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Synthesis of Human Factors Research on Older Drivers and Highway Safety

Volume I: Older Driver Research Synthesis

Research and Development
Turner-Fairbank Highway Research Center
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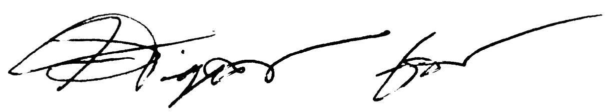
McLean, Virginia 2210l-2296

FOREWORD

This research produced a handbook containing highway design and operational recommendations to accommodate older drivers, plus companion synthesis documents summarizing, respectively, the findings of past studies of age differences in driver capabilities, and of experiments and analyses in the area of human factors and highway safety. A relational data base devoted to the present research topics is also described, and future research program recommendations are presented.

This report will be of interest to researchers concerned with issues of older road user safety and mobility, and to transportation engineers, urban planners, and users of current AASHTO and FHWA policies on highway design and operations.

Copies of the report are being distributed to FHWA Resource Centers, Division offices, and to State highway agencies. Additional copies of this document are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161. A charge is imposed by NTIS for copies provided.



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Research and Development

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16. Abstract

The overall goals in this project were to perform literature reviews and syntheses, using meta-analytic techniques, where appropriate, for a broad and comprehensive body of research findings on older driver needs and (diminished) capabilities, and a more focused body of work concerning human factors and highway safety, to support the development of specific research products. The research products completed through these activities included: (1) an applications-oriented ***Older Driver Highway Design Handbook*** intended to supplement standard design manuals for practitioners; (2) an ***Older Driver Research Synthesis,*** oriented toward human factors professionals and researchers; (3) a ***Human Factors and Highway Safety Synthesis*** capturing major findings and trends in studies of driver use of (and difficulties with) a wide range of highway elements; (4) future research program recommendations that are focused on specified applications and are consistent with the needs identified through other work in this project; and (5) the shell of a relational data base ***(RIDHER)*** structured to encompass the information elements in these research syntheses.

The two synthesis documents in this set of deliverables are published as companion volumes. This is volume I. The other volume in this set is:

FHWA-RD-97-095 Volume II: Human Factors and Highway Safety Research Synthesis

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	**ha**
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3

NOTE: Volumes greater than 1000 l shall be shown in m^3

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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LIST OF ABBREVIATIONS

AAA . . . . American Automobile Association
AARP . . . . American Association of Retired Persons
ALA . . . . American Library Association
DMQ . . . . Decision Making Questionnaire
DSQ . . . . Driving Style Questionnaire
DVA . . . . Dynamic Visual Acuity
ES . . . . Effect Size
FHWA . . . . Federal Highway Administration
HSRC . . . . Highway Safety Research Center
MITS . . . . Michigan Information Transfer Source
MUTCD . . . . *Manual on Uniform Traffic Control Devices*
NTIS . . . . National Technical Information Service
RIDHER . . . . Relational Integration of Driver and Highway Engineering Research
SAE . . . . Society **of** Automotive Engineers
TRIS . . . . Transportation Research Information Services
TRRL . . . . Transport Road Research Laboratory
UFOV . . . . Useful Field of View

DATA SOURCE IDENTIFICATION AND REVIEW PROCEDURES

The initial steps in this synthesis of age differences in driver capabilities involved defining key content areas for literature review; identifying and accessing data sources from which relevant technical literature could be obtained; narrowing all potentially useful citations to a target set and acquiring these reference materials; and establishing formal analysis procedures that would permit the comparison and integration of review outcomes across a number of different experts in the various content areas.

DATA BASE SEARCH AND TARGET SET IDENTIFICATION

A fundamental premise in this work is that there exists clear and unambiguous evidence that older drivers-who represent both the fastest-growing segment of the population and the demographic group with the highest rate of exposure-corrected (non-alcohol-related) accident involvement-are, as a group, characterized by needs and limitations that merit special consideration in design, operational, and safety decisions in the U.S. highway system. The aging of the driving population is clearly illustrated by the following statistics. In 1988, 12 percent of the population was age 65 or older. By the year 2020, it is estimated that 17 percent of the population will be age 65 or older, and almost half of those persons will be age 75 or older. At the same time, use of the automobile as the primary means of transportation is increasing for this segment of the population. In 1977, 83 percent of the trips made by persons ages 65 to 74, and 73 percent of the trips made by persons age 75 or older were made by automobile. By 1983, these percentages had increased to 86 percent and 82 percent, respectively, for the two older driver age groups (Transportation Research Board, 1988). The ways in which these aging operators differ from their younger counterparts, with respect to the functional capabilities underlying safe and effective vehicle control in everyday traffic situations, thus establishes a framework for defining the key content areas of this synthesis activity. Guided by the results of related, though less extensive, reviews of literature on age differences performed in other U.S. DOT-sponsored older driver research, broad content areas for this synthesis were defined as follows: (1) visual sensory functions and visual attention; (2) memory and cognition; (3) physical and psychomotor response capabilities; and (4) motivation and risk/hazard perception.’

Following definition of the broad content areas identified above, the literature review proceeded through a comprehensive search of foreign as well as domestic sources reporting research findings from 1970 to the present, plus selected references prior to 1970. This effort began with a DIALOG primary data base search in four files: TRIS, NTIS, PsycINFO, and AgeLine. The content of these files is summarized below:

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[1] U.S. DOT/NHTSA No. DTNH22-93-C-05237, “Intersection Negotiation Problems of Older Drivers”
U.S. DOT/FHWA No. DTFH6l-92-C-00142, “Intersection Geometric Design for Older Drivers and Pedestrians”
U.S. DOT/FHWA No. DTFH61-90-C-00008, “Traffic Maneuver Problems of Older Drivers”
U.S. DOTFHWA No. DTFH61-86-C-00044, “Traffic Control Design Elements for Accommodating Drivers with Diminished Capacity”

- TRIS (File 63): TRIS is produced by the U.S. Department of Transportation and Transportation Research Board, and contains over 386,845 files from 1968 to the present. This data base provides transportation research information on: air, highway, rail, and maritime transport; mass transit; and other modes of transportation. Subjects include: regulations and legislation; energy; environmental and maintenance technology; operations; traffic control; and communications.

- NTIS (File 6): NTIS is produced by the National Technical Information Service, and contains over 1.8 million records from 1964 to the present. This data base provides access to the results of U.S. Government-sponsored research, development, and engineering, plus analyses prepared by Federal agencies, their contractors, or grantees. NTIS also provides access to the results of government-sponsored research and development from countries outside of the U.S.

- PsycINFO (File 11): The PsycINFO data base is produced by the American Psychological Association and contains over 720,000 records from 1967 to the present. This data base provides access to the international literature in psychology and related behavioral sciences, including psychiatry, sociology, anthropology, education, pharmacology, and linguistics.

- AgeLine (File 163): The AgeLine data base is produced by the American Association of Retired Persons and contains over 28,000 files from 1978 to the present, with selected files back to 1966. This data base provides bibliographic coverage of social gerontology, which is the study of aging in social, psychological, health-related, and economic contexts.

Within each DIALOG file, search terms describing the four broad content areas were first crossed using the operator “AND” with (Driv? and Safety) to eliminate records not related to driving and safety. The results of this first set were then crossed with [Age or Aging or Old?()Driv? or Elder?() Driv?] to pinpoint records that may have data related to older drivers. Next, the search set was limited to exclude articles about: (1) teenagers, children, newborns, and infants; (2) driving under the influence of alcohol or drugs; (3) the effects of carbon monoxide on driving and information processing; and (4) transportation modes such as trucks, buses, trains, and aircraft. The search terms employed within each broad content area, and the resulting numbers of citations obtained through application of the search strategy outlined above, were as follows.

