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RECENT DEVELOPMENTS IN VISION, AGING, AND DRIVING: 1988-1994

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16. Abstract

This report provides a comprehensive review of recent research on age-related changes in vision and visual perception as they relate to concomitant age-related changes in driving behavior. Basic research as well as applied/human factors studies have been included in this review. The primary focus of the report is on work conducted since 1988—the year in which TRB Special Report 218 on improving the mobility and safety of older drivers was published. (203 references)

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I. INTRODUCTION

In 1988, the Transportation Research Board published Special Report 218, *Transportation in an Aging Society: Improving the Mobility and Safety of Older Persons*. This report is a landmark document as it has focused the interest and resources of both the public and private sectors upon the emerging needs of older drivers. Since the introduction of Special Report 218, research involving older driver issues has been increasing exponentially. The current report provides a review of the vision literature which has appeared since 1988, with a focus upon basic and applied research that has direct consequences for understanding age-related changes in driving behavior. Previous reviews of age-related visual changes can be found in Owsley and Sloane (1990) and Schieber (1992).

II. BASIC RESEARCH

A. ANATOMICAL CHANGES

Advanced age is accompanied by characteristic changes in the eye, retina, and visual nervous system. Knowledge about these changes is essential to any attempt to understand the mechanisms underlying age-related changes in visual function. Information about neuroanatomical changes in the visual system also helps guide the development of strategies for compensating for age-related deficits in visually guided skills. Several recent developments in this area are noteworthy with respect to these joint goals of understanding and remediating age-related declines in visual function. It is well known that the maximum diameter attained by the pupil begins to decline with advancing age (i.e., *senile miosis*). Under conditions of dim illumination, the resting diameter of the pupil falls from approximately 7 mm at age 20 to around 4 mm at age 80 (Lowenfeld, 1979). Senile miosis markedly reduces the amount of light which reaches the retina and can have detrimental effects upon performance — especially given low luminance conditions. Human factors "source books" have speculated that the visual performance of older adults might be enhanced if manipulations (e.g., eye drops) were employed to exogenously increase pupil size. However, a recent study strongly suggests that smaller pupil size may actually benefit older observers under some viewing conditions by acting to minimize the emerging optical imperfections of the aging lens (see Sloane, Owsley, and Alvarez, 1988).

Microscopic examination of the retina reveals more profound age-related changes such as the loss of photoreceptors (Youdelis and Hendrickson, 1986) and atrophy of retinal ganglion cells (Curcio and Drucker, 1993; Johnson, Miao and Sadun, 1987). However, recent evidence shows that the cones which contribute to central (foveal) vision appear to remain relatively intact in older adults (Curcio, Millican, Allen and Kalina, 1993). In contrast, the number of rods in the near periphery appears to decline significantly with advancing age. Curcio, et al. (1993) reported that nearly 30% of the rods in the central 30 degrees of vision are lost by age 90. There is also some evidence that rods in the far periphery may succumb to the negative effects of aging (Gao and Hollyfield, 1992).

Initial studies of the human visual cortex reported highly significant cell loss with advancing age. For example, Devaney and Johnson (1980) found that the number of cells in the primary visual (striate) cortex declined by approximately 25% as early as age 60. However, more recent studies of human striate cortex have reported that there is *no decrease* in neuron density with aging (see Haug, Kuhl, Mecke, Sass and Wassner, 1984; Leuba and Garey, 1987). The findings that (1) the number of retinal rods — but not cones — drops with age; and (2) the number of cells in the visual cortex may not decline with advancing age represent fundamental challenges to the "working models" underlying most theoretical and conceptual attempts to understand age-related changes in visual information-processing. New models will need to be developed. There is no doubt that these new theoretical developments will have direct and far-reaching impact on the way we think about aging and visual function.

B. EYE MOVEMENTS

The visual system's ability to resolve fine spatial detail is mediated by a relatively small region of the central retina known as the *fovea.* Optimal spatial resolution depends upon the oculomotor system's capacity to acquire, track and image a visual target at or near the fovea. This acquisition and maintenance of visual fixation is accomplished by two separate but interacting perceptual-motor systems: the *saccadic* and *pursuit* eye-movement systems. The saccadic eye-movement system generates brief, high velocity, ballistic excursions of the eye, which serve to move a target image onto the fovea. The pursuit eye-movement system mediates large amplitude, continuous motions which serve to accurately track moving targets and, thus, enhance visual function by extending the useful range of high-resolution foveal vision.

Studies of age differences in saccadic eye movements have focused upon horizontal excursions of the eye. There is general agreement in the literature that horizontal saccades among the elderly have reduced peak velocities together with protracted onset latencies. Despite the slowing that is apparent in the latency and peak velocity of saccadic eye movements among older observers, Hotson and Steinke (1988) found no age differences in the accuracy of short saccadic eye movements. However, Huaman and Sharpe (1993) report that age-related decreases in positional accuracy emerge for saccades to more eccentric locations. Huaman and Sharpe (1993) have extended these results to studies of vertical saccadic eye movements. Older adults also appear to require more saccades to acquire a target in the periphery, especially under dual-task conditions characterized by high attentional load (Lapidot, 1987) or when searching complex visual scenes containing many "distracting" background stimuli (see Plude and Doussard-Roosevelt, 1989). Scialfa, Thomas and Joffe (in press) provide evidence that the age-related increase in the number of saccades needed to acquire peripheral targets stems from the restriction in the "useful field of view" which often accompanies advancing adult age.

Wacher, Buser, Bernhard and Lachenmayr (1993) have recently measured the latency of saccadic eye movements to the onset of peripheral targets while varying both target luminance and contrast. Saccadic latency dropped significantly with decreases in stimulus contrast, especially at low luminance levels. In fact, saccadic latency to low luminance/low contrast targets were on the order of 600 msec instead of the more typical 200-250 msec values used in human factors design and modeling. Although this data was collected using young observers (ages 23-28), one would expect similar or even greater declines in saccadic latencies exhibited by older adults under identical conditions. These finding have important implications for nighttime driving.

Age-related declines in the pursuit eye-movement system have also been noted. Sharpe and Sylvester (1978) reported that young subjects could accurately track targets at velocities up to 30 degrees/sec, whereas the fixational accuracy of pursuit eye movements began to breakdown for older observers when target velocity exceeded 10 degrees/sec. More recently, Kaufman and Abel (1986) have demonstrated that age differences in pursuit accuracy are exacerbated in the presence of competing or distracting stimulus backgrounds. Although the age-related oculomotor changes described above may lead to functional limitations in dynamic viewing situations, there is evidence that older adults demonstrate no loss in the ability to maintain accurate fixation while viewing a small, stationary stimulus (Kosnik, Kline, Fikre and Sekuler, 1987).

Another aspect of oculomotor function that appears to be affected by aging is the range or extent of upward gaze (i.e., the maximum vertical extent of visual fixation which can be achieved without the benefit of head movements). The classic ophthalmology reference volumes note that the limits of voluntary upward gaze fall somewhere between 40 and 45 degrees (Alder, 1933; Duke-Elder, 1949). However, Chamberlain (1971) has reported that this value becomes markedly reduced with increasing adult age. An assessment of 367 persons aged 5 to 94 years revealed that maximum upward gaze declined linearly across the lifespan from 40 degrees at ages 5 to 14 down to 16 degrees at ages 75 to 84. More recently, Huaman and Sharpe (1993) used improved technology (i.e., a high-resolution magnetic search coil) to assess the limits of both upward and downward gaze in young (mean = 28.3 years), middle-aged (mean = 49.8 years) and older observers (mean = 71.9 years). Maximum upward gaze was 43.1, 42.0, and 32.9 degrees for the young, middle-aged, and older groups, respectively. Similar findings were obtained for the extent of downward gaze.

C. DARK ADAPTATION

Dark adaptation represents a neurochemical process through which the visual system increases its gain (i.e., absolute sensitivity) in order to resolve the very small differences in luminance that define surfaces within the nighttime environment. Dark adaptation is slow. Furthermore, the process proceeds at separate rates for central/cone vision (8 minutes) and the more protracted peripheral/rod vision (30 to 40 minutes). Eisner, Fleming, Klein and Mauldin (1987) examined the process of dark adaptation in older adults (ages 60 to 88) who had first been fully preadapted to high photopic luminance levels. All observers were free from ophthalmic disease and had corrected visual acuity of 20/20 or better. Red light was used to assess sensitivity in an attempt to minimize age differences in light attenuation by the preretinal optic media. Eisner, et al. found that the maximum sensitivity achieved under full dark adaptation fell by nearly 0.1 log units per decade of advancing age. However, they found no evidence for an age-related change in the *relative* rate at which dark adaptation took place. Colie and Barker (1992) recently collected functional dark adaptation data and photopigment regeneration levels from the same observers. They found that light sensitivity declined more with age than did the rate of photopigment regeneration. The rate of recovery of the two processes appeared to move together within individuals. These findings suggest that age differences in retinal dynamics may play an important role in determining the absolute sensitivity of the visual system.

D. SPATIAL RESOLUTION

1. Acuity

Even when screened for good ocular health and optimal refractive status, older adults, as a group, demonstrate reduced levels of visual acuity (Frisen and Frisen, 1981; Pitts, 1982). Several investigations have also revealed that age differences are exacerbated when acuity is measured under low luminance conditions. A recent study by Sturr, Kline, and Taub (1990) measured acuity as luminance was decreased from very high (245.5 cd/m^2) to very low (0.2 cd/m^2) levels in a sample of 60 young (ages 18 to 25) and 91 older (ages 60 to 87) healthy observers. Acuity differences between the groups increased as stimulus luminance level decreased. Sturr et al. calculated the percentage of each age group that surpassed the 20/40 acuity criterion (the typical cutoff used by state motor vehicle licensing administrations) at 2.45 cd/m^2. This luminance level was selected as representative of the brightness level of highway signs encountered while driving at night. Although 77% of the 60-64 year-olds "passed" this nighttime acuity screening, only 28% of the 65 to 74 year-olds and 4% of the 75+ group were able to demonstrate this minimal level of visual competence.

Age differences in acuity are further exacerbated at low levels of luminance contrast. Owsley, Sloane, Skalka and Jackson (1990) found that reductions of stimulus contrast had no demonstrable effects upon young observers; but older persons exhibited a 10 to 25% decline in acuity as letter contrast was decreased from 96% to 4% (i.e., Regan Low Contrast Acuity Charts). Other investigators have also demonstrated that apparent good acuity among older adults can become significantly compromised under low contrast and low luminance viewing conditions. Adams, Wong, Wong, and Gould (1988) examined age differences in acuity over a wide range of stimulus luminance and contrast. All observers demonstrated 20/20 (1 minarc) acuity under typical high-luminance/high-contrast assessment conditions. At the lowest luminance-contrast condition (10% contrast at 5.4 cd/m^2), acuity dropped to 20/50 (2.5 minarc) for the young group (under 30 years-old) and all the way down to 20/80 (4.0 minarc) for the older observers (50-72 years-old). Similar results have been reported by Taub and Sturr (1991).

2. Contrast Sensitivity

The capacity to visually detect and identify spatial form varies widely as a function of target size, contrast and spatial orientation. As a consequence, an assessment of visual acuity (i.e., the ability to resolve small, high-contrast targets) very often does not predict an individual's ability to detect objects of large size and/or diminished contrast. The *contrast sensitivity function* (CSF), however, yields information about an individual's ability to detect low-contrast targets over an extended range of target size — complementing and extending our ability to assess functional visual capacity.

The CSF is determined by calculating the minimum amount of contrast needed to detect the presence of sine-wave grating targets. Sine-wave gratings possess useful research properties (e.g., contrast and luminance can be varied independently). Furthermore, researchers have discovered that early stages of visual processing are optimally sensitive to such targets. Contrast thresholds are typically collected using vertically oriented gratings which vary in spatial frequency from 0.5 cycles/degree (very wide) to 32 cycles/degree (very narrow). Because high levels of visual sensitivity are associated with low contrast thresholds, a reciprocal measure (1/threshold) termed the contrast sensitivity score is computed. These sensitivity scores are plotted across the range of spatial frequencies examined during the assessment procedure and constitute an individual's CSF.

Advancing adult age is associated with moderate contrast sensitivity losses at intermediate spatial frequencies with progressively greater losses emerging as target spatial frequency is increased. These age differences persist even when observers have been optimally refracted to the test viewing distance (e.g., Crassini, Brown and Bowman, 1988; Elliot, 1987; Elliot, Whitaker and MacVeigh, 1990; Scialfa, Tyrrell, Garvey, Deering, Leibowitz, and Goebel, 1988). Owsley, Sekuler, and Seimsen (1983) found that age-differences in contrast sensitivity were not eliminated when young subjects viewed the stimulus gratings under conditions of simulated ocular aging (viz., markedly reduced retinal illumination and induced refractive error). Similarly, neither the elimination of age differences in pupil size (Sloane, Owsley, and Alvarez, 1988) nor the replacement of cataracts with transparent interocular lens implants (Owsley, Gardner, Sekuler, and Lieberman, 1985) succeeded in eliminating the age-related loss of contrast sensitivity for intermediate- and high-spatial-frequency targets. These results suggest that the residual age difference in contrast sensitivity represented an age-related change in the neural, rather than optical, characteristics of the visual system. When laser interferometry is used to "bypass" the effects of age differences in the optics of the eye, substantial age differences in contrast sensitivity at intermediate and high spatial frequencies persist (e.g., Morrison and McGrath, 1985; Elliot, 1987 — but see Burton, Owsley and Sloane, 1993 for a dissenting opinion). Owsley and Sloane (1990) reanalyzed the monocular versus binocular contrast sensitivity data of Ross, Clarke, and Bron (1985) and found that the binocular summation process appeared to be less efficient in older observers who demonstrated a mere 11 to 27% binocular increase in contrast sensitivity as compared with young observers who demonstrated a 41to 129% binocular enhancement effect. This pattern is consistent with a neural mechanism of age-related decline in contrast sensitivity. Other findings also strongly indicate that much of the age-related change in contrast sensitivity results from neural differences in visual processing (Elliot, Whitaker, and MacVeigh, 1990).

Pelli, Robson, and Witkins (1988) have developed an improved procedure for assessing contrast sensitivity at intermediate spatial frequencies. The Pelli-Robson Chart consists of 48 Sloan letters arranged in groups of 3 letters each. Instead of varying the size of the optotypes as in an acuity chart, letter size stays constant while letter contrast decreases. The first group of 3 letters has a contrast of 90%. The contrast of each succeeding letter-triplet is decreased by 0.15 log units until a terminal value of 0.5% contrast is reached. The procedure is fast, reliable, and provides important information about functional status not necessarily revealed by a traditional high-contrast acuity assessment. Owsley, Ball, Sloane, Roenker, and Bruni (1991) found that Pelli-Robson contrast sensitivity was significantly decreased in older observers ($r = -0.36$). In addition, reduced

Pelli-Robson contrast sensitivity was found to be significantly associated with increases in automobile accident frequency among a sample of older adults. These findings have been replicated by two large-scale followup investigations, which will be discussed in a subsequent section of this report (see Ball, Owsley, Sloane, Roenker, and Bruni, 1993; Brown, Geaney, Mitchel, and Lee, 1993).

