aging, and driving: The problems of older drivers. *Journal of Gerontology: Psychological Sciences.*
Kruk, R., and Regan, D. (1983). Visual test results compared with flying performance in telemetry-tracked aircraft. *Aviation, Space, and Environmental Medicine, 54*, 906–911.
LeClaire, J., Nadler, M. P., Weiss, S., and Miller, D. (1982). A new glare tester for clinical testing: Results comparing normal subjects and variously corrected aphakic subjects. *Archives of Ophthalmology, 100*, 153–158.
Madden, D. J. (1986). Adult age differences in the attentional capacity demands of visual search. *Cognitive Development, 1*, 335–363.
McKnight, A. J., and Adams, B. (1970, November). *Driver education task analysis: Vol. 1. Task description* (DOT Tech. Report HS800-367). Washington, DC: U.S. Department of Transportation.
McKnight, A. J., Shinar, D., and Hilburn, B. (1985, April). *Visual tasks: driving analysis of monocular versus binocular heavy duty truck drivers* (DOT Contract DT-FH-61-83-C-00134). Washington, DC: U.S. Department of Transportation.
Michael, H. L. (1989). Roadway environment and older drivers. In *Commitment to action: Conclusions and recommendations of the Highway Safety Forum on Older Drivers and Pedestrians and Younger Drivers.* Chicago: National Safety Council.
Mortimer, R. (1988). Headlamp performance factors affecting the visibility of older drivers in night driving. In *Transportation in an aging society* (Special Report 218; pp. 379–403). Washington, DC: National Research Council, Transportation Research Board.
Mourant, R. R. (1979). Driving performance of the elderly. *Accident Analysis and Prevention, 11*, 247–253.
National Research Council, Transportation Research Board. (1988). *Transportation in an aging society: Improving mobility and safety for older persons* (Special Report 218). Washington, DC: Author.
Olson, P. L., and Sivak, M. (1989). Glare from automobile rear-vision mirrors. *Human Factors, 26*, 269–282.
O'Neal, M. R., and Miller, R. E. II (1987). Further investigation of contrast sensitivity and visual acuity in pilot detection of aircraft. In *Proceedings of the Human Factors Society 31st Annual Meeting* (pp. 1189–1193). Santa Monica, CA: Human Factors Society.
Owsley, C., Sekuler, R., and Siemsen, D. (1983). Contrast sensitivity throughout adulthood. *Vision Research, 23*, 689–699.
Owsley, C., and Sloane, M. E. (1987). Contrast sensitivity, acuity, and the perception of "real-world" targets. *British Journal of Ophthalmology, 71*, 791–796.
Owsley, C., and Sloane, M. E. (1990). Vision and aging. In F. Boller and J. Grafman (Eds.), *Handbook of neuropsychology* (Vol. IV; pp. 229–249) Amsterdam: Elsevier.
Pelli, D. G., Robson, J. G., and Wilkins, A. J. (1988). The design of a new letter chart for measuring contrast sensitivity. *Clinical Vision Science, 2*, 187–199.
Pulling, N. H., Wolf, E., Sturgis, S. P., Valliancourt, D. R., and Dolliver, J. J. (1980). Headlight glare resistance and driver age. *Human Factors, 22*, 103–112.
Rackoff, N. J. (1975, October). An investigation of age-related changes in drivers visual search patterns and driving performance and the relation to tests of basic functional capacities. In *Proceedings of the 19th Annual Meeting of the Human Factors Society* (pp. 285–288). Santa Monica, CA: Human Factors Society.

Retchin, S. M., Cox, J., Fox, M., and Irwin, L. (1988). Performance-based measurements among elderly drivers and non-drivers. *Journal of the American Geriatrics Society, 36,* 813–819.

Rogers, R. (1989). Vehicle design and older drivers. In *Commitment to action: Conclusions and recommendations of the Highway Safety Forum on Older Drivers and Pedestrians and Younger Drivers.* Chicago: National Safety Council.

Schieber, F. (1988). Vision assessment technology and screening older drivers: Past practices and emerging techniques. In *Transportation in an aging society* (Special Report 218; pp. 325–378) Washington, DC: National Research Council, Transportation Research Board.