Search Terms: Driver Age Differences in Vision and Visual Attention

The following terms were used to retrieve citations of reports addressing driver age differences in vision and visual attention. The DIALOG search resulted in 732 citations:

- visual attention
- vigilance
- attention span
- head up display
- visual search
- visual masking
- processing speed
- visual function
- visual perimetry
- peripheral vision
- central vision
- visual acuity
- contrast sensitivity
- pattern discrimination
- processing resource
- visual localization
- visual identification
- visual recognition
- information processing rate
- residual attention
- motor vehicle crash
- perceptual noise
- mental speed
- parallel processing
- task complexity

Search Terms: Driver Age Differences in Memory and Cognition

The following terms were used to retrieve citations of reports addressing driver age differences in memory and cognition. The DIALOG search resulted in 317 citations:

- memory
- attention
- cognition
- working memory
- long term memory
- spatial memory
- spatial cognition
- way finding,
- divided attention
- selective attention
- dual task

Search Terms: Driver Age Differences in Physical Capabilities

The following terms were used to retrieve citations of reports addressing driver age differences in physical capabilities. The DIALOG search resulted in 348 citations:

- strength
- flexibility
- mobility
- physical ability

Search Terms: Driver Age Differences in Motivation and Risk/Hazard Perception

The following terms were used to retrieve citations of reports addressing driver age differences in motivation and risk perception. The DIALOG search, which for this content area only also included "NOT" logic to exclude references concerning education, training, arousal and fatigue, resulted in 139 citations:

- motivation
- attitude
- decision making
- risk
- risk perception

Final Target Sets for Synthesis

The citations in the four broad content areas, in the numbers noted above, were provided to reviewers with a request to sort the citations into three groups: (I) article is definitely relevant for synthesis; *(2)* article is definitely *not* relevant for synthesis; and *(3)* article is possibly relevant, but an abstract is required to determine whether article is needed for synthesis. Based on reviewers' responses, preliminary target sets for the synthesis were then defined to include all references belonging to subset *(1)* and to exclude all references belonging to subset *(2)*. For references belonging to subset *(3)*, abstracts were obtained, also through DIALOG, and a second inspection of candidate references by reviewers was performed. Based on their responses at this stage, the preliminary target set was expanded in each content area as required.

All articles contained within the preliminary target set were obtained through various sources. Journal articles were largely obtained by visiting university libraries in the Philadelphia area, including Drexel, Temple, West Chester, and University of Pennsylvania, and photocopying articles from journals in their holdings. In addition, the Scientex Corporation Transportation Library was formally established so that Scientex could participate in American Library Association (ALA) interlibrary loan procedures to obtain reports and articles not already in Scientex's possession and not available from local libraries in the Philadelphia area. Interlibrary loans were obtained from Northwestern University's Transportation Research Library, The U.S. DOT Library, AARP Library, the Transport Road Research Laboratory (TRRL) Library, and Michigan Information Transfer Source (MITS). When reports were not available from local or remote libraries, direct contacts were made with the research sponsor and/or author of the report to obtain the desired reference. Finally, reports and articles that could not be borrowed from libraries or obtained from the researchers themselves were purchased. Reports were purchased from the Society of Automotive Engineers (SAE), the Highway Safety Research Center (HSRC) and the National Technical Information Service (NTIS).

Once all reports included in the preliminary target set were obtained, they were distributed to reviewers covering the various content areas. After further inspection of the articles, it was sometimes determined that either the content was not relevant or the data were not valid for inclusion in the research synthesis, in the judgment of a given area expert. In such cases, the size of the target set was further reduced. The initial number of citations retrieved from the DIALOG search and the resulting number of articles included in the final target set within each content area for review in this effort are shown in table 1.

Table 1. Number of citations obtained and resulting number of articles in final target set for each content area.

Content Area	Number of Citations Obtained from Dialog	Number of Articles in Target Set
Driver Age Differences in Vision and Visual Attention	732	311
Driver Age Differences in Memory and Cognition	317	66
Driver Age Differences in Physical Capabilities	348	21
Driver Age Differences in Motivation and Risk/Hazard Perception	139	17

LITERATURE REVIEW AND SYNTHESIS PROCEDURES

Following the definition of the final target sets for this research synthesis, a structured approach to facilitate the integration of the large body of findings into a clear identification of major trends and gaps in the literature was developed and conveyed to the experts contributing to this effort. This approach focused upon the use, where appropriate, of the technique of *meta-analysis* in particular, the quantification of the level of similarity and difference across studies was tied to the calculation of effect size (ES) - the standardized mean differences between treatment and control groups.

A meta-analysis software application was devised by the Contractor to facilitate data input and inferential testing of effects across/between studies; this was distributed on diskette to each reviewer, and documentation and consultation were provided to help with its application. Briefly, meta-analysis differs from primary-level statistical analysis, such as analysis of variance, in that meta-analysis treats the results of a given study as a data point, just as the observations in each study considered in the meta-analysis defined data points for the primary-level analysis. This technique, in theory, thus provides an objective tool for comparing and combining the effects documented in separate studies, which can be replicated by other reviewers following the same procedures.

Based on the text, *Basic Meta-Analysis: Procedures and Programs* (Mullen and Rosenthal, 1985), a menu-driven "cookbook" procedure was prepared for calculating effect sizes or significance levels when *combining* the results of several studies, and for *comparing* several studies to determine whether their results are significantly heterogeneous (i.e., to decide whether the studies are sufficiently different from one another that they should not be treated as coming from the same population). Both of these operations were important for the task at hand. The programs included on the computer diskettes distributed to reviewers supported conduct of the following meta-analytic procedures: (1) comparison of significance levels for two studies; (2) comparison of effect sizes for two studies; (3) combination of significance levels for two studies; (4) combination of effect sizes for two studies; (5) comparison of significance levels for three or more studies; (6) comparison of effect sizes for three or more studies; (7) combination of significance levels for three or more studies; and (8) combination of effect sizes for three or more studies.

Some explanation of meta-analysis, insofar as comparisons of ES are interpreted, is warranted.Taking as an example a review of research examining the relationship between visual acuity and crash involvement, it may be the case that some studies find a significant relationship between these variables, while others do not. In those instances where the findings are *totally consistent* across studies, a meta-analysis would yield an *insignificant* result, because the studies do not differ from one another in their findings. On the other hand, a *significant* meta-analysis outcome would be indicative of the fact that there are inconsistencies within the literature surrounding that particular measure. This could result for a variety of reasons. The studies may all be consistent in finding a particular relationship, but sample sizes may vary widely such that in one study the probability of error is ***p=0.04,*** and in another study with a similar finding, p=0.0044. While the same conclusion has been drawn in both cases, the effect sizes may differ significantly. Or, less equivocally, both the direction ***and the*** magnitude of effects could differ, resulting in a significant meta-analysis test statistic. It is important to keep these distinctions in mind when examining the meta-analysis results presented in this document.

Unfortunately, only in a minority of cases could a basic requirement for the performance of meta-analyses be satisfied, i.e., the existence of multiple studies of a common independent variable, which employed the same or similar measures of effects. Given the absence of appropriate data to enter into the program, only a limited number of analyses were completed, and the planned use of meta-analysis in these efforts was not fully realized. The results presented in this volume thus include meta-analyses of selective data sets; most often, such analyses were permitted in areas of visual performance, and, to a lesser extent, in the synthesis of findings in the area of memory and cognition. In other areas, groups of studies that were related but were not amenable to meta-analysis are summarized graphically; and finally, when data accessible to reviewers were not sufficient to permit such comparisons and contrasts, the research synthesis outcomes proceeded through a traditional, qualitative review and discussion format.

SYNTHESIS OF RESEARCH ON DRIVER AGE DIFFERENCES

This section is an exhaustive report of the literature review and (partial) meta-analysis results received from the contributors identified earlier in this report. The following sections cover age differences in: (1) vision and visual attention; (2) memory and cognition; (3) physical capabilities; and (4) motivation and risk/hazard perception.

DRIVER AGE DIFFERENCES IN VISION AND VISUAL ATTENTION

Many aspects of sensory and cognitive function deteriorate in later adulthood, and it is usually assumed that these deficits contribute to a decline in the ability to drive safely. Among the senses, the importance of vision is presumed to be paramount. Since most older adults rely heavily on the automobile to maintain their independence, it is important to determine the extent to which declines in visual (and visual attentional) functions affect the ability to drive and avoid crashes.

The following literature review and meta-analysis is broken down into several functional measures that have received some attention in the older driver literature. These measures include static and dynamic visual acuity, contrast sensitivity, night vision, glare sensitivity, depth perception, visual fields, useful field of view, and field dependence. Within each variable (e.g., static acuity, dynamic acuity, etc.) a meta-analysis is performed across those studies that evaluated the impact of that particular measure on crash frequency. In many instances, other dependent measures have also been evaluated, but there are great inconsistencies across these studies making meta-analysis inappropriate. These studies have been discussed, however, with respect to how they fit in with the overall trends in the literature.

Static Visual Acuity

Since driving is a highly visual task, it has traditionally been expected that the higher prevalence of visual problems and eye disease in the elderly is a primary cause of their driving difficulty (Ball and Owsley, 1991). This assumption is reflected by the practice of assessing visual acuity (and in some States, peripheral vision) at State driver licensing sites.

Letter acuity declines during adulthood (Pitts, 1982) and older adults' loss in acuity is accentuated under conditions of low contrast, low luminance, and where there is crowding of visual contours (Adams, Wong, Wong, and Gould, 1988; Sloane, Owsley, Nash, and Helms, 1987). Pitts (1982) has reviewed the literature relating static visual acuity and the aging process, and reports that acuity remains relatively constant throughout life until approximately age 50, and then declines progressively faster with increasing age. Other research has confirmed changes beginning around age 45 (Decina and Staplin, 1993) and more severe declines after age 60 (Burg, 1966; Pitts, 1982; Laux and Brelsford, 1990). Normal physiological causes for the decline in acuity include pupillary miosis and changes in the ocular media, which result in greater sensitivity to glare and a reduction in contrast sensitivity. Many of these changes can be remediated through increased illumination and optical correction. Several diseases contribute to declining acuity, including cataracts, macular degeneration, and glaucoma.