The additional information provided by the CSF — over and above the simple measure of visual acuity — would be expected to yield an improved ability to predict age differences in real-world visual performance. Numerous studies have provided evidence to support this expectation. Owsley and Sloane (1987) found that age-related problems with the detection and identification of human faces — which could not be accounted for by differences in acuity — were associated with contrast sensitivity losses at intermediate spatial frequencies. Similar findings with other classes of "real world" stimuli have been reported by other investigators (see Evans and Ginsburg, 1985; Kline, Ghali, Kline, and Brown (1990).

3. Dynamic Visual Acuity and Contrast Sensitivity

Dynamic visual acuity (DVA) is a measure of one's ability to resolve spatial detail in moving targets. DVA performance declines as target velocity increases; and, persons with identical static visual acuities may demonstrate markedly different dynamic acuities. The limits placed upon DVA apparently result from errors in stimulus capture by the pursuit eye movement system which result in a "smearing" of the retinal image. Since oculomotor accuracy appears to decline somewhat with advancing age one would expect to observe a concomitant age-related change in DVA (Morrison 1980). Burg (1967) examined static and dynamic acuity in 17,000+ California drivers between the ages of 16 and 92. The ability to resolve fine detail in a moving target was found to decline more dramatically with age than traditional static acuity measures. Burg's DVA measure was also found to be significantly related to traffic accident frequency in older drivers. (Thus, the fascination with DVA which pervaded the traffic engineering community during the 1970's.) However, the effect observed in the Burg (1967) study was very small — DVA accounting for only around 3% of the accident variance.

Age-related declines in DVA performance may involve mechanisms other than oculomotor pursuit. For example, Long and Crambert (1990) recently reported large age differences in DVA even when stimulus exposure times were too brief to engage pursuit eye movements (i.e., 200 msec). Once more, Long and Crambert found that the DVA performance of their young (ages 17 to 23) and old (60 to 75) groups did not differ when the presumed age-related reduction in retinal illuminance was experimentally eliminated. It should be noted, however, that their compensatory increment in retinal illuminance was also accompanied by a confounded increment in target contrast. Hence, interpretation of their results becomes less straightforward.

Scialfa, Garvey, Tyrrell and Leibowitz (1992) examined age differences in static vs. dynamic contrast sensitivity. Dynamic sensitivity was assessed by projecting small sine-wave gratings along a circular path on a viewing screen. Gratings ranged in spatial frequency from 1.5 to 18 cycles/degree and moved at a rate of 0, 5, 10, or 15 degrees/sec. Older adults demonstrated the classic pattern of contrast sensitivity loss for the stationary patterns; viz., moderate decline at intermediate frequencies with progressively greater loss at the higher spatial frequencies. The sensitivity reducing effects of stimulus motion emerged at lower target velocities for the older (mean age: 69) subjects relative to their young (mean age: 24) counterparts. These results were interpreted as representing an age-related deficit in the gain of pursuit eye-movement mechanisms and/or a reduction in the efficiency of spatiotemporal integration (Elliot, et al., 1990).

4. Peripheral Vision

Most research regarding human visual functioning deals with *foveal* vision; that is, sensitivity for fine spatial detail and color which are both mediated by the central region of the retina. However, mounting evidence reveals that some of the most profound age-related changes in visual functioning may involve peripheral, rather than central, visual processing. Because of its critical role in diagnosing ophthalmic disorders, *static visual perimetry* is one of the most widely studied area of aging and visual function (Garzia and Trick, 1992). This procedure measures one's ability to detect small spots of light superimposed upon a constantly illuminated background (i.e., increment threshold) at locations throughout the visual field. The result is a map which depicts the sensitivity of the peripheral as well as central retina. Jaffe, Avarado, and Juster (1986) found age-related decrements in sensitivity across the entire visual field. This loss appears to accrue gradually across middle-age, but then begins to accelerate beyond age 60 (Collin, Han and Khor, 1988). These age-related changes are not due to optical factors, and, hence, appear to reflect age-related neural losses (see Owsley and Sloane, 1990). Finally, since age-related sensitivity losses in the visual field (e.g., due to stroke) below the horizontal midline appear to be more relevant to driving than field losses above the midline, Parisi, Bell, and Yassein (1991) recommend that horizontal field assessments for driver screening be performed at 10 degrees below the midline rather than directly upon the midline as currently practiced.

Spatial resolution has long been known to decline markedly as targets move away from central vision into the parafoveal and far peripheral retina. Acuity for letters will fall to half its maximal level before targets reach a retinal eccentricity of 1 degree (Ludvigh, 1941). As target eccentricity increases from 1 to 25 degrees, acuity continues to decline (but at a slower rate). Anstis (1974) has demonstrated that letter size must be incremented by a factor of 0.046 per degree across this range. Recent evidence suggests that the rate of loss in visual sensitivity associated with retinal eccentricity becomes accelerated in older observers. For example, Collins, Brown, and Bowman (1989) examined peripheral visual acuity in young and old observers with 20/20 (or better) central acuity. A high-contrast acuity target with a critical detail of 2.4 minarc (larger than that needed to achieve 20/40 central acuity) was moved away from the central fixation point until observers could no longer reliably determine its orientation. Young observers could discriminate the critical detail up to 61.6 deg of eccentricity while older observers could do so only through 45.7 deg, representing a 23 percent age-related reduction in the "useful field of acuity." The magnitude of the observed age difference in peripheral acuity was reduced when a larger (i.e., 4.8 minarc) target was employed. Similar accelerated losses in visual sensitivity with retinal eccentricity in the aged have been noted for measurements of contrast sensitivity (Crassini, Brown, and Bowman, 1988). Again, the analyses performed by these investigators suggest that age-related peripheral losses stem from neural rather than optical aging mechanisms. However, opportunities for optical contributions to such effects remain. Although the relative magnitude of peripheral refractive error does not appear to increase as a function of age (Scialfa, Leibowitz, and Gish, 1989), there are several ways in which age differences in peripheral refractive error could be introduced into the results of an experiment. For example, most older participants in a study would be expected to wear eyeglasses. Unfortunately, these eyeglasses, which correct refractive error in the central area, tend to introduce astigmatic error in the periphery. Studies of age differences in peripheral vision could be confounded by such effects.

Age-related losses in extrafoveal visual perception have also been noted using complex visual search paradigms. Cerella (1985) demonstrated that age differences in letter recognition times increased with the retinal eccentricity of the target. Others have found that older adults suffer from a restricted "useful field of view" in visual search tasks (Sekuler and Ball, 1986). Such age-related decrements in the ability to process parafoveal targets appear to depend heavily upon competition for "attentional resources" imposed by the concurrent presentation of "distractor" stimuli rather than upon limits imposed by the sensory/perceptual systems (Ball, Beard, Roenker, Miller, and Griggs, 1988; Scialfa, Kline and Lyman, 1987). The cognitive/attentional aspects of visual search are detailed elsewhere in this report.

5. Depth and Distance Perception

There are many classical studies that have purported to examine age differences in *stereopsis* (i.e., binocular depth perception based purely upon retinal disparity information). However, no clear consensus has emerged about the magnitude of the age difference (see Owsley and Sloane, 1990, for an excellent review). Most of the studies that have failed to demonstrate age differences in stereopsis have used relatively insensitive clinical screening tools or random-dot stereogram tests which load upon a variety of visual mechanisms beyond the level of stereopsis (see Greene and Madden, 1987; Yekta, Pickwell, and Jenkins, 1989). This pattern of results suggests that age differences in stereopsis, if they exist as a general rule, appear to be small in magnitude.

Very little work has been done to investigate the possible effects of aging upon higher-order depth perception that is based upon cues other than stereopsis (e.g., ocular vergence effects, spatial and motion parallax, spatiotemporal texture gradients, etc). Recent evidence suggests that space/distance judgments may become "distorted" at luminance levels representative of nighttime driving due to "vergence insufficiency" (Bourdy, Cottin, and Monot, 1991). Such processes may be exacerbated in the elderly driver due to a breakdown in the accommodation-vergence feedback loop (expected to result due to the onset of presbyopia). Lack of information in this area is unfortunate, especially since recent experimental work suggests that older drivers may be more heavily dependent upon distance (as opposed to velocity) cues in their execution of critical driving maneuvers (see work by Staplin, Lococo, and Sim, 1993, which is discussed below).

6. Glare and Glare Recovery Time

Disability glare occurs when the introduction of a stray light source reduces one's ability to resolve spatial detail. Advancing adult age is known to be associated with significant increases in susceptibility to the deleterious effects of glare (see Schieber, Fozard, Gordon-Salant, and Weiffenbach, 1991). Pulling, et al. (1980) measured the tolerance for disability glare in a sample ranging from 5 to 91 years of age. They found that glare tolerance declined exponentially with advancing age — the rate of decline becoming markedly accelerated beyond age 40. Schieber, et al. (reported in Dewar, Kline, Schieber, and Swanson, 1994) found that the introduction of a glare source (designed to mimic the headlights of an approaching car at a distance of 100 ft) yielded a small but significant reduction in the contrast sensitivity of healthy older adults (ages 65-80). No measurable reduction in contrast sensitivity was observed for their young or middle aged (ages 40-55) subjects. It should be noted, however, that similar glare levels can yield nearly a complete loss of contrast sensitivity (i.e., functional blindness) in older persons with advanced cataract, even if they maintain reasonably good level of visual acuity (Nadler, Miller, and Nadler, 1990).

Most models of disability glare attribute its effects to intraocular scatter of light (Schieber, et al., 1991; Schieber, 1992). Such off-axis scattering of light within the eye covers the retina with a "veiling luminance," which effectively reduces the contrast of the images formed upon it. For this reason, Schieber (1988) has proposed that low contrast optotypes are better suited for the quantification of disability glare effects than high contrast optotypes which have been traditionally employed in glare assessment procedures. Newly developed glare tests, such as the Berkeley Glare Tester, now incorporate such low contrast optotypes in their design (Bailey and Bullimore, 1991).

One aspect of disability glare which remains poorly understood is the time required to recover visual sensitivity following exposure to a transient glare source (e.g., oncoming headlights while driving at night). There is ample clinical evidence that the time needed to recover from glare increases with age. However, little systematic work has been done to substantiate this claim (see Olson and Sivak (1984) for an exception). Schieber (1994) carefully estimated glare recovery time in young (ages 18-24), middle-aged (ages 40-55) and older (ages 65-74) adults with good acuity and contrast sensitivity. The time needed to identify two large, low-contrast letters after the onset of a very bright peripheral glare source (78 lux) was measured. The mean glare recovery time for the old group (2142 msec) was significantly slower than that obtained for the middle-aged subjects (1189 msec); who, in turn, took significantly longer to recover from the effects of "veiling" glare than the young group (790 msec). Finally, there is evidence that older adults suffering from diseases that effect the retina (e.g., diabetes, hypertension, macular degeneration, etc.) require even greater durations to recover from the deleterious effects of brief glare exposures (see Collins (1989) for a review).

E. COLOR VISION

Human color vision is exquisitely sensitive. Normal observers are capable of distinguishing over 100,000 hues generated from various combinations of three "primary color" light sources (Geldard, 1972). Most investigations of age differences in color vision have employed *color confusion tests* in which the observer is required to arrange sets of "color caps" into an ordinal series extending between two anchored color exemplars (e.g., the Farnsworth-Munsell 100 Hues or FM-100 Test). The number and type of errors exhibited via this arrangement of color samples is quantified into a color sensitivity profile. Numerous studies utilizing this technique have reported that color discrimination errors increase significantly with advancing age. These errors are primarily limited to fine discriminations within the "blue-green", or short wavelength, region of the spectrum (e.g., Knoblauch, Sanders, Kusada, Hynes, Podgor, Higgins, and de Monasterio, 1987). Similar findings of a differential blue-green color discrimination weakness among older adults have been reported using color matching (i.e., anomaloscopic) techniques (e.g., Eisner, Fleming, Klein, and Mauldin, 1987). Cooper, Ward, Gowland and McIntosh (1991) examined color discrimination using the Lanthony New Color Test in a large group of observers ranging from 30 to 89 years of age. They found that the ability to distinguish desaturated shades of blues and greens was the first age-related loss to emerge — beginning around age 60. This change was followed soon thereafter by a less severe loss in the ability to distinguish between desaturated reds and yellows. Most of the age-related weakness in color discrimination appears to result from reduced retinal illumination due to optical changes in the eye. In fact, Knoblauch, et al. (1987) showed that young observers demonstrate similar blue-green weaknesses at low illumination levels and that age differences in color discrimination performance were minimized at high levels of target illumination. Although the magnitude of the age-related loss in blue-green color discrimination is small, Cody, Hurd, and Bootman (1989) demonstrated that older adults with poor FM-100 test scores were more likely to make errors discriminating between medicine capsules with similar color-coded markings. Knoblauch, et al.'s findings, however, suggest that such errors can be minimized if optimized lighting conditions are employed.

F. TEMPORAL RESOLUTION

Perhaps the most fundamental age-related change in visual function is the loss of the ability to detect and process rapid temporal changes in the visual environment. Temporally contiguous visual events that would be seen as separate and distinct by young observers often appear as "fused" or indistinguishable by older individuals. This age-related "slowing" of the visual system not only affects higher-order events such as those revealed in sequential integration of form and backward masking studies, but also can be demonstrated in the form of age-related losses in rudimentary visual functions such as flicker sensitivity and motion perception (Kline and Schieber, 1982).

1. Flicker Perception

The *critical flicker frequency (CFF) threshold* has been the most frequently employed paradigm for assessing age differences in the temporal resolving power of the visual system. The CFF is the minimum frequency of a pulsating light source at which the light *appears* to be "fused" into a continuous, rather than flickering, stimulus. The CFF threshold is interpreted to represent the point at which the visual system can no longer track rapid temporal modulations in stimulus luminance. There is a well documented age-related decline in the temporal resolving power of the visual system as indexed by the CFF threshold (see Kline and Schieber, 1982, for a review). For example, Wolf and Shaffra (1964) collected CFF measures from 302 observers ages 6 through 95. CFF thresholds increased (i.e., flicker sensitivity decreased) gradually until around aged 60 and then rapidly thereafter. Although a large part of the age-related loss in flicker sensitivity certainly results from a reduction in retinal illumination (due to senescent increases in the opacity of the lens and a reduction in pupillary diameter), there is sufficient experimental evidence to support the notion that a portion of the age difference in the CFF is due to changes in the senescent visual nervous system (Kline and Schieber, 1985).