Schieber, F. (1991). Aging and the senses. In J. E. Birren, R. B. Sloane, and G. Cohen (Eds.), *Handbook of mental health and aging* (pp. 251–306). New York: Academic.

Schmidt, I. (1961). Are meaningful night vision tests for drivers feasible? *American Journal of Optometry and Archives of the American Academy of Optometry, 38,* 295–348.

Scialfa, C. T., Garvey, P. M., Tyrrell, R. A., Leibowitz, H. W., and Goebel, C. C. (1989). Age differences in dynamic contrast sensitivity. *Investigative Ophthalmology and Visual Science, 30*(Suppl.), 406.

Scialfa, C. T., Kline, D. W., and Lyman, B. J. (1987). Age differences in target identification as a function of retinal location and noise level: Examination of the useful field of view. *Psychology and Aging, 2,* 14–19.

Scialfa, C. A., Tyrrell, R. A., Garvey, P. M., Deering, L. M., Leibowitz, H. W., and Goebel, C. C. (1988). Age differences in Vistech near contrast sensitivity. *American Journal of Optometry and Physiological Optics, 65,* 951–956.

Sekuler, R. (1986, February). Visual perception and aging: Items for a research agenda. Paper presented at the National Academy of Sciences Invitational Conference on Work, Aging, and Vision, Washington, D.C.

Sekuler, R., and Ball, K. (1986). Visual localization: Age and practice. *Journal of the Optical Society of America, 4,* 864–867.

Shinar, D. (1976, April). *The effects of age on simple and complex visual skills.* Paper presented at the annual convention of the Western Psychological Association, Los Angeles.

Shinar, D. (1977, May). *Driver visual limitations, diagnosis, and treatment.* (Tech. Report DOT-HS-5-01275). Bloomington: Indiana University.

Shinar, D., and Gilad, E. (1987). Contrast sensitivity as a predictor of complex target detection. In *Proceedings of the Human Factors Society 31st Annual Meeting* (pp. 1194–1197). Santa Monica, CA: Human Factors Society.

Shinar D., McDonald, S. T., and Treat, J. R. (1978). The interaction between driver mental and physical conditions and errors causing traffic accidents: An analytical approach. *Journal of Safety Research, 10,* 16–23.

Sivak, M., Olson, P., and Pastalan, L. (1981). Effects of driver's age on nighttime legibility of highway signs. *Human Factors, 23,* 59–64.

Sloane, M. E., Owsley, C., and Alvarez, S. L. (1988). Aging, senile miosis and spatial contrast sensitivity at low luminance. *Vision Research, 28,* 1235–1246.

Sturgis, S. P., and Osgood, D. J. (1982). Effects of glare and background luminance on visual acuity and contrast sensitivity: Implications for driver night vision testing. *Human Factors, 24,* 347–360.

Sturr, J. F., Kline, G. E., and Taub, H. A. (1990). Performance of young and older drivers on a static acuity test under photopic and mesopic luminance conditions. *Human Factors, 32,* 1–8.

Treat, J. R., Tumbas, N., McDonald, S. T., Shinar, D., Hume, R. D., Mayer, R. E., Stansifer, R. L., and Castellan, N. J. (1977). *Tri-level study of the causes of traffic accidents* (Final Report DOT-HS-034-3-535-77-TAC). Bloomington: Indiana University.

Vola, J. L., Cornu, L., Carruel, C., Gastaud, P., and Leid, J. (1983). Age and photopic and mesopic visual acuity [French; English abstract]. *Journal Français D'Ophtalmologie* (Paris), *6,* 473–479.

Wolf, E. (1960). Glare and age. *Archives of Ophthalmology, 64,* 502–514.

Yanik, A. (1990, May). Research and development needed to improve the safety and mobility of older drivers: Vehicle factors. Presented at the Society of Automotive Engineers Government-Industry Meeting, Washington, D.C.

Zaidel, D. M., and Hocherman, I. (1986). License renewal for older drivers: The effects of medical and vision tests. *Journal of Safety Research, 17,* 111–116.