With respect to driving, static visual acuity has consistently been found to have weak relationships to traffic crashes and convictions. For example, in a large sample study investigating the relationship between visual function and crash rate, Burg (1967) reported that the three static visual tests evaluated in their protocol had the second strongest relationship with crashes, with dynamic acuity having the strongest relationship. These three correlations, ranging from -0.053 to -0.129, were small but significant given the large sample size (n > 17,000). In other smaller sample studies, Henderson and Burg (1974) found a significant relationship between static acuity and crash rates for younger drivers only (ages 25 to 49). One study found a stronger relationship between acuity and reported crash rate (Hofstetter, 1976). Hofstetter reported that the percentage of drivers with poor acuity who reported three or more crashes was approximately double the percentage of drivers with good acuity who reported three or more crashes. However, this analysis did not apply the same acuity criterion in each age group for determining the quartile cutoffs for "poor" and "good" acuity. In this way "poor" acuity in the young group (averaging 20/20) was better than "good" acuity in the old group (averaging 20/60). If poor acuity is the basis for crash involvement, then the same acuity criterion should hold across all age groups. Furthermore, it is difficult to know how to evaluate self-reported crashes as opposed to those on record with the Department of Motor Vehicles.

In another study, Rogers and Janke (1992) compared the driving records of heavy-vehicle drivers whose vision was unimpaired, with the driving records of heavy-vehicle drivers who were found to have a deficit in static acuity. The visually-impaired group was further subdivided into those who were moderately impaired and those who were severely impaired. As a group, the visually-impaired drivers were found to have a higher incidence of crashes and convictions than the unimpaired drivers. However, the incidence of crashes for moderately-impaired and unimpaired drivers did not differ significantly, regardless of age. In fact, the older drivers in this sample had lower conviction and crash rates, despite their overall poorer visual acuity as a group. This points to the difficulty with drawing age-related conclusions based on age group averages.

Two more recent studies have evaluated the relationship between static acuity and crash frequency in older drivers (Owsley, Ball, Sloane, Roenker, and Bruni, 1991; Ball, Owsley, Sloane, Roenker, and Bruni, 1993). In these studies, the subject population was stratified with respect to age group and crash frequency. Correlations between visual acuity and crash frequency varied in the two studies ($r=0.0$ and $r=0.20$, respectively). This variation was most likely a result of sampling differences, since the second study expanded on the first with a much larger sample size and less restriction of range within each of the independent variables. With respect to the second study (Ball et al., 1993), one useful way of characterizing any particular predictor variable is in terms of its ability to identify drivers who have a history of crashes from those who do not. To determine whether a particular measure, such as static acuity, can adequately make this discrimination, the criteria for good and bad performance can be varied and drivers can be sorted into four categories: (1) those with "good" acuity and clean driving records; (2) those with "good" acuity and crashes on record; (3) those with "poor" acuity and clean driving records; and (4) those with "poor" acuity and crashes on record. Hits and false alarms can then be determined, where a hit represents the correct categorization of a crash-involved driver as *at risk*, and a false alarm represents the incorrect categorization or a crash-free driver as *at risk*. Using this procedure, no cutoff criterion in acuity was found that would place persons in the high-risk category without including a significant number of crash-free drivers in this category as well. Thus, a particular acuity cutoff, as imposed in driver licensing, is a somewhat arbitrary decision with regard to crash risk.

Finally, several other studies have linked visual acuity to other types of driving performance measures. For example, Shinar, McDonald, and Treat (1978) found a relationship between acuity and improper lookout behavior. However, Kline, Ghali, Kline, and Brown (1990) found no difference in the distance at which young, middle-aged, and the elderly were able to see highway signs, regardless of illumination levels. There are multiple differences between studies of these types, as well as multiple dependent variables involved; therefore, it is impossible to make quantitative comparisons across the various experimental findings.

Static acuity is relatively easy to measure, and it is routinely checked by all States before issuing an initial driver's license as well as renewal licenses in some States. Meta-analysis across studies investigating acuity and crash risk confirms that there is a weak, but consistent relationship between these variables (see table 2). While the overall comparison of effect sizes is significant ($x^2 = 19.79$, p=0.00054) these differences are largely due to the level of significance that varies with sample size.

There are several reasons why one might not expect to find a strong relationship between acuity and crash rate. Good acuity is probably beneficial to driving in instances where the vehicle is stopped or moving at a slow rate, such as at an intersection or in a parking lot. It is of less benefit while driving at normal speeds. Furthermore, unlike real visual scenes that vary in complexity, contrast, and illumination, the stimuli used to measure static visual acuity are small, of high contrast, and of low complexity. Therefore, many have argued that this type of measure bears little resemblance to the visual requirements of driving, and should not be expected to be strongly tied to crash involvement.

Dynamic Visual Acuity

Dynamic visual acuity (DVA), like static acuity, also declines with age (Burg, 1967; 1968; 1971), with some suggestion that the age-related declines in DVA are larger than for static visual acuity (Burg, 1966). Dynamic acuity reflects the ability to resolve the details of a moving target, and therefore it has been proposed that this measure of acuity should be more relevant to driving. Some activities that appear to rely on dynamic acuity are reading street signs while in motion, locating road boundaries when negotiating a turn, and making lateral lane changes. In these situations, greater speeds are associated with poorer DVA. The earlier studies on driving and the elderly that have assessed both static and dynamic acuity have indeed found that DVA is more strongly associated with crash risk than static acuity. However, the statistically significant correlations between dynamic visual acuity and crash rate have also been consistently weak. For example, the correlation between DVA and crash rate for the older drivers, as reported by Hills and Burg (1977), was too low (r=0.054) to be of any practical significance for identifying at-risk drivers.

Table 2. Meta-analysis results for static visual acuity.

AUTHORS	RESEARCH FINDINGS
Ball et al. (1993)	Found a weak relationship between static acuity and crashes (r=0.20).
Burg (1964) Burg (1967)	Found consistent, but weak, relationships between static acuity and crashes in a large sample study (n > 17,000).
Burg (1971)	Found significant relationships between static acuity and conviction rates, but only for female drivers.
Buyck, Missoften, Maes, and Van de Voorde (1987)	Found that people with slight impairments of visual acuity did not represent a greater danger on the road (higher crash frequencies).
Crancer and O'Neall (1969)	Found that on the average, poor-record drivers had better static acuity than clean-record drivers.
Davison (1985)	Found significant relationships between crash frequency and static acuity. Associations were strongest for the older drivers.
Henderson and Burg (1973)	Did not find a significant relationship between static acuity and crashes.
Henderson and Burg (1974)	Identified significant relationships between static acuity and crashes, but only for young drivers (ages 25 to 49).
Henderson and Burg (1974)	Found consistent, but weak, relationships between static acuity and crashes and conviction rates.
Hofstetter (1976)	Found that drivers with poor static acuity were more likely to be involved in multiple crashes.
Kline, Ghali, Kline, and Brown (1990)	Found no age differences in the ability to detect highway signs, regardless of illumination levels.
Owsley et al. (1991)	Found no relationship between static acuity and crashes (r=0.0).
Rogers, Ratz, and Janke (1987)	Found that visually-impaired drivers (poor acuity) had significantly more total crashes and convictions than did nonimpaired drivers.
Rogers and Janke (1992)	Found that drivers with poor static acuity had significantly higher conviction rates, but found no differences in overall crash rates.
Shinar et al. (1977)	Found consistent, but weak, relationships between static acuity and crashes.
Shinar, McDonald, and Treat (1978)	Found a significant relationship between static acuity and improper lookout behavior.
Strickland, Ward, and Allen (1968)	Found that poor static acuity reduced drivers' ability to detect the distance of an object on the road in the presence of oncoming headlights.
Static Acuity Meta-Analysis	**Found significant differences in effect sizes across studies with crashes as the dependent measure (χ^2 = 19.79; *p* = 0.00054)**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
Static Visual Acuity: Crash Frequency	19.79	-0.0244	-0.0244	0.0006	0.5122 to 0.4878	0.0488

Burg (1964) has made several points concerning dynamic visual acuity as it relates to the driving task. First, DVA becomes worse as target speed increases. Declines are noted when the lateral rate of the target approaches 20 degrees/s. Above 30 degrees/s, smooth eye pursuit becomes impossible and saccadic movements must be used to keep the target in central vision. Second, DVA improves with longer viewing time, brighter illumination, and practice. Third, DVA is best for foveal targets since all visual acuity deteriorates as targets are presented more eccentric to central vision (Shinar, McDowell, and Rockwell, 1977). Finally, DVA varies widely from one person to the next, and is frequently uncorrelated with static acuity.