A more recently developed tool for examining the temporal resolving power of the visual system via flicker perception is the *temporal contrast sensitivity function* (TCSF). The TCSF is analogous to the spatial CSF described above. The contrast of a small illuminated target is sinusoidally modulated at a given temporal frequency. Then the minimum amplitude of contrast modulation required to detect the presence of flicker is determined for a range of temporal frequencies which typically extends from 1 to 50 Hz. Wright and Drasdo (1985) observed significant age-related increases in the amount of contrast needed to detect flicker. The magnitude of this age difference grew from a 1.6- to a 4.8-fold reduction in temporal sensitivity as stimulus frequency was increased from 3.3 to 30 Hz. The investigators attributed much of this loss to age differences in retinal illuminance resulting from normal senescent changes in the eye. A similar pattern of results was observed by Mayer, Kim, Svingos, and Glucs (1988). However, they observed somewhat smaller age-related declines in temporal sensitivity — consistent with the fact that they had partially controlled for age differences in retinal illumination by using a long wavelength test stimulus and mathematically adjusting performance on the basis of each observer's pupillary diameter. Similar findings have been reported by other investigators (Kuyk and Wesson, 1991; Tyler, 1989). Finally, Mayer and associates (1994) have found that older individuals with early macular disease (one of the most common age-related visual disorders) exhibit markedly reduced flicker sensitivity. Membership in the macular degeneration versus normal groups could be assigned with 100% accuracy on the basis of diminished temporal CSF performance.

2. Motion Perception

Numerous studies have demonstrated age-related declines in motion sensitivity. However, both the nature and the magnitude of observed age differences in motion perception vary widely as a function of the paradigm employed to investigate them. This pattern clearly reflects the conventional belief that motion perception is a complex phenomenon mediated by several independent visual mechanisms. Buckingham, Whitaker, and Banford (1987) measured threshold sensitivity for the detection of horizontal oscillatory motion as a function of age and temporal frequency (1-20 Hz). At all frequencies of oscillation, older (mean age = 69.7) observers were, by about a factor of 2, less sensitive to the detection of motion than middle-aged (mean age = 48.0) observers who, in turn, were only slightly less sensitive than the young (mean age = 20.7). When the grating oscillated at a frequency of 8 Hz, young, middle-aged, and older observers required oscillation amplitudes of approximately 39, 52, and 97 seconds of arc, respectively, to detect the occurrence of motion. Similar age-related losses in motion sensitivity have been demonstrated using a horizontally oscillating line segment (Whitaker and Elliot, 1989) and a small, vertically oscillating dot (Schieber, Hiris, Brannan, and Williams, 1990). Controls implemented by these later studies clearly revealed that the age-related deficit was independent of refractive error and retinal illumination and was, hence, probably of neural origin.

Several groups of investigators have recently utilized random dot-motion paradigms to investigate age differences in *global motion* detection mechanisms. Observers are presented with a large number of randomly positioned dots on a computer display. These dots then take "random walks" across the screen during a brief stimulus exposure. Under these conditions, the observer can detect no principal direction of motion in the flow of the dot pattern (because there is none). The experimenter gradually adds more and more correlated directional motion to the display until the subject can reliably detect a directional trend in the flow of dots. The amount of correlated motion required to yield a percept of directional flow is the *global motion threshold.* Motion is said to be global since the dots participating in the "correlated direction of flow" vary randomly from one animation frame to the next. That is, the observer can not detect the flow of motion by observing any given dot but must instead extract a global directional trend introduced into the entire population of dots moving in the aforementioned quasi-random pattern (see Watamaniuk, 1992). Trick and Silverman (1991) used a random dot technique to examine age differences in global motion discrimination thresholds. They found a linear decrease in sensitivity with age such that the motion discrimination threshold doubled between the ages of 25 and 80 years. Gilmore, Wenk, Naylor, and Stuve (1992) also found an age-related deficit in global motion sensitivity; however, their observed deficits were largely the result of a differential loss of sensitivity among their elderly female participants. A similar age by gender interaction was also reported by Schieber, Hiris, Brannan, and Williams (1990). Like sensitivity for oscillatory motion described above, age differences in global motion discrimination appear to be independent of ocular factors such as reduced retinal illumination or blur due to refractive error. They, therefore, are probably mediated by age-related changes in higher-order "cooperative" visual mechanisms.

Visually guided locomotion through the environment, whether via walking or driving, depends upon the ability to accurately and effortlessly extract velocity and heading information from the flow of light patterns across the retina. Warren, Blackwell, and Morris (1989) conducted a study to assess possible age differences in the ability to utilize such information by having young (ages 16-25) and older (ages 61-78) subjects estimate their apparent spatial heading when presented with a computer-generated optical flow field (i.e., a random pattern of projected dots, which expanded in such a way as to simulate either translational or curvilinear self-motion through space). Significant age differences were found in the accuracy of the perceived heading within the optical flow fields. However, these age differences were quite small. Heading estimate errors for the flow field simulating translational motion were 1.1 and 1.9 degrees for the young and old groups, respectively. In the curvilinear condition, respective heading errors of 1.4 and 2.9 degrees were obtained for the young and older groups. These findings, together with the small age differences observed for the global motion studies examined above, suggest that the visual guidance system (i.e., ambient vision) remains reasonably intact upon reaching the later years of life.

3. Speed/Velocity Perception

Age differences in thresholds for the detection of angular displacement over time (Hills, 1975) and motion in depth or "looming" (Shinar, 1977) have been reported in the literature (but see Brown and Bowman, 1987 who observed no age differences in motion sensitivity). Staplin and Lyles (1992) argue that these deficits combine to eliminate important cues needed for driving and may directly impact the safety of older drivers. Consistent with this claim, several studies have demonstrated systematic age differences in the ability to judge the speed of automobiles (e.g., Hills, 1980; Scialfa, Guzy, Leibowitz, Garvey, and Tyrrell, 1987). Older females, in particular, appear to exhibit pronounced errors in estimating the "time-to-arrival" of approaching vehicles

(Schiff, Oldak, and Shah, 1992).

Scialfa, Guzy, Leibowitz, Garvey, and Tyrrell (1991) examined age differences in the magnitude estimations of vehicle velocity for actual automobiles travelling around a test track at speeds varying from 15-50 mph (24-80 kph). Young (mean age: 22.2) observers tended to underestimate the speed of slowly moving vehicles (15 mph) and overestimate the speed of the most rapidly moving vehicle (50 mph). Older (mean age: 65.3) observers demonstrated a similar, but less severe, slow-underestimation/fast-overestimation bias. The resulting psychophysical functions suggested that older observers were less sensitive to relative changes in speed; but, at the same time, they demonstrated more accurate absolute judgements of speed at the two ends of the velocity range examined. Although the ability to make relative speed judgments in driving is clearly important, the role of absolute speed judgments remains less well understood. Staplin, Lococo, and Sim (1993) have recently completed a series of complementary simulation and field studies, which suggest that the perceptual basis of "time-to-collision" and "traffic gap acceptance judgments" changes significantly with advancing adult age.

G. ATTENTION AND VISUAL SEARCH

The ability to detect and orient to events that occur in the parafoveal and peripheral field of vision plays an essential role in driving competence. Such skills have been studied extensively by experimental psychologists interested in normative aging — primarily via visual search protocols. Successful visual search behavior clearly depends upon adequate levels of central acuity as well as reasonably intact peripheral field sensitivity. However, even in the absence of acuity and field deficits, typical older adults tend to demonstrate marked reductions in the efficiency of their visual search behavior. Rather than resulting from sensory deficits, these problems are thought to result from age-related decrements in higher-order "attentional" processes.

Age differences in visual search are exacerbated as the number of background distractor stimuli increases. However, these age differences are minimized somewhat when targets are "featurally distinct" from background distractors (see Plude and Doussard-Roosevelt, 1989; Scialfa, Kline, and Lyman, 1987). The cause of these age differences has been attributed to a variety of perceptual/cognitive mechanisms such as slower rates of feature extraction (see Madden and Allen, 1991) and/or slower feature-to-feature comparisons (Scialfa and Thomas, in press). Other researchers have suggested that age-related deficits in visual search stem from a problem in the allocation — or, perhaps, "deallocation" — of attentional resources to/from nontarget stimuli.

For example, using a cuing procedure, which provided observers with advanced information (accurate or inaccurate) about the location of the target in a to-be-presented stimulus array, Madden (1992) found that older adults demonstrated disproportionate reductions in the speed of visual search when the location of the target was incorrectly assigned to the position of a distractor stimulus. The apparent difficulty that older observers had in reallocating their attention from the distractor to other stimuli in the search array may provide a clue to the basic mechanism underlying the classic adage that *older persons have an inability to ignore task irrelevant information*; and, hence, have disproportionate difficulty with stimuli imbedded in complex and/or cluttered backgrounds (Salthouse, 1991).

Normally the time needed to find a target increases proportionately with the number of background distractors in the stimulus array. Hence, most visual search tasks are thought to reflect "serial" information processing mechanisms (e.g., a feature-by-feature comparison analysis). However, when the target consists of a unique and salient perceptual "feature" which does not overlap the feature space of the background stimulus array, the target may "pop out" and yield parallel search properties (Treisman and Gormican, 1988). That is, the time needed to find such stimulus targets is independent of the number of items in the background stimulus array. Schneider and Shiffrin (1977) have demonstrated how visual search for almost any set of stimulus features can be made to yield near-parallel properties following extensive training with *consistent mapping* of target/distractor stimuli to a mutually exclusive feature space. For example, if the letters "X" and "Y" are designated the targets while the letters "K", "M," and "E" are the distractors, and this target/distractor mapping is consistently maintained over many practice trials, eventually the time needed to find one of the targets imbedded in an array of the distractors will become independent of the number of distractors presented. The emerging efficiency of visual search following extensive practice with consistently mapped stimuli is thought to result because of a change in the dynamics of attentional allocation. That is, the distractors become less able to attract attention while the targets become "attentional magnets." These attentional allocation processes are said to become "automatic" rather than "controlled". According to Hasher and Zacks (1979), such overlearned or "automatic" operations are not only faster but consume very little of an individual's attentional resource capacity; while responses to non-overlearned situations require "controlled" or "executive" processes which are more "effortful" insofar as they require far more attentional resource in order to be executed. As will be seen below, this dichotomy between *automatic vs. controlled* processes has much potential for understanding age-related changes in driving capacity and behavior.

Recent research suggests that highly automatized attentional functions — once established — appear to be very resistent to the deleterious effects of advanced adult aging (Salthouse, 1991). Many of the visual skills of the experienced driver may fall into this "automatized" category, and, hence, escape the effects of advanced aging. However, the ability to acquire *newly* automatized attentional skills appears to be markedly reduced among older adults (see Fisk, Rogers, and Giambra, 1990; Fisk and Rogers, 1991). Again, the problem appears to stem from age-related inabilities to inhibit the allocation of attention to non-target stimuli (see Stoltzfus, Hasher, Zacks, Ulivi, and Goldstein, 1993; Tipper, 1991).

Another line of aging research suggests that visual search in the elderly may be impaired because of a shrinking in the spatial extent (i.e., area) over which attention can be simultaneously allocated. The so-called useful field of view (UFOV) is the area over which visual attention operates at any given instant. Research with young adults reveals that moderate reductions in the UFOV can result from increases in either background complexity (Sanders, 1970) or cognitive task load (Williams, 1989). Recent research has demonstrated that such context dependent reductions in the extent of the UFOV become greatly exaggerated among older adults (see Scialfa, et al., 1987). Ball and her colleagues (Sekuler and Ball, 1986; Owsley, Ball, Sloane, Roenker and Bruni, 1991; Ball, Owsley, Sloane, Roenker, and Bruni, 1993) have demonstrated that the UFOV may become remarkably restricted in many older adults — especially when available processing time is limited. In what has already become a classic study, Owsley, et al.(1991) found that age-related reductions in the UFOV (under limited processing time constraints) accounted for more than 20% of the at-fault accident variance in a sample of elderly drivers. This important study and a larger-scale follow-up are described in detail below (see section III-B "Vision and Driving Accidents").

Some of the most promising work relating aging to driving function has emerged from research in the area of visual attention. Individual differences in the extent of the UFOV appear to account for a variety of age-related changes in driving performance (see below). Another concept emerging from the visual attention literature which holds great promise for developing a model of visually guided driving behavior is the "automaticity" construct. Many aspects of driving behavior clearly emerge as "automatized" upon a first-pass task analysis. Other aspects — at Michon's (1985) tactical and operational levels of analysis — remain "controlled" or "effortful." The use of the automatic/controlled dichotomy appears to lend itself to the identification of driving information-processing activities, which would be likely to suffer from age-related declines in visual skills. In addition, the finding that the development of "new automaticities" is markedly reduced among the aged appears to raise great concerns regarding the development of new IVHS technologies. The potential significance of these barriers is apparent in the applied research that is reviewed in the following sections of this report.

III. APPLIED RESEARCH

A. VISION LOSS AND DRIVING MOBILITY

In a 10-year longitudinal assessment of mobility patterns, Jette and Branch (1992) found that even the very elderly were heavily dependent upon automobiles to meet their essential transportation needs. A more recent analysis by Hu, Young and Lu (1994) suggests that the dependence of the elderly upon the automobile may be increasing. Data from the 1983 and 1990 administrations of the *Nationwide Personal Travel Survey* were compared. A general increase in driving frequency and mileage was found; those ages 65 and older reported a 14% increase in mileage during the 7-year span examined. This increase in driving frequency occurred despite the fact that the average age of the 65-and-older group actually increased during that same time period — primarily due to the explosive growth of the 80-and-older population (see Barr, 1991). Corn and Sacks (1994) discuss the social, economic and psychological implications of not being able to drive due to diminished visual capacity. (However, this report surveys middle-aged individuals with "low-vision" and, hence, may be only partly generalizable to the elderly population with late-onset visual loss.)

Despite the increase in the amount of driving by the 65-and-older group, a significant number of elderly drivers report giving up their driver's licenses and/or the cessation of all driving activity. Campbell, Bush, and Hale (1993) studied driving cessation patterns in a large sample of ambulatory, community-resident elderly in Florida (ages 70-96). This longitudinal study employed annual screenings in which clinical test data and self-reports of disease, symptoms, and medical complications were collected. During the eighth year of the study the participants were also asked questions about their driving behavior. The sample consisted of 1,656 persons who had been driving at the beginning of the study. Approximately 17% (N=276) of these individuals reported that they had quit driving. Campbell, et al. found that medical problems related to visual loss were the single most powerful predictors of driving cessation (e.g., macular degeneration, retinal detachment, retinal hemorrage, etc). The probability of driving cessation increased exponentially with advancing age, and women — at all age levels — were twice as likely to give up driving as their male counterparts. It is interesting to note, however, that diagnosis of cataract and glaucoma were not statistically related to driving cessation. (These negative finding may reflect the successful treatment of these disorders among this relatively affluent sample.) Campbell, et al.'s findings are consistent with the self-report data of Kosnik, Sekuler, and Kline (1990) who found that older persons who had quit driving were more likely to report serious problems with everyday vision. Laux (1991) also reported that frail elderly with poor vision were more likely to quit driving at a 15-month follow-up.