As stated earlier, dynamic visual acuity has been found to be weakly associated with crash involvement in several correlational studies (Burg, 1968; Shinar, McDowell, and Rockwell, 1977; Laux and Brelsford, 1990). In other studies, Shinar, Mayer and Treat (1975) noted that drivers found recently to be at fault in a crash had poorer dynamic visual acuity than a group of persons who had not been in a crash for 2 years. Similarly, Henderson and Burg (1974) found that among professional drivers over 50 years of age, those in the top 10 percent-with respect to performance on a dynamic acuity measure-had a lower crash rate than the mean, while the worst 10 percent had a higher crash rate. Thus, a comparison of extremes reveals some difference with respect to crash risk. As with static acuity, however, the strength of the relationships is generally weak, and meta-analysis confirms the consistency of these findings that differ primarily due to sample size discrepancies (see table 3). Therefore, while dynamic visual acuity has been consistently related to increased crash involvement, the magnitude of the relationship has not been strong enough to change licensing policy.

Contrast Sensitivity

A primary function of the visual system is to process contrast information, which underlies our ability to see patterns in the environment. A useful way of characterizing the visual system's contrast-sensing capacities is to measure the system's modulation transfer function, otherwise known as the contrast sensitivity function. This function describes how an observer's contrast sensitivity varies as a function of the spatial frequency of a target. Contrast sensitivity tests measure both the response to sharply-defined, black-on-white targets and those with grayer, less-distinct edges. By measuring the full range of spatial frequencies and regional contrasts, a comprehensive measurement of visual capability can be assessed. Performance with respect to higher spatial frequencies has been found to predict real-world target detection, such as detecting simulated aircraft targets (Ginsburg, Evans, Sekuler, and Harp, 1982), reading road signs (Evans and Ginsburg, 1985), understanding early visual development (Banks, 1982), and understanding disease processes in human vision (Bodis-Wollner and Camisa, 1980). Response to low spatial frequencies has been linked to visual performance under poor viewing conditions (Ginsburg, Easterly, and Evans, 1983; Ginsburg, 1980; Ginsburg, 1981).

There has not been universal agreement concerning how aging affects spatial contrast sensitivity (Owsley and Burton, 1991). In general, older adults tend to have decreased contrast sensitivity, especially for higher spatial frequencies (Owsley, Sekuler, and Siemsen, 1983).

Table 3. Meta-analysis results for dynamic visual acuity.

AUTHORS	RESEARCH FINDINGS
Burg (1968)	Found that dynamic acuity was the ability most highly correlated with crash involvement, of the visual skills assessed.
Crancer and O'Neall (1969)	Found that on the average, poor-record drivers had better dynamic acuity than clean-record drivers.
Henderson and Burg (1974)	Found that professional drivers who were over age 50, and among the top 10 percent with respect to dynamic visual acuity, had lower-than-average crash rates, while the bottom 10 percent had higher-than-average crash rates.
Hills and Burg (1977)	Found that dynamic acuity was the ability most highly correlated with crash involvement, of the visual skills assessed.
Laux and Brelsford (1990)	Found that dynamic visual acuity was the ability most highly correlated with crash involvement, of the visual skills assessed.
Shinar, Mayer, and Treat (1975)	Found that drivers who were determined to be at fault in crashes were most likely to have poorer dynamic visual acuity than comparable groups of drivers with clean records.
Shinar et al. (1977)	Found that dynamic visual acuity was the ability most highly correlated with crash involvement, of the visual skills assessed.
Dynamic Acuity Meta-Analysis	**Found significant differences in effect sizes across studies with crashes as the dependent measure ($\chi^2=19.09$, $p=0.00075$).**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
Dynamic Visual Acuity: Crash Frequency	19.09	0.0542	0.0541	0.0029	0.4730 to 0.5271	0.1084

This loss is more pronounced at lower light levels (Sloane, Owsley and Alvarez, 1988; Sloane, Owsley, and Jackson, 1988) and can result in a heightened sensitivity to glare (Wolf, 1960; Fisher and Christie, 1965; Pulling, Wolf, Sturgis, Vaillancourt, and Dolliver, 1980).

Schieber (1988) has discussed the relationship between contrast sensitivity and driving performance. In one study, the relationship between contrast sensitivity and the ability to detect highway signs was evaluated in 13 younger and 7 older subjects (Evans and Ginsburg, 1985). In this study, sign detection was found to be predictable based on declines in contrast sensitivity, particularly in the middle range of frequencies. In a later study, Kettles, Kline, and Schieber (1990) found that the maximum visibility distance of visual pictorial displays of varying spatial frequency content could be predicted by the observer's contrast sensitivity function. These authors concluded that signs that emphasize low spatial frequencies or large features would be the most effective in reducing the maximum visibility distance, especially for older drivers.

Staplin, Breton, Haimo, Farber, and Byrnes (1987) have noted that aging, coupled with complex environments full of signs and high background complexity, leads to increased error rates in sign recognition and identification. Gordon, McGee, and Hooper (1984) suggest that the *Manual on Uniform Traffic Control Devices* (MUTCD) standard be adjusted from a legibility of 6 m/cm (50 ft/in) of letter height, to 3.12 m/cm (26 ft./in) to accommodate drivers of all ages. Kline (1991) has also pointed out that even young observers with excellent acuity may have difficulty with visibility of signs under the current standards.

More recent studies that have included contrast sensitivity as a predictor of driving crashes have shown that, while it is a slightly better predictor than acuity, the strength of the relationship is still relatively weak (r C 0.25) (Ball and Owsley, 1991; Owsley et al., 1991; Ball et al., 1993). Decina and Staplin (1993) failed to find a significant relationship between contrast sensitivity and crash rates in a 3.67 year retrospective study. However, they did find that a composite measure including contrast sensitivity, binocular visual acuity, and horizontal field measurement was related to crash involvement for drivers ages 66 and older. These authors concluded that the identification of drivers in the oldest age groups-who are at increased risk due to visual impairment-could be improved substantially through inclusion of contrast sensitivity measures as part of a periodic vision screening program including not only referral of failing drivers to a vision specialist, but also education of drivers regarding the risks associated with poor contrast sensitivity. While meta-analysis confirms the consistency of the findings thus far with regard to contrast sensitivity (aside from sample size variations), there are still relatively few studies that have evaluated the impact of this type of testing systematically (see table 4).

Night Vision

All forms of spatial vision discussed above deteriorate under decreasing illumination levels. Thus, night vision is characterized by degraded acuity and contrast sensitivity for individuals of all ages. However, visual degradation resulting from lower illumination levels has been found to have more of an impact in older age (Laux and Brelsford, 1990; Forbes and Vanosdall, 1973; Shinar, McDowell, and Rockwell, 1977; Henderson and Burg, 1974). Thus, lower illumination could potentially cause more of a problem for older individuals driving at night.

To evaluate this problem, Sturr, Kline, and Taub (1990) tested the static acuity of younger (ages 18 to 25) and older (ages 60 to 87) persons under varying luminance levels ranging from day to night vision. They found very little differentiation between age groups at the highest level of illumination, but at lower illumination levels, older persons were at a disadvantage. Specifically, at 2.45 candelas per square meter (cd/m^2), large age differences became apparent. Richards (1977) has estimated that the average nighttime illumination level on urban roads is approximately 1.03 cd/m^2. Thus, based on their data, Sturr, Kline, and Taub concluded that older drivers are at a disadvantage in nighttime driving.

Table 4. Meta-analysis results for contrast sensitivity.