Persson (1993) interviewed 56 residents of retirement communities who had quit driving. They ranged in age from 66 to 96 (mean age of 81). The majority were women (63%), widowed (68%), and Caucasian (98%). Although all the participants had stopped driving within the last 5 years, only 37% of them no longer held a valid driver's license. Like the studies cited above, visual problems were reported as critical factors behind the decision to stop driving. Trouble seeing cars and pedestrians (20%) was second only to "advice from doctor" (27%) as a major reason for quitting. The four most commonly diagnosed diseases among the sample of former drivers were, in order of prevalence, arthritis, cataracts, macular degeneration and glaucoma. It should be noted, however, that 61% of the former drivers rated their eyesight as "excellent" or "good."

B. VISION AND DRIVING ACCIDENTS

Several recent studies have reconfirmed the previously established link between visual field loss and automobile accidents among elderly as well as young drivers (see Keltner and Johnson (1992) for a brief review). Szlyk, Brigell and Seiple (1993) studied the driving simulator performance of 6 elderly patients with hemianopic visual field deficits resulting from strokes (mean age: 71, range: 53 to 80). Data was also collected from 7 healthy older subjects (mean age 70) and 31 younger controls (mean age 39). Participants operated an Atari driving simulator for 15 minutes on a practice course and then for 5 minutes along an experimental route upon which data was collected. Performance indices measured included number of lane boundary crossings, lane position, steering wheel position, vehicle angle to the road, average slowing and slopping distance to traffic signals, mean speed, gas pedal pressure, brake pedal pressure, and simulator accidents. Older field loss patients differed from both control groups on a number of driving simulator performance measures. They demonstrated significantly greater numbers of lane boundary crossings, slower average stopping rates, slower average speed, greater variability in accelerator and brake pedal pressures, and far more simulator accidents. Eye movement monitoring suggested that patients with field loss tended to compensate by making greater use of head and eye movements. In fact, those with the most active head/eye movements were the patients with the fewest simulator accidents. These findings suggest that active training of eye movement scanning patterns might serve to remediate driving deficits resulting from visual field loss. Although such a conclusion is highly speculative given the small number of persons observed, it should be noted that similar conclusions have also been reported by Lövsund, Hedin, and Törnros (1991) and in another study of patients with severe visual loss (retinitis pigmentosa) reported by Szlyk, Alexander, Severing, and Fishman (1992).

An automated visual-field tester engineered to rapidly assess driver license applicants was recently developed by Smith-Kettlewell Eye Research Institute (see Brabyn, Haegerstrom-Portnoy, Schneck and Hennessy, 1994). Unlike a clinical device used to measure static visual fields, the Smith-Kettlewell field tester used suprathreshold stimuli presented along 5 meridians tailored to sample the visual space most critical for automobile driving (i.e., 60, 185, 225, 315 and 355 degrees). Hennessy (cited in Janke, 1994) used this device to examine the relationship between visual fields and accidents. Preliminary results collected from 1,179 license renewal applicants (ranging in age from 26 to 93) revealed few measurable declines with age and no significant relationship to accident history. However, Hennessy reports that a modification of the device — so that visual fields are collected under divided attention conditions — appears to increase its sensitivity to both age-related changes as well as recent crash experience (see below). Other negative findings regarding the relationship between visual fields and driving have also been reported. Owsley, et al. (1993) measured far peripheral field sensitivity (using a Humphrey automated static perimeter) in a sample of 53 older drivers ranging in age from 57 to 83 (mean age: 70). Although the loss of far peripheral sensitivity was significantly related to age ($r = 0.36$), field loss was not found to be significantly related to the number of accidents accrued during the prior 5 years. The pattern of results reported above clearly suggests that visual field deficits yield measurable increases in crash risk, but not until the sensory losses become quite severe.

Decina and Staplin (1993) assessed binocular visual acuity, contrast sensitivity, and the extent of horizonal visual field in 12,400 Pennsylvania license-renewal applicants. The visual acuity screener was capable of measuring values ranging from 20/20 to 20/200. Suprathreshold horizontal visual fields were assessed using mini-lamps placed at 45, 55, 75, and 85 degrees (temporal and nasal). Contrast sensitivity was measured using sinusoidal test patches presented at 6, 12, and 18 cycles/degree. Pass/fail cutoffs were based upon Pennsylvania state law for acuity and fields and age-related norms for contrast sensitivity. Neither visual fields nor acuity alone were related to driving crash rate regardless of driver age. However, a composite score based upon the pass-or-fail outcome for these two measures plus contrast sensitivity was found to be significantly related to increased crash rate (per mile driven) for drivers 66 years of age or older. Once more, no increase in crash rate was observed among older drivers who passed all three visual screens. It is interesting to note that a composite metric of visual function based upon the same triumvarate of measures (i.e., acuity, horizontal field, and contrast sensitivity) has also been shown to be related to subjectively rated driving proficiency scores among 40, mostly elderly, low-vision patients (Buyck, Missotten, Maes, and van de Voorde (1988).

Perhaps the most ambitious and programmatic line of research relating vision to driving safety (i.e., accidents) among older adults has been initiated by Ball and her colleagues (see Sekuler and Ball, 1986; Owsley, Ball, Sloane, Roenker, and Bruni, 1991; Ball, Owsley, Sloane, Roenker and Bruni, 1993). Owsley and Ball (1993), lamenting the equivocal findings of past research attempting to relate driving accidents to visual function, wrote:

> Despite the intuitive appeal of a link between vision and driving ability, [past] studies have found only weak correlations between visual deficits (e.g., visual acuity, visual field loss) and vehicle crashes (Henderson and Burg, 1974; Shinar, 1977). These correlations were often statistically significant due to very large sample sizes *but accounted for less than 5% of the crash variance* in these studies. Thus, the (existing) data are *insignificant* in reaching the practical goal of successfully identifying which older drivers are seriously at risk for crash involvement (p. 389) (itallics added for emphasis).

Ball and her colleagues have developed a measure of visual function which they term the "useful field of view" (UFOV) and have reported that UFOV scores account for significantly more crash variance among older drivers than the "insignificant 5%" reported by previous investigations. Because of the great contemporary interest in the UFOV, this line of research will be discussed at length.

The term "useful field of view," as applied by Ball and her colleagues, is somewhat of a misnomer. Their UFOV measure is actually a composite score based on performance upon 3 complementary information processing subtasks, which are administered by a proprietary computerized device known as the *Visual Attention Analyzer* (Visual Resources, Inc). These three subtasks are:

(1) Information Processing Speed. This test measures the processing time required to identify a centrally presented target (i.e., the silhouette of a car vs. a truck). Stimuli are presented at durations ranging from 40 to 240 msec. Available processing time is controlled via backward masking. Scores range from 0 (no problem) to 30 (great difficulty). A score of 0 would be earned if an observer achieved 75% correct identification performance given an available processing time

of 40 msec; whereas, a score of 30 would result given the inability to acheive 75% correct identification performance at 240 msec — the longest available processing time.

(2) Divided Attention. In this test the observer is simultaneously presented with a central target identification task (i.e., car versus truck) as well as a peripheral target localization task. The peripheral target can appear at a radial displacement of 10, 20, or 30 degrees from fixation along any of 8 principal meridians. Exposure duration is initially linked to performance on the Information Processing Speed subtest. Processing time is again controlled via backward masking. Immediately following the stimulus presentation, the observer is required to make the central task identification by touching one of two icons (car versus truck) which appear upon the touch-sensitive computer display screen. This response is followed immediately by the localization of the peripheral target by touching one of 8 radial line segments, which represent the possible meridians along which the stimulus could have been presented. Scoring is based upon the pattern of localization errors weighted by available processing time. An observer who was unable to accurately localize peripheral targets located 10 degrees from fixation given the maximum processing time of 240 msec would earn a score of 30 (maximum deficit); whereas, an observer who could correctly localize peripheral stimuli presented up to 30 degrees from fixation given the minimum exposure duration of 40 msec would earn a score of 0 (no deficit).

(3) Selective Attention. The requirements and scoring for this task are nearly identical to the Divided Attention test except that the peripheral target is embedded in an array of background distractor stimuli (i.e., triangles). This component loads heavily upon the well documented age-related declines in the ability to search through cluttered or complex environments (see above). On the basis of extensive research with the Visual Attention Analyzer, Ball et al. report that performance upon these three subtests is both independent and linearly additive. Hence, an observer's scores across the 3 subtasks are added together to yield a composite UFOV score that ranges from 0 to 90. A score of 0 is interpreted as meaning "no deficit" while a score or 90 (the worst possible) is interpreted as a 90% reduction in the normally expected useful field of view. All of the work reporting links between UFOV scores and driving accidents utilized this composite score. It would be most interesting to examine the strength of the predictive relationship to accidents obtained for each of the subtests separately or in pairwise combinations. Such analyses might reveal the component substructure of the "causative" links between UFOV and driving. They might also suggest more simple and less time-consuming techniques for assessing the relationship between visual attention and driving safety.

The first major evidence linking UFOV to automobile crashes was reported by Owsley, Ball, Sloane, Roenker, and Bruni (1991). They administered an extensive battery of visual and cognitive tests to a sample of 53 subjects ranging in age from 57 to 83 years (mean age: 70). These subjects were recruited from a university ophthalmology clinic. Self-reports as well as official reports of accident records for the previous 5 year period were collected. Owsley, et al. found that self-reported accident histories tended to severely "under report" the frequency of at-fault accidents as compared to official state driving records (p. 407). Simple correlational analyses revealed that UFOV was the only measure that was significantly related to crash frequency ($r = 0.36$) — accounting for 13% of the at-fault crash variance. Neither the correlations for acuity nor peripheral field measures were significant. An interesting finding was that performance upon a brief mental status exam designed to assess the magnitude of age-related dementia (i.e., the Matis Organic Mental Status Syndrome Examination, or MOMSSE) was also highly related to crash frequency ($r = 0.34$, or 11.6% of the at-fault crash variance). Taken together, the UFOV and the MOMSEE jointly accounted for 20% of the crash variance — far exceeding the predictive power demonstrated by previous studies of the relationship between vision and driving accidents. Although the UFOV and MOMSEE were highly correlated with one another ($r = 0.32$), LISREL "causal modeling" of accident frequency suggested that each had a relatively independent influence upon driving safety. However, such conclusions are highly speculative and require confirmation via follow-up modelling upon an independent dataset (see Ball, et al., 1993). Owsley, et al. rank ordered their subjects on the basis of their UFOV scores and found that those in the "worse" half of the distribution were 4.2 times more likely to have experienced an at-fault crash during the last 5 years than those in the "better" half of the distribution. Finally, the relationship between UFOV and driving safety was reanalyzed for the type of crash for which the elderly appear most vulnerable — intersection accidents. As expected, the majority of the crashes reported (67%) occurred at intersections. The correlations between the UFOV and intersection accident frequency was 0.46. UFOV, by itself, accounted for 21% of the crash variance. Those in the "worse" half of the UFOV distribution accounted for all but one of the intersection accidents reported; they, therefore, were 15.6 times more likely to have experienced an intersection accident than those with UFOV scores in the "better" half of the distribution — a truly remarkable relationship.

As remarkable as Owsley, et al.'s (1991) findings were, it must be noted that their predictions were based upon the observation of a mere 25 accidents (Ball, et al. (1993), p. 3111). Ball, Owsley, Sloane, Roenker, and Bruni (1993) conducted a confirmatory study of the Owsely, et al. UFOV model based upon a highly stratified sample of drivers aged 55 and older. The sampling strategy consisted of 7 age groups (55-59, 60-64, 65-69, 70-74, 75-79, 80-84, and 85+) crossed with 3 levels of 5-year crash history (0, 1-3, and 4+ accidents). Subjects were recruited from licensed drivers in Jefferson County, Alabama in an attempt to fill the 21 resulting sample cells. The final sample consisted of 294 adults ranging in age from 56 to 90 (mean age: 71). The distribution of subjects by crash history category was: 33% with no accident involvement, 49% with 1-3 accidents and 18% with 4 or more accidents. (A total of 364 at-fault accidents occurred.) Simple analyses revealed statistically significant correlations between accident frequency and several visual measures, including far peripheral fields ($r = 0.26$), contrast sensitivity as measured with the Pelli-Robson chart ($r = -0.24$), binocular acuity ($r = 0.225$), and UFOV ($r = 0.52$). These measures accounted for 6.8, 5.8, 5.1, and 27% of the crash variance, respectively. Again, the UFOV was far more closely associated with accident risk than any of the other visual measures. In fact, the relationship was even stronger than the one demonstrated in the small-scale Owsley, et al (1991) study described above. The mental status exam (MOMSEE) was also significantly related to at-fault crash frequency ($r = 0.34$). Confirmatory LISREL analysis upheld the original model proposed by Owsley, et al. (1991) — adding strength to the conclusion that mental status (MOMSEE) and UFOV were related to crash frequency through relatively independent mechanisms. Ball, et al. argued that the UFOV test demonstrated statistical properties which make it a good candidate for mass screening of at-risk older driver license renewal applicants. Namely, assuming a 40% reduction in the UFOV as a pass-or-fail cutoff score, the test yielded a *sensitivity* of 89% and a *specificity* of 81%. That is, given that a subject was crash-involved, the probability of failing the UFOV test was 0.89; whereas, given that a subject was not crash-involved, the probability of passing the UFOV test was 0.81. A frequency table supporting these calculations appears below.

UFOV SCORE	CRASH-INVOLVED	NO CRASHES
Failed (UFOV > 40)	142	25
Passed (UFOV ≤ 40)	18	109

It is unlikely, however, that the sensitivity and specificity levels observed in this study will hold up under real-world mass screening conditions. The Ball, et al. sampling technique was highly "contrived" and greatly oversampled the at-risk population. For example, the probability of randomly drawing a person with an accident from this sample was 67%. Significantly greater than one would expect if sampling from the general population of elderly license applicants (The probability of randomly drawing a person with 4 or more accidents was an astounding 18%. Such drivers are exceedingly rare in the actual older driver population. In fact, based upon national statistics, it would appear that Ball, et al. sampled virtually every older driver in Jackson County, Alabama (N=118,553) with 4 or more at-fault crashes). Whenever a subject "failed" the UFOV test in the Ball, et al. study, the *a priori* probability that he/she was also accident-involved was 67%. This *a priori* probability, by mathematical necessity, greatly inflates the value of any sensitivity and/or specificity estimate. However, an elderly driver sampled from the general population — as in the case of a mass screening application — will have a much lower *a priori* probability of being crash-involved. Hence, *Bayes' theorem* dictates a marked drop in sensitivity and specificity when the same UFOV test is applied in a real-world situation. The next study to be reviewed provides a rough estimate of the predictive power of the UFOV battery under "less optimized" conditions.