AUTHORS	RESEARCH FINDINGS
Ball et al. (1993)	Found that contrast sensitivity was a stronger correlate of crash frequency than static acuity, although the relationship was still weak (r =0.24).
Buyck et al. (1987)	Found no relationship between contrast sensitivity and crash frequency.
Decina and Staplin (1993)	Found no significant relationship between contrast sensitivity alone and crash rates; however, when included as part of a composite measure, contrast sensitivity was related to the incidence of crashes for drivers ages 66 and older.
Evans and Ginsburg (1985)	Found that sign detection was predictable based on declines in contrast sensitivity.
Owsley et al. (1991)	Found that contrast sensitivity was not significantly related to crash frequency (r=0.10).
Contrast Sensitivity Meta-Analysis	**Found significant differences in effect sizes across studies with crashes as the dependent measure (χ^2=7.73, p=0.0209).**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
Contrast Sensitivity: Crash Frequency	7.73	0.1339	0.1331	0.0177	0.4334 to 0.5666	0.2687

Another factor to consider in night driving is that visual acuity depends upon the level of adaptation. During dark adaptation, the size of the pupil and sensitivity of the retina change dramatically over a 30-min period. While driving at night, the eye must accommodate many levels of illumination (ranging, for example to very high illumination from headlights of other vehicles, to almost complete darkness when driving in low traffic on non-illuminated roadways). Studies that have evaluated measures such as acuity under mesopic conditions, however, have not found them to be strongly linked to crash frequency. For example, Henderson and Burg, (1973) found no relationship between low illumination acuity and crash rate, and Burg (1964) found no relationship between dark adaptation and crash involvement. Similarly, Owsley, et al. (1991) found an insignificant relationship between acuity measured under low illumination and crash rate (r=0.10). In contrast, Shinar, Mayer, and Treat (1975) found that as a group, drivers judged to have committed recognition errors during a crash had poorer low illumination acuity than drivers who had not committed a recognition error. Differences between these studies could result from the fact that older drivers in general avoid night driving, and when they must drive at night, they probably exercise great caution. In Shinar's study, the drivers were obviously on the road since they were grouped due to crash involvement, but in the correlational analyses it is not clear how much or when individuals are actually driving their vehicles. Finally, in a study that evaluated nighttime accidents specifically, Shinar et al. (1977) found that acuity under dim illumination was associated with nighttime crashes, and particularly so for older drivers.

With respect to alternate dependent variables, Sivak, Olson, and Pastalan (1981) found that 60-year-old drivers had to be up to 35 percent closer in order to read signs under nighttime conditions when compared to 25-year-old drivers, even when they were matched on photopic acuity. These authors, as well as others, have concluded that separate testing for acuity under low levels of illumination should be considered for inclusion in driver screening examinations. While it is true that visibility conditions are reduced for older drivers at night, and that these visibility problems show up when measuring the drivers' actual ability to read the signs, the relationship between acuity measured under low illumination and crash involvement is mixed (see meta-analysis in table 5). Three studies reported insignificant relationships in this area, and only one reported a significant relationship with nighttime crashes. Here again, true relationships may be obscured, since older drivers (as a group) tend to avoid night driving, which dramatically decreases the risk exposure. Thus, night driving may be one area where older drivers have successfully modified their behavior to compensate for increased risk under these conditions.

Table 5. Meta-analysis results for night vision.

AUTHORS	RESEARCH FINDINGS
Burg (1964)	Found an insignificant relationship between dark adaptation and crash involvement.
Henderson and Burg (1973, 1974)	Found no relationship between acuity measured under low illumination and crash rates.
Owsley et al. (1991)	Found an insignificant relationship between acuity measured under low illumination and crash rate in a sample of older drivers.
Shinar et al. (1977)	Found that acuity under low illumination levels was associated with nighttime crashes, and particularly so for older drivers.
Sivak, Olson, and Pastalan (1981)	Found that 60-year-old drivers had to be up to 35 percent closer to read signs under nighttime conditions than 25-year-old drivers, even when matched for photopic acuity.
Night Vision Meta-Analysis	**Found significant differences in effect sizes across studies with crashes as the dependent measure (χ^2=10.37, p=0.015).**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
Night Vision: Crash Frequency	10.37	0.0235	0.0235	0.0006	0.4882 to 0.5118	0.0471

Glare Sensitivity

Glare has been defined as brightness within the field of vision that is substantially greater than the luminance to which the eyes are adapted (McCormick and Sanders, 1982). Glare is mostly debilitating to central vision, since this region is most sensitive to light and is instrumental for seeing detail (Henderson and Burg, 1974). In the driving environment, two types of glare-veiling glare and spot glare-are relevant (Shinar et al., 1977). Veiling glare is a uniform luminance masking, while spot glare is characterized by areas of concentrated luminance (e.g., headlights).

As self-reported by many older drivers, poorer dark adaptation and heightened glare sensitivity contribute to exaggerated nighttime driving difficulties. Studies have shown a progressive elevation of both rod and cone thresholds with age (Pitts, 1982), with an accelerated loss above the age of 60. The implication of a loss in rod sensitivity is that a much brighter or more salient peripheral stimulus will be needed to properly orient visual attention to potential hazards in the environment. At intersections, glare (introduced by roadside light sources, traffic signals, and other traffic) can be treated as a contrast sensitivity reduction factor, and its effect can be compared with the direct effect of age on contrast sensitivity noted earlier.

Some researchers have found age-related declines for contrast sensitivity and static acuity in the presence of glare. However, age differences vary somewhat across studies, making it difficult to draw conclusions concerning aging and glare effects. Allen and Vos (1967) and Burg (1967) examined contrast sensitivity in the presence of glare and found that performance remained relatively unaffected until the mid-to-late 40’s. Burg reported that glare recovery followed a similar pattern. Shinar et al. (1977) measured acuity in the presence of both veiling and spot glare. These data suggested that significant differences do not appear as a function of age until around age 65. Further evidence that glare effects are not significant until after the 40’s was provided by Finlay and Wilkinson (1984). They found no differences in glare-related performance effects for an older group (ages 43 to 56) as compared to a younger group (ages 19 to 24). The lack of consistency among studies may be due, in large part, to the extreme individual differences found in glare sensitivity. While pathologies such as cataracts and glaucoma may have only a small impact on acuity (depending on their location), they still may increase light scattering in the eye, resulting in increased glare effects (Shinar et al., 1977).

Trade-offs exist for older drivers relative to the costs and benefits of increased illumination versus increased glare (Cushman and Crist, 1987). On one hand, older drivers require extra illuminance and contrast to see adequately (Sivak, Olson, and Pastalan, 1981). In fact, the proper use of lighting can be effective in increasing visibility for all drivers (Mortimer, 1988). On the other hand, it seems plausible that increased illuminance could be problematic for older drivers, based on the evidence for age-related changes in glare sensitivity. Older drivers have a lower glare tolerance to sources such as automobile headlights (Mortimer, 1988). Shiny surfaces and exposed light sources, such as headlights, may serve to disable older drivers. This problem is increased at night, when illuminance from headlights reduces the contrast of objects relative to their backgrounds (Attwood, 1979).

Despite evidence that glare sensitivity and glare recovery are important age-related visual changes, evidence is sparse that glare is associated with actual driving performance. Burg’s (1967) study and the reanalysis by Hills and Burg (1977) demonstrated a significant relationship between glare recovery rate and crash rate; however, the relationship was relatively weak. Headlight glare was attributed as a possible “environmental” factor in approximately 2.3 percent of night accidents in another study (Indiana University, 1975;

cited in Mortimer, 1988). Glare was mentioned as a factor in 3 of 30 crashes where drivers ran off of the road, in a study by Boyce, Hochmuth, Meneguzzer, and Mortimer (1987; cited in Mortimer, 1988). Further, glare was named as a factor in 30 of 231 crashes in which adverse environment was involved (Sabey and Stoughton, 1975; cited in Mortimer, 1988). The time needed to recover from glare was also included in Burg's (1971) study, and was found to correlate weakly with accident rates. Other studies, however, have failed to find a direct relationship between glare sensitivity measures and driving performance (Shinar et al., 1977; Wolbarsht, 1977; Burg, 1967; Owsley et al., 1991).

Still other evidence suggests that glare tolerance in relation to driving performance declines with age. Henderson and Burg (1974) found that 50-year-old drivers who had the lowest 10 percent of visual acuity in the presence of veiling and spot glare had crash rates higher than that of the population mean. Fulling, Wolf, Sturgis, Vaillancourt, and Dolliver (1980) studied the acceptable level of oncoming headlight illuminance using a simulated driving task. Prior to age 70, performance slowly decreased and individual differences were large, but after age 70 the ability to tolerate glare decreased rapidly.

With respect to the consistency of the findings relating glare to crash involvement, results are mixed (see meta-analysis in table 6). Several studies found no relationship between glare and crash involvement, one study found a weak relationship with only female crash rates, and one study found a significant effect of glare on crash rates for drivers over age 50. One possible reason that glare is not implicated as a significant factor in crashes is that only drivers with the poorest tolerance to glare are affected to the point where crashes could occur. A second explanation might be that glare is not a constant part of the driving environment. In other words, abilities such as static and dynamic acuity are always relied upon, and thus are more likely to be associated with crash occurrence. Furthermore, the effects of glare are uncomfortable, and therefore the older drivers most affected by glare probably elect not to drive at night or in the rain. Because glare sensitivity and recovery are only salient in the presence of glare within approximately 10 degrees of the line of sight, and because sources of glare are not present, the relationship with all crashes is understandably weak.

Depth Perception

Stereoacuity is a person's ability to judge relative distances without reliance on monocular cues such as superposition. Depth perception has been defined as the ability to judge the distance, and changes in distance, of an object (Burg, 1964). Depth perception cues can be one of two types: physiological and environmental (Coran, Porak, and Ward, 1984). Most physiological measures come from the eye itself. When shifting one's gaze to a closer or further distance, the lens provides a cue about the distance of an object. This cue is only accurate at near distances, however, since beyond approximately 3 m (10 ft) the lens becomes totally relaxed. Furthermore, due to hardening of the lens and weakening of the ocular muscle, this type of cue becomes increasingly less effective with age.

Table 6. Meta-analysis results for glare sensitivity.

AUTHORS	RESEARCH FINDINGS
Attwood (1979)	Found that older drivers are less able to tolerate glare (e.g., from automobile headlights) than younger drivers.
Burg (1967)	Failed to find relationships between glare sensitivity measures and driving performance.
Burg (1971)	Found that glare sensitivity correlated weakly with female crash rates.
Henderson and Burg (1974)	Found that 50-year-old drivers who had poor visual acuity in the presence of glare had higher crash rates.
Mortimer (1988)	Found that older drivers are less able to tolerate glare (e.g., from automobile headlights) than younger drivers.
Owsley et al. (1991)	Failed to find a relationship between glare sensitivity and crash records.
Pulling et al. (1980)	Found that after age 70, the ability to tolerate glare from (simulated) headlights decreases.
Shinar et al. (1977)	Failed to find a relationship between glare sensitivity measures and driving performance.
Sivak et al. (1981)	Indicated that older drivers required more light and contrast in order to see adequately.
Wolbarsht (1977)	Failed to find relationships between glare sensitivity measures and driving performance.
Glare Sensitivity Meta-Analysis	**Found significant differences in effect sizes across studies with crashes as the dependent measure ($\chi^2=17.66$, $p=0.003$).**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
Glare Sensitivity: Crash Frequency	17.66	0.0171	0.0171	0.0004	0.4914 to 0.5086	0.0342

The second source of depth perception cues is environmental. When judging the distance of objects, cues such as surface texture gradients, relative heights of objects, linear angles, and retinal disparity are used (Goldstein, 1989). For judging the distance of objects in motion, cues in the form of changes to the relative size of the images (i.e., expansion or contraction) and motion parallax also contribute to depth judgments.

The ability to make accurate judgments concerning depth decreases with age (Bell, Wolf, and Bernholtz, 1972; Henderson and Burg, 1973, 1974; Shinar and Eberhard, 1976). A recent study indicated that the angle of stereopsis (seconds of arc) required for a group of drivers ages 75 and older to discriminate depth using a commercial vision tester was roughly twice as large as that needed for an 18- to 55-year-old group to achieve the same level of performance (Staplin, Lococo, and Sim, 1993). Furthermore, glare sensitivity and visual acuity under dim illumination have been shown to have an influence on one's ability to detect depth (Yanik, 1986; Rock, 1953; cited in Henderson and Burg, 1974). Degradations in depth perception begin to be noticeable before age 40, increase significantly by age 50, and continue to increase thereafter (Bell, Wolf, and Bernholtz, 1972).

Failure to yield the right-of-way has been found to be a primary cause of older drivers' casualty accidents (Gebers, Romanowicz, and McKenzie, 1993). Hakamies-Blomqvist (1993) found the predominant type of accident for older drivers to be one in which one vehicle was crossing the path of another. One factor in crashes involving right-of-way violations when vehicles' paths are crossing may be a decline among older drivers in the ability to detect angular movement, as reported by Staplin and Lyles (1991). As they also reported, research has shown that relative to younger drivers, older drivers underestimate the speed of approaching vehicles. Older persons apparently tend to accept a gap to cross in front of an oncoming vehicle that is a constant distance, regardless of the vehicle's speed. Such decrements in distance/speed perception and judgment may account, in part, for the relative increase among older drivers in right-of-way accidents, most particularly accidents involving an improper left turn. For example, in Iowa 20 percent of crash-involved drivers over age 75 were attempting a left turn when their collision occurred. Staplin and Lyles concluded that left turns are clearly the most challenging maneuver for older drivers since they experience difficulty in judging time to collision and acceptable gap lengths; these problems are exacerbated by their generally slower response speeds. Compounding the general perceptual problems, at signalized intersections age-related decrements have been found in understanding permissive (unprotected) turn right-of-way rules for a left turn in situations requiring integration of information from both sign and signal displays (Staplin and Fisk, 1991). One possible solution to this problem is to eliminate confusion by avoiding the use of both protected and unprotected left-turn phases at the same intersection. At protected intersections drivers would then turn left on the green arrow only, and older drivers could seek these intersections rather than the unprotected variety. This is actually a practice commonly reported by older drivers (e.g., they will drive an extra block or two to be able to turn left at a protected intersection).

Shinar et al. (1977) have stated that the ability to judge the distance between one's vehicle and other vehicles moving at approximately the same rate of speed is one of the most critical driving abilities. This is important when steering to follow a desired path, as well as in avoiding vehicles in a line of traffic (Henderson and Burg, 1974). Detection of angular motion in the periphery may be one of the first clues that other vehicles are there, or that hazards are appearing from the side.

Judging motion in-depth is made difficult by the fact that when no lateral displacement occurs, the primary depth cue is the expansion or contraction of the image sizes of other vehicles (Hills, 1980). It appears that older drivers have difficulty controlling vehicles in this type of situation (Ranney and Pulling, 1990). Using a battery of closed-course driving and laboratory tests, Ranney and Pulling found that older drivers (ages 74 to 83) made more gap execution errors (i.e., struck objects/drove at excessively slow speed) and more gap judgment errors than did a group of younger drivers (ages 30 to 51). In Henderson and Burg's (1973) study of truck drivers, those who had central movement in-depth thresholds greater than 16 min of arc/s for small targets had higher crash rates than the population mean. However, Henderson and Burg (1974) failed to replicate each finding. In the 1974 study, only ability to detect depth of a large expanding target (i.e., simulated movement of a car on a collision course) was associated with crash rates for adults over age 25.

McKnight, Shinar, and Hilburn (1985) studied the importance of retinal disparity-the difference between the images of the eyes-by comparing visual and driving performance of 40 monocular and 40 binocular tractor-trailer drivers. Monocular and binocular drivers differed on only one measure related to driving performance, that being the distance at which they were able to read road signs. Thus, retinal disparity may have only minor importance with respect to driving. In agreement with this, Owsley et al. (1991) found that the correlation between stereoacuity measured in the lab and vehicle crashes was insignificant ($r=0.12$, $p>0.05$).

Following too closely is another problem driving behavior that has been identified as possibly being related to depth perception deficits. Boyar, Couts, Joshi, and Klein (1985) found that following too closely was the second most common mistake leading to commercial vehicle crashes in 1983. Judging distance through angular movement may be a critical contributor to these types of incidents.

Depth perception appears to be a promising variable for predicting driving performance, as indicated by both simulated driving tasks and some correlational studies (see meta-analysis in table 7). Examining the tasks that have been studied, it appears that depth perception is an important contributor of information leading to decisions, such as when to turn left. One promising finding in the literature is that practice, with or without feedback, was able to improve ability to detect movement of angular targets (Johnson and Leibowitz; cited in Shinar et al., 1977). The effects of practice were still detected 3 months later. A test-retest study by Henderson and Burg (1974), provided convergent evidence for this finding. Thus, depth perception may be an ability that declines with age, but may be remediated through intervention.

Visual Field Sensitivity

Visual sensitivity throughout the field of view has also been thought to be relevant to driving and is also adversely affected by the aging process. Studies using kinetic perimetry have indicated that the borders, or isopters, of the visual field are constricted in older adults (Drance, Berry, and Hughes, 1967; Wolf, 1967; Burg, 1968; Williams, 1983). More recently, a number of studies using automated, static-type perimetry have found that older adults exhibit a generalized loss in sensitivity throughout the central 30 degrees of the field with some studies suggesting a slightly greater sensitivity reduction in more peripheral areas (Jaffe, Alvarado, and Juster, 1986; Johnson, Adams, and Lewis, 1989). Most of the earlier studies examining visual field sensitivity and crashes have failed to find a relationship between them (Burg, 1967, 1968; Allen, 1970; Henderson and Burg, 1974; Council and Allen, 1974; Shinar et al., 1977; Waller, Gilbert and Li, 1980). One exception is a large sample study (n= 10,000) by Johnson and Keltner (1986) who found that the small subset of drivers with severe binocular visual field loss

Table 7. Meta-analysis results for depth perception.