The Hartford Insurance Company, in association with the American Association of Retired Persons (AARP), conducted a large-scale field study of factors related to accidents among older drivers (Brown, Greaney, Mitchel and Lee, 1993). The Hartfort study sampled 1,475 AARP-Hartford automobile insurance policy holders in 3 states (Connecticut, Florida, Illinois). The age distribution of the sample was such that 26% were ages 50-64, 54% were ages 65-74, and 20% were ages 75 or older. An attempt was made to over-sample those policy holders who had experienced accidents during the past 3 years so as to yield an "increase in the statistical power of the study." Drivers with at-fault accidents — determined on the basis of insurance company records as well as official state reports — represented 42% of the sample. Thus, accident-involved drivers were over-represented relative to the insurance population. However, the number of extreme cases (i.e., multiple accidents) was far fewer than those observed in the Ball, et al. (1993) study described above. A wide variety of assessment procedures were administered to each participant, including a number of visual tests. The visual tests included acuity, stereopsis, color blindness, contrast sensitivity (Pelli-Robson chart), UFOV (Ball's Visual Attention Analyzer), the UNLV driver vision test battery (see Temple, 1989), and a questionnaire surveying self-reported visual problems related to driving. Simple correlational analyses were performed relating these measures of visual function to at-fault accident frequency incurred during the previous 3 years (1989-1991). The results of these correlational analyses are summarized in the table below:

Hartford Study Correlational Analyses of At-fault Accident Frequency
(Significant at $p < 0.05$ unless denoted as "N.S.")

Vision Test	Correlation
Pelli-Robson Contrast Sensitivity	-0.11
UNLV-Form Detection	0.10
UNLV-Visual Tracking	0.09
UFOV (Attention Analyzer)	0.05
Acuity/Stereopsis/Color	N.S.
Vision Problems Questionnaire	N.S.

The principal investigators in the Hartford study hypothesized that the UFOV test would be the most powerful predictor of at-fault accidents among older drivers. This was clearly not the case. Although the observed correlation of 0.05 was statistically significant (due to the large sample size), it accounted for less than 1% of the crash variance. By Owsley and Ball's own criterion, it failed as a viable test for identifying at-risk elderly drivers (1993, p. 389). The visual test with the strongest link to crash history was contrast sensitivity. This finding contributes to a growing body of evidence which suggests that low contrast vision is deficient in many older adults and predictive of performance problems with many everyday activities (also see below). The Hartford study reported a linear increase in the likelihood of accident-involvement as Pelli-Robson contrast sensitivity decreased. For example, those with a contrast sensitivity of 89 (log CS = 1.95) had a 0.47 probability of being accident-involved. This probability increased to 0.65 for those with a contrast sensitivity of 22 (log CS = 1.35). However, even contrast sensitivity accounted for only slightly more than 1% of the total crash variance.

The Smith-Kettlewell driver visual field tester (described above) has been modified to increase the attentional load placed upon the observer. This modification was clearly driven by an attempt to develop a quick and economical assessment of the "useful field of view" — in the broadest sense of the term. In many ways, the Smith-Kettlewell Attentional Field Test resembles the divided attention subtest of Ball and Owsley's Visual Attention Analyzer. The device assesses suprathreshold target detectibility into the far peripheral field along 5 driving-critical meridians. Attention is divided, and the required effort increased, by also having the observer concurrently monitor and count the number of times the fixation point flashes on-and-off. Hennessy (cited in

Janke, 1994) has conducted a preliminary assessment of the Attentional Field Test with over 1100 driver license renewal applicants ranging in age from 20 to 92. The test has been found to be much more sensitive to the age factor than its non-attentional counterpart described above. Hennessy also reported that performance on the test was predictive of 3-year crash histories among drivers aged 70 and older. Test sensitivity and specificity levels of 53 and 58%, respectively, were reported.

Even with the "latest and greatest" tools, our ability to predict crash involvement and identify at-risk drivers on the basis of safety criteria remains weak. However, given careful thought, this really should not be seen as a surprise. Accidents are caused by many factors as well as the interactions among those factors. These combinations of causative influences rarely repeat themselves; and, in fact, it has often been claimed that "no two accidents are alike." As such, the size of statistical main effects relating accident variance in a large population to *any* factor will be small (see Shinar and Schieber (1991) for a commentary on accident-based driving research). It has become clear that advances in driving research, especially in the domain of older drivers, will accrue only to the extent that we free ourselves from the "tyrranny of the accident criterion" and focus upon performance-based driving criteria. This shift from a focus upon driving *safety* (i.e., accidents) to driving *competence* (i.e., performance) is already underway as evidenced by the studies reviewed in the following section of this report. However, an important barrier remains before this shift in the prevailing research paradigm can become fully actualized — namely, the issue of research support and funding. The principal source of support for driving-related research has been from agencies of the U.S. Department of Transportation (FHWA and NHTSA) and DOT-funded programs at the state level. The mission of these agencies has been the improvement of safety. Hence, the criterion for the assessment of safety has been — and remains — the frequency or rate of accidents. The research community must develop initiatives to demonstrate the logic and value of the performance-based paradigm. Recent interest in the mobility of older drivers and the explosive growth of IVHS human factors have reinforced the need for performance-based research. This trend must be actively cultivated and supported by those interested in advancing the "state of the art" in driving research.

C. VISION AND DRIVING PERFORMANCE

1. Acuity

Several recent studies have examined the relationship between acuity and road test performance in samples of "representative" community-resident older adults. All of these studies have failed to demonstrate measurable declines in road-test performance in the presence of age-related reductions in acuity among licensed drivers. The largest of these studies was reported by Schreuder (1988). Data was collected from 903 middle-aged and older members of the Royal Dutch Touring Club — an active group of driving enthusiasts from the Amsterdam area. All drivers completed a highly formalized 1-hour road test as well as a battery of optometric tests including visual acuity (left eye, right eye, and binocular). Seven items on the road test were related to perceptual aspects of driving (e.g., perception of traffic and roads, detection of traffic signs and signals, proper "look ahead," etc). A composite score based on these 7 road test items was related to visual status via correlational analyses. No relationship between acuity and road test performance was demonstrated.

Schlag (1993) examined 80 older (ages 60-82) and 30 middle-aged drivers (ages 40-50). All drivers were given a comprehensive road test and completed a battery of laboratory assessments including: photopic acuity, night acuity (using the Rodenstock Nyktometer) and a tachistoscopic test of the recognition of common roadway hazards. The driving test consisted of a 35-km standard route encompassing many types of traffic situations (in Cologne, Germany). The instrumented test vehicle was capable of measuring time, distance, velocity, brake operation, accelerator pedal position, and steering wheel angle. Factor analysis of the road-test performance data together with the variates of age and traffic-situation yielded a four-factor solution — several of which were highly loaded on the age variable. The first and statistically most powerful factor was "velocity." This factor was highly loaded on age and reflected the higher driving speed of the middle-aged drivers (usually at the maximum allowed by the prevailing speed limit) as well as their faster accelerations, more frequent passing maneuvers and smaller gap acceptance times (especially for left turns). The second factor also loaded heavily upon age and appeared to reflect "inadequate" or "inappropriate" reactions of the older drivers at critical locations (e.g., ungated railroad crossings, right-turn on red situations, etc.). The third factor delineated a "style" of driving characterized by rapid acceleration and sharp braking before intersections. This style factor loaded equally on both age-groups. The last factor appeared to stem from a characteristic behavioral pattern of older drivers on winding country roads were they tended to maintain steady speeds and greater distances between themselves and the vehicles in front of them. (A more complete description of the analysis can be found in a german language technical report by Ellinghaus, Schlag, and Steinbrecher, 1990.) Although significant age-related performance deficits were observed for all of the laboratory tasks, on-the-road assessment of driving performance was not statistically linked to age-related declines in acuity.

Another recent study also failed to demonstrate a relationship between age-related acuity changes and road-test performance. Carr, Jackson, Madden and Cohen (1992) used the Miller Road Test to assess the driving skills of 20 very young (ages 18-19), 20 young (ages 25-33) and 20 older (ages 69-84) adult volunteers. The average visual acuity for each of these age-groups was 20/15, 20/15 and 20/36, respectively. The acuity loss for the oldest group was statistically significant. Despite the sizable decrement in acuity, however, no age-related decline in road-test performance was noted. In fact, the oldest group performed better than either of the younger groups in several test categories.

None of the studies discussed in this section employed large numbers of subjects with remarkable levels of acuity loss. Once more, none of the road-tests employed represented situations that "challenged" the drivers to perform at or near the "edge of the envelope." As such, the failure to observe a statistical relationship between acuity and driving performance was to be expected. Studies that examine older individuals with pronounced acuity losses due to macular degeneration and related disorders are needed. Initial research in this area might be best served through simulation protocols that could push all drivers to their limits in order to detect even small behavioral deficits. Great success has recently been demonstrated using this strategy in studies of visual field disorders and their relationship to driving-related performance (see below).

2. Contrast Sensitivity

Measures of contrast sensitivity have recently been demonstrated to be significant predictors of age-related driving problems. As already noted above, contrast sensitivity (assessed via low-contrast letter charts) provides for greater differentiation between young versus older observers than high-contrast acuity (Owsley, et al., 1990); and, accounts for a significant proportion of the accident variance among older drivers (Brown, et al., 1993). Recently, contrast sensitivity has been shown to be associated with age-related changes in the number and magnitude of self-reported visual problems, models of roadway visibility at night, legibility distance of highway signs, and closed-course driving performance of older persons with cataract.

Schieber, Kline, Kline, and Fozard (1992) used a survey instrument to examine the extent to which normal adult aging affects self-reported visual problems related to driving. A large number (N=397) of male and female adults from the Baltimore Longitudinal Study on Aging were examined. They ranged in age from 22 to 92 years with over half of the participants being aged 65 or older. Contrast sensitivity data was also collected from approximately half of the sample. Factor analysis of the survey responses revealed that visual problems related to driving increased in their frequency and magnitude with advancing adult age. These emerging age-related visual difficulties occurred in five major problem areas: unexpected vehicles appearing in the peripheral field of vision, instrument panels that were too dim, uncertain judgment about vehicular speed, difficulty seeing through windshields, and the inability to read street signs. Canonical correlation analysis revealed that age-related reductions in contrast sensitivity — at both intermediate and high spatial frequencies — were significantly associated with age-related increases in self-reported visual problems. These findings served to partially validate the previously reported vision survey results of Kline, et al., 1992 and contribute to the growing database linking contrast sensitivity measures to age-related driving problems.

Wood and Troutbeck (1994) examined the effects of age and cataracts upon driving performance on a closed-circuit driving course. Ten young (mean age 22.6), 18 old (mean age 67.7) and 18 old-with-cataract (mean age 68.6) drivers served as subjects. All subjects received a comprehensive visual assessment consisting of a disability glare test (Berkeley Glare Test), contrast sensitivity (Pelli-Robson low-contrast letter chart) and a modified "useful field of view" test. Participants drove five laps around the track during which the following behaviors were assessed: peripheral stimulus awareness, car maneuvering, reversing, reaction time detection of an instrument panel alarm, speed estimation and maintenance, lateral position keeping and overall time to complete the course. Results indicated that the young performed significantly better than the normal-old who performed better than the old-with-cataracts on most of the driving-related tasks. Among the three visual measures, the contrast sensitivity data were, by far, the most successful for discriminating between subjects on the basis of age, cataract and — by inference — driving performance. (This looks to be a most interesting study. However, the TRB technical report communicating its methods and results was most "spartan." Hopefully, a more comprehensive document detailing this work will appear in the near future.)

Kline, Ghali, Kline, and Brown (1990) studied age differences in the relative legibility distances of text versus symbol highway signs. They found that acuity was not significantly related to individual differences in observed legibility distance. This finding was not surprising since they utilized a rigorous screening criterion which resulted in virtually all observers having visual acuities of 20/20 or better (i.e., a restricted range which eliminated the opportunity to observe covariation). Despite near equivalence on the visual acuity measure, sizable individual differences in contrast sensitivity at intermediate and high spatial frequencies remained. Upon conducting a simple regression analysis, Kline, et al. found that contrast sensitivity accounted for nearly half of the variance in the legibility distance data. These findings replicate and extend previous work reported by Evans and Ginsburg (1984).

Bhise, Matle, and Farber (1989) have incorporated age-specific contrast sensitivity data (of Blackwell and Blackwell) into their DETECT model of nighttime visibility (under automobile headlights). Simulations generated with the revised model revealed that the 50th percentile 80-year-old could detect a pedestrian on the side of the road at a distance of 140 ft — a distance that is less than half of that expected for the 50th percentile 20-year-old (313 ft). Adding the age-specific contrast sensitivity data to the model had a much more deleterious effect upon visibility distance than incorporating an age-related glare parameter.

Contrast sensitivity has emerged as one of the most — if not the most — powerful links between visual status and driving-related performance. The work of Bhise, et al. (1989) demonstrates the potential value of this quantitative index of visual function for generating models of driver performance. Such models would be invaluable for a variety of automotive and highway engineering endeavors. Work is needed to develop such models but must also be expanded to *validate* them against real observations from the field.

3. Peripheral Vision

Previous research has repeatedly demonstrated that greatly reduced fields of peripheral vision are associated with increases in both simulator and real-world driving accidents (e.g., Hedin and Lövsund, 1986; Keltner and Johnson, 1992; Szlyk, et al., 1992; 1993). Lövsund, Hedin and Törnros (1991) found that driving competence (in a specially constructed simulator) was difficult to predict on the basis of clinical assessment of visual field loss. This was because of wide individual variations in the nature and magnitude of the compensatory behaviors exhibited by patients with nearly identical types of field loss. However, eye-movement monitoring revealed that the "successful" drivers clearly tended to overscan the area in which they had experienced severe losses of visual sensitivity. What remains a mystery is why some individuals develop such compensatory behaviors while others do not. Clearly, the possibility of training eye movement strategies which may help overcome these deficits remains an intriguing issue that is worthy of future research. The results of such work might also be readily generalizable to older adults demonstrated to have greatly restricted "useful fields of view."

Retchin, Cox, Fox, and Irwin (1988) found that horizontal field loss (together with diminished dynamic visual acuity and grip strength) was associated with significant decreases in driving frequency — and, hence, mobility — in a sample of 143 male patients recently admitted to a Veterans Administration hospital (mean age: 70). (It is historically interesting to note that this is the only driving-related research using the *dynamic visual acuity* measure that will be mentioned in this report. Apparently, DVA is no longer being actively investigated as a predictor of driving performance and/or accident involvement.)