AUTHORS	RESEARCH FINDINGS
Boyar et al. (1985)	Found that following too closely was the second most common mistake leading to commercial vehicle crashes in 1983.
Henderson and Burg (1973)	Found that truck drivers with in-depth thresholds greater than 16 min of arc/s for small targets had higher than average crash rates.
Henderson and Burg (1974)	Failed to replicate the 1973 results except for the finding that the ability to detect depth of a large expanding target was associated with crashes for adults over age 25.
Hills and Johnson (1980)	Found that older drivers were more likely to underestimate the speed of oncoming vehicles and base the last safe moment at which to make a turn in front of an oncoming vehicle on a constant distance rather than on the speed of the oncoming vehicle.
Hills (1975)	Found age-related decrements in the ability to detect motion when vehicles were moving closer, but no age differences in this ability when the vehicles were moving away.
McKnight, Shinar, and Hilburn (1985)	Compared the visual and driving performance of 40 monocular and 40 binocular tractor-trailer drivers. The only driving-related measure on which these drivers differed was the distance at which they were able to read road signs.
Owsley et al. (1991)	Found that stereoacuity and crash frequency were unrelated in a sample of older drivers.
Ranney and Pulling (1990)	Found that when forced to rely on a single depth cue (the expansion and contraction of the image size) older drivers (ages 74 to 83) made more gap execution and judgment errors than a group of younger drivers (ages 30 to 51).
Staplin and Lyles (1992)	Found older drivers' (ages 70 to 75) time-to-collision estimates were elevated by a magnitude of 100 percent when compared to younger drivers (ages 20 to 29); older drivers significantly overestimated the time-to-collision of an oncoming vehicle.
Depth Perception Meta-Analysis	**Did not find significant differences in effect sizes across studies with crashes as the dependent measure (χ^2=6.62, p=0.085)**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
Depth: Crash Frequency	6.62	0.3094	0.2999	0.0899	0.3501 to 0.6499	0.6287

(mostly older drivers) had crash and conviction rates twice as high as those with normal visual fields. Ball, et al. (1993) provided a confirmation of these findings in a smaller sample (n=294) where they reported that those older drivers with severe sensitivity loss in both eyes had twice the number of crashes as did older drivers with normal visual field sensitivity. The correlation, in general, between crash frequency and visual field sensitivity was relatively weak (r = 0.26) and was thus consistent with earlier reports that peripheral vision is not a strong correlate of crash involvement. No study to date, in fact, has established a link between crash rate and the more subtle types of visual field loss that are more typical of aging rather than disease.

The meta-analysis across studies that investigated visual field effects on crash involvement found significant differences in effect sizes (see table 8). These discrepancies can be explained somewhat by the method in which the visual field effects were reported. For example, the relationship between visual field size and crash rate is consistently found to be weak (as with other sensory measures of visual function). A comparison of drivers with severe binocular field deficits against those with normal visual fields, however, results in a much more significant difference. Generally speaking, these results ranged from none to fairly substantial depending on the method used to partition the levels of visual field.

Useful Field of View

Driver inattention and deficiencies in information processing are major factors in accident causation (Shinar, 1993). Treat, Bumbas, McDonald, Shinar, Hume, Mayer, Stansifer, and Castellan (1977) suggested that hazard recognition errors can be interpreted more as attention failures than as sensory deficiencies. Consistent with this interpretation, Staplin et al. (1987) pointed out that searching and scanning behaviors (involving selective attention and attention switching), which are of particular importance for driving, become less efficient with aging. In experimental tasks involving the location of targets embedded within an array of stimuli, older adults are slower and make more errors than younger individuals. In actual driving situations, there is also evidence that the visual search of drivers becomes less efficient as a function of increasing age. This is especially interesting because failure to yield the right-of-way becomes the primary cause of older drivers' accidents as early as age 50 (Gebers et al., 1993). In problem-solving situations requiring visual search-such as those that may arise at intersections-older individuals (as a group) tend to be less flexible mentally, to perseverate in their responses, and to become distracted by irrelevant information.

It is intuitively obvious that individuals can attend to only a very small percentage of the many stimuli in their surroundings at any given time. It is also obvious that some objects are easily noticed (i.e., are conspicuous), while others are inconspicuous, and may require considerable time and effort to locate. These common experiences capture the basic distinction between the two processes proposed in many models of visual information processing. While they go by different names in different models (e.g., ambient vs. focal; automatic vs. effortful; and parallel vs. serial), the systems of processing termed "preattentive" and "attentive"-used by Neisser (1967, 1976), Julesz (1981), and others-will be adopted for this review.

One measure of the preattentive component of the visual information processing system is the "useful field of view" (UFOV), which provides a measure of the spatial area within which individuals can be alerted to stimuli under a variety of situations. Measures of the UFOV are very different from measures of visual field size, and can be very much smaller than the area of visual sensitivity *per se.* The UFOV is usually measured

Table 8. Meta-analysis results for visual field testing.

AUTHORS	RESEARCH FINDINGS
Ball et al. (1993)	Found a significant correlation between peripheral vision and crash involvement (r=0.26). Older drivers with binocular visual field loss were twice as likely to have had a crash.
Burg (1968)	Found that crash and conviction rate were associated with visual field loss only when the loss was greater than would be expected with normal aging.
Buyck et al. (1987)	Found no significant differences between visual field and crashes.
Cole (1979)	Found a significant, but weak relationship between total visual field and crash rate for drivers over age 70.
Council and Allen (1974)	Found that crash and conviction rates were associated with visual field only when there was significant binocular field loss (greater than occurs with normal aging).
Henderson and Burg (1974)	Found a nonsignificant relationship between visual field and crash involvement.
Johnson and Keltner (1983)	Found that crash and conviction rates for drivers with significant binocular visual field loss were double those of other drivers.
Owsley et al. (1991)	Found a weak relationship between visual field and crash involvement.
Shinar et al. (1977)	Found that crash and conviction rates were associated with visual field only when the loss was greater than would be expected with normal aging.
Szlyk et al. (1991)	Found that subjects with peripheral visual field loss reported significantly more crashes than control subjects matched on age, gender, driving experience, and miles driven.
Visual Field Meta-Analysis	**Found significant differences in effect sizes across studies with crashes as the dependent measure (χ^2=27.26, p=0.0001).**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
Visual Field: Crash Frequency	27.76	0.0158	0.0158	0.0003	0.4921 to 0.5079	0.0315

binocularly, and can involve the detection, localization, or identification of targets against more complex visual backgrounds (Sanders, 1970; Verriest et al., 1983; Verriest et al., 1985). The limits of the UFOV are affected by many factors, such as requiring the performance of a concurrent central task that forces divided attention (Leibowitz and Appelle, 1969; Sekuler and Ball, 1986; Ball **et** al., 1988), the presence of distractors or multiple stimuli in the field of view (Sekuler and Ball, 1986; Scialfa, Kline, and Lyman, 1987; Ball et al., 1988), and the time available to process the display (Bergen and Julesz, 1983; Ball, Roenker and Bruni, 1990). The impact of these variables has been found to be much greater for older individuals (Rabbitt, 1965; Plude and Hoyer, 1985; Sekuler and Ball, 1986; Ball et al., 1988, Ball, Roenker and Bruni, 1990); thus, aging is associated with a restricted UFOV. Furthermore, an older adult's UFOV can be many times smaller than that of a younger adult (Ball et al., 1988; Ball, Roenker and Bruni, 1990) suggesting that traditional visual field tests-which frequently do not differ dramatically for younger and older adults-underestimate the extent of older adults' functional visual problems (Ball, Owsley, and Beard, 1990).

Recent work (Ball, Roenker and Bruni, 1990) has established the contribution of three attentional factors as bases for age-related reduction in the UFOV in the absence of visual impairment: (1) reduced speed of visual processing (as reflected by a greater impact of reducing stimulus duration on UFOV area); (2) reduced ability to divide attention (as reflected by a greater impact of increasing center task complexity on UFOV area); and (3) reduced salience of the target against its background (as reflected by a greater impact of distractors on UFOV area). Results demonstrated that the bases for reduced UFOV operate independently, in that some individuals experience a decline in only one of the factors (e.g., divided attention), while others experience declines in multiple factors. It was also found that the effects of multiple deficits, when they occurred, were additive such that individuals with all three deficits, on the average, had a loss of 84.28 percent of the field relative to the group experiencing none of the problems. Furthermore, while age accounted for approximately 50 percent of the variance in the size of the UFOV, the degree of shrinkage due to the three attentional components accounted for 91 percent of the variance in UFOV, indicating that the shrinkage of the UFOV, while ***age-related,*** can be accounted for without knowledge of age. Thus, the general age trends observed in this task are due to a higher prevalence of the three specific problems in an older age group rather than a general age-related decline in one or more of the three areas.