Wood and Troutbeck (1992) examined the effects of restricted fields of view upon driving performance on a closed-circuit track. Although no elderly subjects were examined, the effects of age-related visual field losses were simulated in a group of nine drivers ranging from 24 to 35 years of age. Four visual field conditions were studied: baseline (full fields), monocular vision, and two levels of peripheral field restriction (20 degrees versus 40 degrees — total binocular field). Field restrictions were implemented through the use of a modified pair of swimming goggles. Compared to baseline performance, constriction of the binocular field did not significantly affect driving speed estimation (i.e., maintaining a constant speed without access to the vehicle's speedometer), emergency stopping distance in response to an object thrown directly in front of the vehicle, or the time taken to reverse into a parking space or maneuver through a narrow, winding lane delineated by two lines of traffic cones. However, binocular field restriction did significantly reduce performance in a number of other driving areas: (1) The time taken to complete the course increased, and there was a markedly reduced ability to (2) detect and correctly identify road signs, (3) avoid obstacles and (4) maneuver through restricted spaces; and, (5) the accuracy of lane keeping and reversing were also impaired. The monocular condition did not significantly affect performance for any of the driving tasks assessed. McKnight, Shinar and Hilburn (1991) also reported similar negative findings in an assessment of commercial heavy-truck drivers with monocular vision. Given a wide variety of performance assessments, monocular truck drivers were found to be deficient in only one category: highway sign reading distance.

4. Divided Attention

In a recent series of reviews, Parasuraman and Nester (1991; 1993) have concluded that divided attention deficits play a major role in mediating age-related driving difficulties — especially among cognitively impaired drivers (e.g., those with dementia). Their analyses revealed that attention "switching" appeared to be the critical element linking clinical assessment to driving history. Emerging age-related problems in attention switching from one aspect of the driving environment to another is consistent with the difficulties older adults demonstrate in the "deallocation" and/or "reallocation" of attention in complex visual search tasks (see section II-G above).

Ranney and Simmons (1992) recently investigated the effects of uncertainty upon age differences on a driving-related divided attention task. Middle-aged (ages 30-45) and older (ages 65-75) subjects drove a closed-circuit course with a simulated Y-intersection. Upon approaching the intersection, information was provided as to which fork-in-the-road to take. This information could come from either a changeable message sign (CMS) or from an arrow indicator located in an overhead traffic signal. The driver's task was to report the prescribed direction by engaging the car's turn signal (left or right) as quickly as possible. During some trials, the driver was informed as to which source would be providing the task-critical information (CMS or overhead traffic light). On other trials, no advance information was provided and the drivers had to divide their attention across both spatial locations. Although decision-time was slowed as a result of positional uncertainty for both age groups, the older drivers demonstrated significantly more slowing (16%) than their younger counterparts (11%). These results mirror the findings observed in the laboratory — viz., older adults demonstrate slower visual search times in complex environments. Positional uncertainty appears to exacerbate this emerging age-related deficit.

Ponds, Brouwer and van Wolffelar (1988) examined age differences in the ability to divide visual attention in a simulated driving task. The primary task measure was lane-keeping accuracy in a compensatory steering ("sidewinds") driving simulation. The secondary task consisted of a rapid "dot counting" protocol in which either 7, 8, or 9 dots were presented in a 1 by 2 degree imaginary matrix, which was superimposed upon the simulator display. On half of the trials 8 dots were presented. Subjects responded — as quickly as possible — via a 2-position switch as to whether the pattern consisted of "8 dots" or "not 8 dots." An interesting aspect of the Ponds, et al. study was that the difficulty level of each task, when performed in isolation, was matched to each individual's unique capacity. That is, the difficulty of the steering task was manipulated to maintain 90% "time on target" accuracy for each individual. Whereas self-pacing was used to equate the information-processing load imposed by the dot-counting task. When drivers of different ages were tested in the dual-task condition, it was found that the introduction of the dot-counting task significantly reduced simulated driving performance in the old (mean age: 68.6) but not the young (mean age: 27.5) or middle-aged (mean age: 46.7) participants. Hence, older drivers appeared unable to absorb all the "costs" of divided attention. The authors speculated that this age-related simulated driving performance deficit emerged as the result of diminished "supervisory task control." However, they offered an alternative explanation which has received some additional support in subsequent investigations – namely, that the elderly had excessive difficulty coordinating the two different motor programs required to execute the dual-task responses (steering versus button-pressing) into one smoothly operating motor plan. It would appear that an age-related problem due to a motor-level coordination deficit would be much easier to compensate via engineering-based solutions than one resulting from a cognitive-level deficit.

Brouwer and his colleagues have performed a series of follow-up studies to the Ponds, et al. (1988) experiment, which have focused upon age-related problems in divided attention during simulated driving. Brouwer, Ickenroth, Ponds and van Wolffelaar (1990) repeated the Ponds, et al. study with a minor, but theoretically interesting, modification to the nature of the response in the secondary (dot-counting) task. Subjects made their response via a push button as in the original study or via a verbal response, which was processed by a voice-activated reaction time apparatus. Again, older subjects (mean age: 66.2) demonstrated declines in steering performance in the dual-task condition, and the young subjects (mean age: 30.2) did not. However, the size of the age-related reduction in steering accuracy under divided attention conditions was cut in half when a vocal response was required on the secondary task (as opposed to a manual response). Similar findings have been reported by van Wolffelaar, Brouwer, and Rotthengatter (1991). This pattern of results suggests that both cognitive (i.e., supervisory task control) and motor (i.e., dual-response coordination) deficits mediated the age-related performance problems in the Ponds, et al. (1988) study and that age-related deficits in driving performance may be offset somewhat by reducing the programming load of the motor channel. These findings appear to have great significance for the design of emerging IVHS interfaces, which must meet the needs of drivers without overloading the attentional capacity of the elderly. Experimental work in other domains also offers support for the potential gains in attentional efficiency among the elderly through the use of the voice channel in response selection and execution (see Salthouse, 1985).

Korteling (1994) has also performed a series of simulator-based studies exploring age differences in the dynamics of divided attention during driving. Young (mean age: 27) and older (mean age: 70) subjects performed a steering and car-following task in an advanced driving simulator. Since both of these component subtasks of driving are such "well learned skills" one would expect that they might not represent sufficiently sensitive instruments for assessing age-related attentional declines in normal, healthy populations. To increase the potential sensitivities of these measures a stimulus-response incompatibility was introduced. That is, during some driving sessions pressing the gas pedal increased acceleration (normal condition) but, in other sessions, its function was reversed — pressing down on the gas pedal caused deceleration (inverted condition). No age-group differences in performance were observed for the "normal" condition, but a fascinating pattern of age differences emerged for the "inverted" condition. The age-related deficit in performance was found only for the steering task — not for the car following task, which required the difficult compensation due to the reversal of a previously overlearned skill. The older drivers clearly tended to focus their attentional resources upon the compensatory activities required to meet the challenges imposed by the "impaired" operational subtask, but at the expense of another important subtask — steering. This result is somewhat surprising since contemporary attentional theory would suggest that well learned skills (such as steering a car) have become "automatized" and, hence, are usually immune to performance deficits during competition for attentional resources. These findings are most intriguing and provide the foundation for the development of an operational/tactical-level theory of driving behavior in the elderly. Korteling's group at the TNO Human Factors Research Institute (Soesterberg, The Netherlands) appears to be actively pursuing such an agenda.

5. Useful Field of View

The area of the visual field over which visual attention may operate at any given time (i.e., single fixation) has been shown to operationally decrease with advancing age (see section II-G above). These findings have recently been generalized from the laboratory to the driving environment. Brouwer and Ponds (in press) have modified their divided attention simulator (described in section III-C-4) to include a tertiary peripheral search task. While operating the basic driving simulator, the subjects must monitor two areas located approximately 30 degrees to the left and right of the display midline. Arrows pointing to either the left or right are occasionally presented at these positions. The subject's task is to detect and identify these arrows by pushing a "left" or "right" button (manual condition) or by verbally reporting their direction (voice condition). Older drivers failed to detect significantly more of the peripheral targets (7.2%) than their young counterparts

(2%) during dual-task simulator driving. This finding is consistent with the assertion that the functional field of view in older adults becomes narrowed by the attentional demands of driving. Once again, however, the size of the age-related peripheral detection deficit was reduced when a voice rather than manual response was required. This suggests that *motor program integration activities have substantial attentional costs among older drivers.* [Note: Brouwer and Ponds also ran 3 Alzheimer's patients on this task. While they could successfully steer the simulated vehicle — their peripheral detection scores were poor — namely, 50, 90, and 100% detection failures, respectively.]

Walker, Sedney and Mast (1992) had young (ages 20-25), middle-aged (ages 40-45) and older (ages 65-70) adults operate a part-task driving simulator in which the difficulty of the central tracking (i.e., steering) task was manipulated. The part-task simulator was augmented by full side and rear views of simulated driving scenes. In addition to maintaining performance upon the central tracking task, the subjects were also required to monitor their peripheral vision for the appearance of overtaking vehicles, which could appear on either the right or left side. Age-related declines for the point at which the overtaking vehicles could be detected were consistent with the hypothesized "narrowing of the useful field of view." These age-related effects, however, appeared to be limited to the most difficult levels of the central task. No reductions in the useful field of view or effects of central task load were observed for the other two age groups. Once again, it appears that the attentional requirements associated with driving result in a "resource shortfall" for the older operator.

Perry, Koppa, Huchingson, Ellis, and Pendleton (1993) initiated what appears to have been an effort to "reproduce" Ball, et al's (1991; 1993) Visual Attention Analyzer in an attempt to predict age differences in closed-circuit driving performance. Their "brief field of view" (BFOV) test was modeled after Ball, et al.'s "divided attention" subtask of the Visual Attention Analyzer (see section II-G for details). The central task required the observer to identify and report a pair of letters presented within the fixation box (possible letters were A, E, M, O, T, and Y). The peripheral task required the observer to detect and report the radial location of a hexagonal "STOP" sign, which could appear 5 to 25 degrees from fixation along any of 6 principal meridians. All other possible locations at which the peripheral target could appear were occupied by rectangular boxes, which served as visual distractors. All stimuli were constructed from narrow, white line segments, which were rear projected at a luminance of 3 cd/m^2 against a blue background held at a luminance of 0.2 cd/m^2. The entire stimulus array (central task letters plus peripheral target and distractors) was presented for a duration of 110 msec. Unlike Ball, et al.'s UFOV task, exposure duration was not varied and no backward noise mask was used to control available processing time. The BFOV task was administered to 20 young (mean age: 26) and 20 old (mean age: 73) drivers. Data analyses revealed that both the young and old observers achieved near perfect performance upon the central letter recognition task. However, a significant age by target eccentricity effect was observed for the peripheral target localization task. Young observers correctly localized 93% of the peripheral targets while the older observers correctly localized only 25% of them. Hence, the "brief field of view" of older adults was markedly restricted. The magnitude of this restriction appears to be much greater than the effect noted by Ball and her colleagues. It should be noted that the BFOV procedure consisted of only 24 trials — enough so that the peripheral target could be presented once at each of the 24 possible locations. The lack of ample practice opportunity and repeated measures at each point in the peripheral array may have systematically disadvantaged the older observers. In addition, the featural distinctiveness between the peripheral target and distractors in the BFOV may have been less pronounced than that obtained for the UFOV test — thus, resulting in a less effective utilization of preattentional "pop-out" mechanisms. This possibility is intriguing and merits further investigation.

Next, Perry, et al. (1993) devised a driving task through which they hoped to "validate" their BFOV assessment. Their task consisted of a simulated intersection located toward the end of a long straight section of road. Above the intersection hung three equally spaced traffic signals — each which could be independently set to red, green, or yellow. The subject's task was to drive toward the intersection and report the configuration of the lights when they were simultaneously onset for a period of 110 msec (matching the exposure duration in the BFOV task). The subject had no knowledge about when the signal lights would be illuminated during the drive toward the intersection. The visual angle (eccentricity) subtended by the array of 3 signal lights was manipulated by varying the viewing distance. Trip wires in the roadway were used to present the stimulus array at angular separations of 5, 10, 15, 20, and 25 degrees. (Pilot studies revealed that the task became too difficult at larger angular extents — apparently exceeding the "span of apprehension.") All subjects were given 24 trials. The stimulus array configuration was limited to only four possibilities, which the subjects reported verbally using the designations listed in the following table:

	Overhead Light Position		
Configuration Name	Left	Center	Right
ALL RED	RED	RED	RED
GREEN-LEFT	GREEN	RED	RED
GREEN-CENTER	RED	GREEN	RED
GREEN-RIGHT	RED	RED	GREEN

Performance on this task approached "floor" levels for both age groups — regardless of the angular extent of the stimulus array. Older drivers successfully identified the pattern of the briefly presented light array on only 41% of the trials. This performance level approaches that expected if the subjects were making their judgments simply based upon the mere presence or absence of a green light anywhere within the array. The performance of the young subjects was not much better (56% correct). The inability of the subjects to successfully perform the driving-related task resulted in a markedly "truncated" range of scores for this dependent measure. It follows, therefore, that no significant relationship was observed between BFOV performance and that obtained on the "real-world" driving task. Due to these limitations, the negative findings of the Perry, et al. (1993) study should not be taken as evidence against the potential application of the "useful field of view" concept for accounting for some of the age-related changes in driving behavior noted throughout the current report.

6. Speed and Distance Perception: The Older Driver Maneuvers Study

In 1993, Ketron Corporation (Malvern, PA) completed a three-year study for the FHWA entitled "Traffic Maneuver Problems of Older Drivers" (Staplin, Lococo, and Sim, 1993). The working hypothesis of this comprehensive, performance-based study was that aging is accompanied by marked declines in motion perception abilities and that these deficits are responsible for reducing the driving efficiency and safety of older adults. After accident analyses yielded results consistent with this hypothesis, a series of controlled-field tests and simulator-based assessments of age differences in critical driving maneuvers were conducted. The driving maneuvers were selected such that they would be highly sensitive to age-related deficits in speed/velocity perception and included (1) *time-to-collision* estimations prior to initiating a left turn against traffic as well as prior to crossing a perpendicular traffic stream, (2) *maximum recognition distance* for the detection of a conflict vehicle, and (3) *critical gap acceptance* distances for the initiation of turning/crossing maneuvers. In addition to the above, three different driving-simulator-display technologies were concurrently validated against the on-the-road test results. The three competing display approaches included wide screen video projection, multiple TV monitors, and high-resolution cinema projection. The results of the validation studies were somewhat unexpected. Neither the projection video nor multiple-TV approaches yielded performance values that matched those obtained from the same subjects tested in the field. Only the cinema-based simulation experiments yielded performance patterns that closely replicated those in the field. Qualitative analysis revealed that the attenuation of high spatial-frequency information in the video projection and TV formats compromised critical information needed for the optimal execution of the maneuvers selected for study.

The Staplin, et al. (1993) study used three age groups of subjects. These subjects were used for all three simulation technology assessments as well as the field trials. Hence, there appear to be many opportunities for condition by order effects (e.g., fatigue, practice, etc) to have influenced the findings. Descriptions of the three age groups are listed in the following table:

Group	Age Range	N	Mean Age	Acuity	Stereopsis (arcsec)
Young	20-53	25	33.3	20/24	112
Old	56-72	29	65.1	20/31	117
Oldest-Old	75-91	25	79.4	20/42	217

The first series of maneuvers to be covered will focus upon the field test estimates of the time-to-collision (TTC) with an approach conflict vehicle. In this study, the driver sat in a stationary vehicle facing oncoming traffic in the opposite lane — as if ready to execute a left turn against traffic. The conflict vehicle would approach at a speed of either 30 or 60 MPH. At an actual TTC of either 5 or 7.5 sec the subject's visual contact with the conflict vehicle would be obstructed by a specially constructed mechanical device. The subject's task was to judge when the vehicle would reach his/her position by pressing on the brake pedal at the selected moment. [Note: Staplin, et al. do not mention any special controls which may have been implemented to mask sound cues from the approaching vehicle which could have contaminated the TTC estimates.] The results for TTC's of 5 and 7.5 sec were comparable — so they will be discussed together. All of the drivers examined dramatically underestimated the time-to-collision with the approaching conflict vehicle. These finding serve to underscore the importance of direct visual perception — as opposed to "inferred" cognitive processes. The oldest-old drivers demonstrated significantly foreshortened TTC estimates relative to the young and old driver groups which did not differ from one another. A significant conflict vehicle approach speed effect was observed for all subjects. That is, time-to-collision estimates increased as target velocity was increment from 30 to 60 MPH. The cinema-based simulation analog to the TTC study also assessed maximum recognition distance at which the solitary conflict vehicle could be first detected. The same statistical pattern of results emerged for the analysis of the TTC estimates in the driving simulator.

The gap-acceptance experiments measured the point at which the observer transitioned from a judgment of "safe to proceed" to a judgment of "unsafe to proceed." Unlike the more controversial TTC protocol, observers in the gap-acceptance scenarios maintained continuous, direct perceptual contact with the conflict vehicle. Hence, these results are inherently easier to interpret. The left-turn field study will be discussed first. Drivers were positioned as if they were about to make a left turn against oncoming traffic (as in the TTC study no actual turns were ever executed). A single conflict vehicle approached at a speed of either 30 or 60 MPH. The subject pressed a button at the point of their safe-to-unsafe gap transition. The results indicated that both the old and oldest-old groups required much longer gap acceptance distances than the young group. The effects of approach vehicle speed were interesting. In the young subjects, increasing approach speed was associated with marked increases in the minimum gap size that would be accepted. However, approach speed had no effect upon the size of the gap minimums accepted by either the old or oldest-old group. This finding is perhaps the most interesting one reported in the entire study; and, suggests that older adults do not rely heavily upon velocity "cues" in their execution of critical driving maneuvers.

The simulator-based gap-acceptance studies also looked at a variety of maneuvers not replicated in the field studies. These maneuvers included freeway merging, freeway exiting, car following, car overtaking, highway crossing, and passing. Little systematic variation due to age was observed in these protocols. Does this suggest that older drivers do not have problems with these maneuvers? This is difficult to ascertain given the constraints of the Older Driver Maneuver Study. Despite its ambitious goals, the Staplin, Lococo, and Sim (1993) effort is limited by a small sample size together with a highly convoluted design (i.e., complex factorial nesting and repeated measures without control for order effects). Perhaps the most limiting aspect of the study was the lack of interactivity in the simulation approach adopted. Scenes were prerecorded in advance in order to obtain high fidelity with respect to the complex nature of the visual environment. As a result, the attentional loading placed upon subjects was static; and, could not be dynamically varied in response to individual differences in strategy and/or operational capacity.

Future studies of older drivers must carefully consider trading-off interactivity against visual realism — especially given the emerging evidence that the major age-related declines in driving function are to be found in the attentional/cognitive domain as opposed to limitations in sensory/perceptual mechanisms.

7. Modeling Older Driver Behavior

Section III-C has provided a comprehensive review of recent applied research relating adult aging to visually guided aspects of driving performance. As this review makes clear, much new information has become available since the publication of the TRB's *Transportation in an Aging Society: Improving Mobility and Safety of Older Drivers (Special Report 218),* in 1988. However, this explosion of information has lacked the development of principals for organizing the research findings into models that will serve to foster the generalization of research across application domains and guide the next generation of work. It is becoming increasingly clear that the most fruitful models for understanding older driver behavior will have to incorporate higher-order cognitive/attentional mechanisms at both the micro- and macroscopic levels. A framework of such a model has been proposed by Michon (1985). This model describes driving behavior as a nested hierarchy of subtasks on the strategic, tactical, and operational levels. Brouwer, Rothengatter, and van Wolffelaar (1988) have demonstrated how simulator experiments can be constructed to study the dynamics of higher-order compensatory behaviors in reduced-ability older drivers (i.e., strategic- by tactical-level interactions). This approach allows investigators to consider divergent factors such as motor efficiency, sensory limitations, attention deficits, and adaptive risk-reduction strategies, all within a single, powerful framework. The thoughtful and programmatic development of such comprehensive models will need to be supported before the scientific and engineering communities can achieve their aims of maximizing both the safety and mobility of older drivers.

D. DESIGNING SYSTEMS FOR OLDER DRIVERS

1. Highway Design

In response to the research recommendations put forth in TRB Special Report 218, the FHWA established a High Priority National Program Area (HPNPA) relating to the emerging needs of the older driver (see Mast, 1991 for an outline of this initiative). A number of problem areas have been identified and funded via FHWA research contracts as part of what has become the most massive initiative yet implemented to study human factors issues in the elderly (*Newsletter of the TRB Committee on the Mobility and Safety of Older Drivers*, July 1994, pp. 12-14). The goals and status of these projects are summarized below:

Intersection Geometric Design for Older Drivers and Pedestrians. Intersection design and control was targeted as a critical research area by TRB Special Report 218. Older persons have been consistently shown to be over-involved in intersection accidents — both as drivers and pedestrians. Negotiating complex intersections places high demands upon perceptual, attentional and cognitive abilities — all of which suffer from characteristic age-related declines. This study is being conducted by the Scientex Corporation and will focus on identifying the characteristics of older drivers that influence their behavior at intersections. After a comprehensive literature review and analysis, the principals will identify geometric and operational properties of intersections that can be modified to better accommodate the emerging needs of elderly road users. Formal traffic engineering guidelines will be developed and published as a FHWA technical report.

Pavement Markings and Delineation for Older Drivers. The primary benefits of pavement markings accrue during nighttime driving. It is well known that older drivers report numerous difficulties with nighttime driving and markedly restrict their driving during this period. A study plan was developed to identify the nighttime delineation needs of older drivers and to evaluate strategies for improving their nighttime visibility through enhanced delineation treatments. In September 1990 the FHWA awarded this contract to the *Pennsylvania Transportation Institute*. Preliminary results from laboratory and field studies (Hostetter, 1994) suggest that treatments with both edgelines and above-the-road signing elements yield significantly longer recognition distances and improved driving performance in the negotiation of turns (relative to either treatment alone). These results will be used to identify the delineation requirements of older drivers which will be codified into a set of formal guidelines.

Improving Nighttime Sign Visibility: Legend Size versus Increased Brightness. TRB Special Report 218 documented the need for adding increased legibility distance to highway signs at night. This could be accomplished by increasing text legend size or by increasing brightness through the adoption of new-generation, high-retroreflective materials. The FHWA contract to examine these issues was awarded to The Last Resource, Inc. Preliminary findings from this study indicated that legibility distance improvements due to increasing text character height no longer operated beyond the optimal level of 16 inches. These results have been incorporated into a draft retroreflectivity standard, which is currently under FHWA and public review (see Paniati and Mace, 1993).

Delineation of Roadway Hazards for Older Drivers. Roadway hazard markers are an essential element in highway safety engineering. However, the *Manual of Uniform Traffic Controls and Devices* fails to provide specific guidelines regarding the placement of hazard markers. Furthermore, many drivers, especially the elderly, demonstrate confusion regarding the interpretation of the current hazard identification system. The FHWA contract to study these problems was awarded to Comsis Corporation. This work entails identifying problems with the conspicuity, legibility, and comprehension of existing hazard markers in young and older drivers. Field studies are in progress to assess the efficacy of proposed design and configuration studies upon driver comprehension of warning systems. Preliminary results indicate that problems with comprehension of hazard warning systems remain — especially among the elderly.

Older Driver Traffic Maneuvers Study. This contract was awarded to Ketron Corporation and was completed in 1993. Refer to section III-C-6 above for a description of the project and its major findings.

Older Driver Freeway Needs and Capabilities. A substantial number of older drivers either avoid urban freeway driving or experience major operational difficulties while using them. According to the FHWA, traffic engineers in sunbelt states with large retirement communities have noted reduced freeway capacity due to large numbers of older drivers operating at slow speeds, which disrupt the normal and efficient flow of traffic. The Center for Applied Research has been awarded a FHWA contract to identify the behavioral characteristics of elderly driver populations which enhance or degrade their performance on urban freeways. The study is currently in progress.

Older Driver Perception-Reaction-Time for Intersection Sight Distance and Object Detection. The AASHTO guidelines for roadway geometry are based heavily upon establishing lines-of-sight that provide the driver with a specified window of time in which to detect, perceive, and respond to critical roadway information (i.e., perception-reaction-time or PRT). TRB Special Report 218 pointed out that current AASHTO PRT specifications were based upon simple models of driving behavior derived from young adults. Given the well documented declines in visual information-processing time which accompany old age, it has been suggested that current PRT guidelines may not accommodate the reduced abilities of many older drivers. Comsis Corporation recently completed work on this FHWA sponsored contract (Report FHWA-RD-93-168). Four field studies were determined to assess the appropriateness of PRT values used in intersection and highway design sight-distance equations. Also investigated were several alternative models, including one based upon gap acceptance values. Results indicate that current guidelines meet the needs of all healthy drivers — including the elderly (see Lerner, 1993; 1994).

Symbol Signing Design for Older Drivers. TRB Special Report 218 suggested that the increased use of symbol highway signs might benefit older drivers since well designed symbol signs can be read at distances 2-to-3 times farther than their text sign equivalents. However, not all symbol signs are superior to text. Poorly designed symbol signs can result in a 50% reduction in legibility distance. Yet, this raises a problem for the development of a new generation of symbol signs since guidelines for the design of such signs did not exist. Another problem with symbol signs is that the comprehension of many signs is thought to be quite low — especially among elderly drivers. The contract to study these issues was awarded to Swanson Transportation Associates. This work was completed in the spring of 1994 (see Dewar, et al., 1994). All of the 85 symbol signs in the *Manual of Uniform Traffic Controls and Devices* were assessed with regard to both comprehension and legibility distance (daytime, nighttime, and glare conditions) in young, middle-aged, and older drivers. Problem signs were isolated and redesigned using a new set of guidelines designed to optimize both the comprehension and legibility of new symbol signs. This work included evaluating the "goodness of fit" of a candidate design to a model of visibility based upon the diminished capacity of older observers. It also included the application of a recursive, computer-assisted design technique for increasing the effective legibility distance of symbol sign prototypes (see Schieber, Kline, and Dewar, 1994).

Synthesis of Human Factors on Older Drivers and Highway Safety. This project is the last study in the series initiated by the FHWA's High Priority National Program Area on Older Drivers. The contract was awarded to the Scientex Corporation earlier this year. The objectives of this study are to generate a comprehensive review and metanalysis of older driver needs and capabilities in the areas of highway safety, design, and operations with a special emphasis upon the human factors database. The project goals also include the development of a compendium which will make the synthesized information more readily available to traffic engineers.

2. Automobile Design

Recent years have witnessed a slow but steady flow of applied research studies relating low-level visual parameters to the special needs of the older driver in automotive design. Much of this work has concentrated upon the increased luminance-and-contrast requirements of older individuals.

Unfortunately, most of this work has not been published in the scientific/engineering literature — not even as openly available technical reports. As has been reflected throughout the current report, the interest of the automotive design community in visual aging phenomena has begun to shift from basic sensory factors (acuity, contrast, luminance) to higher-order perceptual/attentional factors (visual search time, divided attention, attentional overload, etc). This shift has been driven by a number of forces — foremost of which has been the growing interest in sophisticated in-vehicle information systems and the emerging realization that the limited visual/attentional capacity of older drivers greatly complicates the development of future IVHS technology. A representative sample of this work is presented below.

During the late 1980s, one of the chief age-related interests of the automotive community revolved around the issue of windshield tinting. New federal rule making was underway to set minimum windshield transmittance values and there was concern that the emerging standard not adversely affect the nighttime visibility of older drivers. Since then, NHTSA and the AAMVA have reached a consensus view that the minimum transmittance for all automotive windows should be 70%. Freedman, Zador, and Staplin (1993) have reviewed the factors leading to this decision and reported an experimental study examining the effects of various windshield tint factors on visibility in young, old and the oldest-old drivers with mean ages of 37.5, 68.9, and 79.8, respectively. Subjects performed a task that simulated looking through the rear windshield of a car while backing out of a driveway at night. Windshield transmittance was varied at 22, 36, 53, 69, and 100%. Obstacles to be detected against a 1.26 cd/m^2 luminance background included low and high-contrast versions of a car, bicyclist, pedestrian, child, and debris in the roadway. Results indicated that decreasing window transmittance reduced detection probabilities for all targets except the car. Detection of low-contrast targets was particularly affected by reducing windshield transmittance. As expected, these problems were greatly exacerbated in the aged — especially in the oldest group. In fact, probability of detection was reduced to the 0.1-0.4 levels at the lowest windshield transmittance for this group. Clearly, windshield transmittances in the range of 22 to 53% represented a safety problem for the oldest-old. These problems were greatly reduced, however, at the higher transmittance levels tested. As a result, Freedman, et al. concluded that the 70% standard appeared to the lowest "safe" value for the older adult population. Related work by Owens, et al. (1992) also suggests that increased scatter of light due to windshield "wear and tear" may yield higher levels of visibility problems among the older driver population. This scatter factor may be a more important determinant of nighttime visibility complaints than reduced windshield transmittance.

One of the problems older drivers complain about is excessive sensitivity to the deleterious effects of glare caused by headlights at night. Flannagan, Sivak, and Gellatly (1992) examined the potential role of rearview mirror reflectivity for mitigating the effects of headlight glare from following vehicles. Reducing rearview mirror reflectivity should ameliorate the effects of glare; but, perhaps at the cost of markedly reducing rearward visibility of the roadway. This effect may be especially problematic for the elderly whose eyes already greatly attenuate the amount of light reaching the retina. The potential for such problems was highlighted by Flannagan and Sivak (1990) who reported that 33% of their subjects avoided the use of the nighttime low reflectivity setting on their rearview mirror due to their perceived inability to see adequately to the rear. Flannagan, et al. investigated the extent to which rearward vision was adversely affected by decreasing levels of mirror reflectivity while, at the same time, estimating the gains in forward visibility realized by the concomitant reduction in rearview mirror glare. Contrast thresholds required to detect the silhouette of a pedestrian in the forward field of view and a rectangular target in the rearward field of view were measured in young (ages 20-25) and older (over age 60) observers in the presence of rearview mirror glare (7.65 lux). Mirror reflectivity levels of 73, 21 and 6% were examined. On average, older observers required more than twice the amount of contrast to detect the presence of the roadway targets than their young counterparts (11 and 5%, respectively). As expected, significantly more contrast was required to detect the stimulus in the rearview mirror because of the adjacent glare source as well as the general reduction in target and background luminance levels. The reduction in rearview mirror glare due to decreasing mirror reflectivity yielded a small, but significant increase in forward visual sensitivity for all observers. However, the visual sensitivity for targets in the rearview mirror declined markedly with decreasing reflectivity. Predictions of target visibility generated by a mathematical model (similar to that employed by Bhise, et al. (1989) and described in section III-C-2 above) yielded results which were highly consistent with the empirical findings — although the model tended to underestimate slightly the visual sensitivity of the older observers. Flannagan, et al. concluded that significant gains in forward visibility due to low levels of rearview mirror reflectivity exacted a great cost in terms of rearward visibility. Related work by Flannagan, Sivak, Battle, Sato and Traube (1993) suggests that "discomfort" glare levels may play a more significant role in automotive design for older drivers than "disability" glare. Indeed, Flannagan, et al. (1992) suggest that optimal mirror design cannot be established without careful consideration of the role of reflectivity in reducing the experience of discomfort due to glare from following vehicles.

Poynter (1988) investigated age differences in the interacting effects of target letter size, luminance contrast, and color contrast upon glance legibility of automotive instrument panel displays. Glance legibility was defined in terms of the amount of contrast needed to be able to identify two out of three letters, which were presented for 600 msec. Display legends varied in size from 0.17 to 0.28 degrees — typical values observed in instrument panel designs. Thirty-five foreground-background color contrast combinations were representatively sampled from CIE color space. Background luminance was constant at 12 cd/m^2. Sixteen young (mean age: 29) and 54 older (mean age: 65) subjects were tested. The median luminance contrast needed to achieve the glance legibility criterion was a factor of 2.98 greater for the older subjects than for their young counterparts. This factor agrees with the value of 2.66 obtained in the classic study by Blackwell and Blackwell (1971). The magnitude of the age-related requirement for increased contrast remained constant across all size and color contrast levels examined. These results reinforce the dictum that "the stuff of which vision is made is not light — but contrast." Wierwille (1990) has reported related work — with similar results — regarding age differences in the effectiveness of instrument panel displays as a function of nominal color contrast levels. This work broadened the definition of performance to include display attractiveness and comfort. This and related work has been summarized by Yanik (1989;1990) who also has discussed the role of emerging technology in ameliorating age-related sensory deficits.

Wierwille (1990) has extended his work regarding age-related differences in instrument panel requirements to encompass changing attentional/cognitive capacities. Again, this change in focus was necessitated by the emergence of first-generation IVHS technology (i.e., the ETAK navigation system). Wierwille had young (less than 25) and "older" (50+) subjects engage in a variety of tasks that required visual acquisition of information from an *advanced* automotive instrument panel. The total display glance time required to complete the information transaction increased from 2.63 sec in the young observers to 4.12 sec in the older observers (i.e., 57% longer). In tasks requiring multiple glances, individual eye dwell times increased from 1.0 to 1.3 sec across the same age groups. Increases in task errors were also reported as a function of age.

Other investigators examining visual information processing with advanced automotive instrument panels have uncovered similar age-related deficits. Pauzie, Letisserand, and Trauchessec (1992) reported age-related problems with the use of IVHS instrument panel interfaces. Young (mean age: 27.5) and "older" (mean age: 58.3) drivers were required to extract information from an advanced information delivery system display while driving on a closed course or in suburban traffic. The older drivers required a greater number of glances with longer glance durations, yet demonstrated more errors (especially errors of omission) and longer response-panel latencies. These problems were especially acute for one subsystem with a low-contrast LCD display. The use of high-contrast/high-resolution display systems reduced the size of the age-related performance deficits. This pattern of results suggests that *age-related declines in sensory level abilities may exact a cost in the attentional domain* as well. Treisman and Gormican (1988) have demonstrated that reductions in target stimulus discriminability — such as those commonly experienced due to age-related reductions in acuity or contrast sensitivity — can influence the slope of visual search time functions (i.e., display size effects). Finally, it should be noted that the "older" samples in the Wierwille (1990) and Pauzie, et al. (1993) studies were actually not that old (i.e., in their fifties). One can speculate that the magnitude of the observed age differences would have been much larger had subjects in their 70s been employed.

Head-up displays (HUDs) have recently been the subject of considerable research interest in the automotive engineering community. It has been suggested that HUD technology, properly applied, might serve to ameliorate age-related problems associated with visual search of complex instrument panel interfaces. Flannagan and Harrison (1994) examined age differences in the ability to obtain information from simulated automotive HUDs positioned 4, 9, and 15 degrees below the visual horizon. The HUDs depicted a graphical navigation display consisting of a schematic roadmap with current heading and final destination information. The HUD map was viewed against a wide-screen (24 by 36 degrees) projection of a realistic roadway scene. Half of the roadway scenes contained a pedestrian who was about to enter the highway approximately 25 m ahead of the vehicle. The roadway scene and the superimposed HUD map were presented for 30 msec using a pair of tachistoscopically controlled slide projectors. The subjects had two concurrent tasks to perform. The primary task was to report the direction (left or right) of the final turn required to reach the destination depicted on the HUD map. The secondary task was to indicate whether or not a pedestrian was present in the otherwise uncluttered highway scene. Analysis of the error rate data for the primary map reading task revealed that older (mean age: 66.1) adults made about twice as many errors as their young (mean age: 21.3) counterparts. Small, but statistically significant, reductions in the number of map-reading errors occurred as the position of the HUD map moved away from the horizon. Errors on the secondary pedestrian detection task demonstrated a marked age by HUD position interaction. That is, large age-related increases in the error rate were observed when the HUD was presented 15 degrees below the horizontal midline. However, the magnitude of this age difference declined sharply as HUD position approached the visual horizon. These findings suggest that near-horizon positioning of complex HUDs may mitigate divided attention deficits in the elderly and help drivers maintain perceptual contact with the outside highway environment during the performance of attentionally loaded information interchanges. The investigators caution, however, that near-horizon HUD placement may be associated with disadvantages as well as advantages (e.g., the masking of critical environmental information due to spatial overlap).

Warnes, Fraser, Hawken, and Sievey (1993) used a driving simulator to assess age differences in performance with an IVHS-inspired system designed to maintain optimal car following distances in heavy traffic. Twenty-five middle-aged (ages 30-44) and 121 older (ages 55-86) drivers participated in a simulated car following task. The performance parameters of interest were following distance and accelerator variability. No age differences in performance were observed for this task. However, when subjects were required to monitor a device that automatically "metered" following distance, performance dropped precipitously in "a sizable minority" of older drivers.

Walker, Alicandri, Sedney, and Roberts (1990) used the FHWA Highway Driving Simulator (HYSIM) to investigate age differences in the ability to "safely" utilize advanced in-vehicle navigation systems. A number of navigation system formats were compared, including audio as well as video display modalities. Navigation task load was manipulated by varying the complexity of the route information; while driving task load was manipulated through the addition of crosswinds, a companion vehicle, gauge monitoring, mental arithmetic, and the narrowing of the simulated roadway. Small age-related deficits in driving performance and route following were observed at intermediate levels of task difficulty but the size of these age differences grew disproportionately at the higher levels of task load (i.e., a significant age by attentional load interaction). One of the most interesting findings of this study was the report that the magnitude of the age difference was reduced when navigation information was provided via the auditory channel. The reduction in attentional load achieved by the switch from the visual channel to the auditory channel appears to have important implications for future IVHS design strategies. However, this finding must be tempered by the fact that significant levels of hearing loss are extremely prevalent among the older adult population (see Schieber, 1992).

5. VISION AND DRIVER LICENSING

The visual requirements for obtaining a driver's license vary from state to state. Some states screen only first time applicants while others require an assessment each time a driver's license is renewed. The latter instance is becoming less the norm as more and more states move to periodic renewal by mail. Nearly half the states screen drivers for minimal peripheral vision. A few states require color and/or depth perception tests but use the results for "advisory" purposes only rather than as a basis for denying licensure. However, all 50 states in the U.S. have a minimum visual acuity requirement for driver's license applicants. The most common acuity requirement for unrestricted licensure is 20/40, which serves as the standard in 41 states (NHTSA, 1985). More rigorous visual requirements are imposed upon commercial driver's license applicants — but few of these drivers are aged 65 or older (see Decina, Breton, and Staplin, 1991).

The 20/40 visual acuity standard has evolved by consensus. Part of the basis for accepting this value is that, for the population as a whole, 20/40 acuity represents an *extreme* level of visual loss. That is, at least 97% of the general population can be corrected to 20/40 acuity or better (U.S. Department of Health, 1977). Ironically, the 20/40 acuity standard does not ensure a good match between the abilities of the licensed driver and the design criteria used to build the nation's highways. For example, current standards for the design of highway signs assume a visual acuity of 20/23 (i.e., *the 50:1 rule* — 50 ft of visibility is afforded by every 1 in of text legend height). Some investigators have argued that the 20/40 acuity standard is far too restrictive. Fonda (1989) found that middle-aged and older drivers (N=8) with intact visual fields (120 degrees or better) and visual acuity of 20/200 (i.e., legally blind) could "recognize" common highway signs at distances sufficient to guarantee their safety as drivers. However, these findings must be interpreted with great caution as the 6 traffic signs used in the study had unique shapes and, hence, could have been discriminated on the basis of gross shape alone. Little firm scientific evidence exists to specify the exact minimum visual requirements for driving. Bailey and Sheedy (1992) write: "It is difficult to determine the high-contrast resolution needs for driving because, apart from signs, most spatial information in the visual tasks of driving is at medium or low contrast" (p. 64). As noted above, contrast sensitivity may be a more critical determinant of minimal visual competence for driving. Yet, none of the states currently employs low-contrast visual assessment techniques.

Although the 20/40 acuity criterion segregates only around 3% of the general driving population, the vast majority of those affected are elderly. According to the Framingham Study (Kahn, et al., 1977), approximately 13% of those between the ages of 75 and 85 have best-corrected visual acuities which are worse than the 20/40 standard. In fact, fully half of this same group is estimated to be legally blind (i.e., 20/200 or worse). Little epidemiological data is available to describe the visual capacity of those older than 85 — although Staplin, et al. (1987) estimate that the incidence of severe visual deficit among the oldest-old is on the order of 33% or higher. The emergence of this age-related pattern of visual deficits begs the question as to whether driver visual-screening requirements (at least retesting schedules) should be based upon chronological age. Clearly, it can be determined that the risk of visual dysfunction climbs exponentially with advancing adult age. It remains only a matter of logical analysis to make a cogent case for increased frequency of visual screening among the older (75+) population. In fact, several investigators have reached this conclusion via independent analysis of the research literature (e.g., Bailey and Sheedy, 1992; North, 1988). Several jurisdictions — including Illinois, Indiana, Louisiana, New Hampshire, Oregon, Utah, and the District of Columbia — have age-specific test/retesting requirements (see Reuben, Silliman, and Traines, 1988). The potential efficacy of retesting vision in older drivers was the topic of a study recently reported by Nelson, Sacks, and Chorba (1992). They compared states with vision retesting requirements for driver license renewal applicants with an "equivalent" sample of states without such requirements and found a statistically significant elevation in the traffic fatality rate among older drivers in the states that did not implement visual screening.

In Pennsylvania, most driver licenses are renewed by mail. However, each month 1,500 drivers (aged 70 and older) are randomly sampled and required to have a physical examination by the physician of their choice and a license reexamination — including visual screening — at a DMV test center. Freedman, Decina, and Knoebel (1986) noted that fully 20% of the approximately 18,000 elderly drivers selected each year for reexamination do not complete the process — accounting for the greatest proportion of license loss. Of those completing the process, about 1% fail. Most of these failures result from remarkable visual losses. In addition, 20% are issued licenses with newly imposed vision-related restrictions, which include the need to wear prescription eyewear while driving, use of outside mirrors, and/or a prohibition of nighttime driving. The random nature of the Pennsylvania screening process represents a potential "gold mine" for epidemiological research regarding age-related deficits and driving.

Visual screening of the elderly can affect the nature of the driving population in several interrelated ways: (1) Screening can identify persons who require optical correction and act to increase the probability they will wear their required corrections while driving. Medical conditions that can be treated to improve visual function (e.g., cataract) are also routinely detected among older driver-license-renewal applicants. These effects combine to increase the overall visual efficiency of the driving population as a whole.

(2) Vision screening can provide valuable feedback about functional status — which can have important implications even for persons with visual problems that cannot be corrected via eyeglasses or medical treatment. Feedback regarding visual problems may provide critical information for older adults in their attempts to self-regulate their driving risk. There is some evidence that older drivers are sensitive to their emerging visual problems and act accordingly to minimize their risk by avoiding such behaviors as driving at night (see Kline, et al., 1992). However, several other studies have found — in the absence of external feedback such as that provided through visual screening — that older persons do not recognize their visual incapacities and fail to adequately self-limit their visually related driving risks. For example, Flint, Smith and Rossi (1988) found no correlation between the amount of self-reported driving by the elderly and their performance on a driving simulator and no correlation between performance on a battery of vision tests and their self-assessed quality of vision. Holland and Rabbitt (1992) also found no correlation between self-reported visual status and objective laboratory tests of acuity, peripheral vision, and glare sensitivity. However, at a 30 day follow-up interview, those who were informed about significant visual problems reported having modified their driving behavior so as to compensate for the perceived increase in risk. In summary, the extent to which older adults can monitor and assess their own visual capacity and then compensate for the deficits through modified behavior has not yet been firmly established (Shinar and Schieber, 1991). The development of new self-assessment tools such as the AARP's *Older Driver Skill Assessment and Resource Guide* (AARP, 1992) and validated surveys of visual function such as Sloan, et al.'s (1992) *Visual Activities Questionnaire* provide the building blocks needed to begin a more careful examination of this important issue.

(3) Finally, visual screening of older drivers serves to limit the risk exposure of the visually impaired through license forfeiture or, more commonly , by means of a special license which restricts driving privileges in such a way that critical personal mobility needs can be met without placing the impaired driver or general public at undue risk (see AARP, 1993; Bailey and Sheedy, 1992). A model program for implementing such a *graduated licensing* schedule has recently been developed by the American Association of Motor Vehicle Administrators (AAMVA, 1992). The National Highway Traffic Safety Administration (NHTSA) and the California

Department of Motor Vehicles are currently conducting a comprehensive project aimed at identifying assessment tools for mapping visual, attentional, and cognitive deficits to specific functional restrictions of driving in support of such a graduated licensing approach (see Janke, 1994).

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