As stated earlier, inattention is frequently cited as a cause of accidents, either in the home, the workplace, or on the road. Indeed, driver inattention has long been cited as an underlying cause of vehicle crashes for older drivers (Shinar et al., 1978). In addition, many, but not all, older adults have deficits in their attentional skills as described above. Two recent retrospective studies have evaluated a battery of potential visual/cognitive predictors of crash involvement and demonstrated that visual attention deficits were the best predictors of accident likelihood in a selected group of crash-involved older adults.

The first study (Owsley, Ball, Sloane, Roenker, and Bruni, 1991) examined how crash frequency (from State records) in 53 older drivers was related to visual/cognitive capacities at a number of different levels, such as ocular disease, visual sensory function, visual attention, and mental status. The best predictor of crash frequency was a model incorporating a composite measure of visual attention (the size of the Useful Field of View), and mental status, which together accounted for 20 percent of the variance in crash frequency. This prediction was much stronger than those reported in earlier studies on **vision** and driving, which only assessed visual sensory function, and excluded measures of information processing skills at higher levels.

This is not to imply, however, that visual function is irrelevant to safety and driving. Obviously, a test of visual attention, like the UFOV, makes use of information coming through the visual sensory channel. For example, individuals in the above study who had serious visual field loss also exhibited an impairment in the UFOV. On the other hand, visual sensory field loss was not a necessary condition for a constricted UFOV. Many older adults who had impairments in the UFOV had normal visual fields. Thus, the UFOV depends on the integrity of visual sensory information, but it also depends on other attentional mechanisms as described earlier. In this sense, it is a more comprehensive measure of information processing ability than visual sensory status alone.

In a second, more recent large sample study which included over 300 older drivers, UFOV was confirmed as a good predictor of crash problems, with the correlation between crash frequency and UFOV exceeding that of the first study (r=0.52; Ball, Owsley, Sloane, Roenker, and Bruni, 1993). Furthermore, UFOV was found to have high sensitivity and specificity in predicting which older drivers were at risk for crash involvement over a 5-year retrospective period. Finally, a 3-year prospective study has been completed on this sample of older drivers, and it was found that the correlation between UFOV and future crashes remained fairly stable (r =0.46), with over 70 percent of the individuals experiencing UFOV reduction of 60 percent or greater involved in at least one an at-fault crash in the subsequent 3 years (Owsley, 1994). In contrast, only 3 percent of the older drivers with UFOV reduction of 30 percent or less were involved in an at-fault crash during this period. The odds of being crash involved during the prospective period was 16 times greater for those identified through UFOV to be high risk than for the low-risk group.

Two other studies have investigated UFOV reduction on alternative measures of driving performance. Wood and Troutbeck (1994) found a significant relationship between driving performance on a closed course and performance on a UFOV condition incorporating a high level of cognitive load. In a study that investigated age-related changes in the UFOV, it was found that increasing task difficulty significantly reduced the UFOV for older drivers in a driving stimulator (Walker, Sedney, Wochinger, Boehm-Davis, and Perez, 1993).

Given that research has only recently begun to identify stronger risk factors for the problems exhibited by older drivers, the development of interventions based on these factors is only in its infancy. An obvious way to minimize unsafe driving in older adults, given the indirect effect of visual function on UFOV, is to insure that older drivers have their best possible vision, and that all eye diseases and conditions have been evaluated by an eye care specialist. Older drivers should be encouraged to undergo an eye health examination on a yearly basis, or more often if they have a condition that requires frequent monitoring. Many eye conditions and diseases are treatable (e.g., cataract, glaucoma), especially when diagnosed early, and thus in many cases permanent vision loss can be prevented. It is also important for the eye care specialist to educate the patient about possible limitations in his/her visual capabilities due to vision impairment or deficits in higher order visual capabilities. Among others, Ball et al. (1993) have indicated that some older adults who are at risk for crashes because they have serious vision impairment, modify their driving behavior by avoiding exposure to difficult driving situations (e.g., driving alone or at night, turning left across traffic). This self-regulation of driving behavior was associated with a lower crash frequency. Therefore, it is possible that if older adults were better informed about their vision problems, some of them might voluntarily impose restrictions on their driving behavior, thus lowering their crash risk.

It should be noted that, while eye care is critical, over 50 percent of the older drivers who were identified as high risk drivers by the UFOV measure had excellent eye health and visual function. Therefore, another potential intervention stems from the finding that shrinkage in the size of the UFOV can be at least partially reversed through training (Ball, Ball, Miller, Roenker, White, and Griggs, 1986; Ball, Beard, Roenker, Miller, and Griggs, 1988; Ball, Roenker, Bruni, Owsley, Sloane, Ball, and O'Connor, 1991; Ball, Beard, Roenker, Miller, and Ball, 1988; Ball, Roenker and Bruni, 1990). Improvements have been demonstrated in the range of from 60 percent to 300 percent, with training programs of only 30 m per day, over a 5- to 10-day period. Studies have shown that improvement is retained for at least 6 months to 1 year without further training (Ball et al., 1988). Furthermore, training has been found to be effective for individuals of all ages, and is transferable to untrained stimuli (Ball et al., 1986; Sekuler and Ball, 1986; Ball et al., 1988; Ball et al., 1991).

While crash measures are important, they are a relatively insensitive measure of driving performance for all of the reasons enumerated earlier. Other outcome measures of safety/driving ability that would offer a more sensitive test of the relative contributions of various risk factors and driving are performance-based measures. These include actual on-the-road measures of driving performance, and/or performance in a theoretically related driving task with real-world depth cues and cognitive demands. While crash measures are critical, many factors contribute to a crash, and the fact that subjects modify their driving performance due to health or visual impairment would work against determining the true effects of any intervention procedure. Therefore, it is critical to incorporate a measure of driving performance in which: (1) the participants will not be placed in any risk; (2) challenging driving situations can be presented; and (3) the transfer of improved attention skills to a novel situational task more closely related to driving can be evaluated.

With regard to measures of mobility, it is important to determine the driving habits of each older adult in the study sample, by obtaining information such as: (1) the number of miles each individual drives in a given week; (2) the types of situations where the individual refrains from driving (e.g., darkness, inclement weather, driving alone; and (3) the types of routes (e.g., familiar vs. unfamiliar) on which driving primarily takes place. Mobility information is crucial for understanding older adults' driving problems and for interpreting safety measures. For example, older adults have very few crashes at night, which might be erroneously interpreted as their having excellent night driving skills. This crash data is better interpreted in light of the fact that most older adults severely limit their driving after dark, which lowers their exposure to crash risk.

The meta-analysis of studies investigating the impact of reduced UFOV on crash frequency reveals consistent findings in this area to date (see table 9). There are, however, relatively few studies using this measure, and large sample studies are in progress that are critical to confirming these findings.

Field Dependence

Another measure of visual processing with some of the same components as UFOV is field dependence. Field dependence refers to a person's ability to perceive relevant targets

Table 9. Meta-analysis results for useful field of view.

AUTHORS	RESEARCH FINDINGS
Ball et al. (1993)	Found that UFOV was significantly related to crash frequency in a sample of 294 older drivers (r=0.52).
Owsley et al. (1991)	Found that UFOV was significantly related to crash frequency in a sample of 53 older drivers (r=0.36).
Walker et al. (1993)	Found that increasing task difficulty significantly reduced the UFOV of older drivers (ages 60 to 65) in a driving simulator.
Wood and Troutbeck (1994)	Found a significant relationship between driving performance on a closed course and a UFOV condition incorporating a high level of cognitive load.
UFOV Meta-Analysis	**Did not find significant differences in effect sizes across studies with crashes as the dependent measure (χ^2=4.42, p=0.22)**

Variables	Chi Square	Fisher Z	Mean R	R Square	Binomial Effect Size	D
UFOV: Crash Frequency	4.42	0.531	0.4861	0.2363	0.2569 to 0.7431	1.113

embedded within a complex pattern (Shinar, McDowell, Rackoff, and Rockwell, 1978). Individuals who are "field dependent" have great difficulty finding the embedded target, because the whole picture takes precedence over its parts. Individuals who are "field independent" have less difficulty finding the embedded target, because they can easily perceive parts of the field as separate from the organized background (Witkin, Lewis, Hertzman, Machover, Meissner, and Wapner, 1954).

Field dependence is typically measured by requiring a subject to scan a complex figure and find the specified target. Field dependence is different from UFOV in that it involves more than target detection or localization. Rather, it requires the use of strategies and flexibility in trying to dissect multiple information sources in the visual scene (Shinar, et al., 1978). Most research indicates that people become more field dependent with increasing age (Shinar, et al., 1978; Ranney and Pulling, 1990; Manivannan, Czaja, Drury, and Ip, 1993).

Field dependency measures have demonstrated some predictive value with respect to driving performance. The manner in which a person organizes environmental information may be a factor in his/her visual performance, especially in situations such as recognizing hazards, identifying road signs, controlling a skidding vehicle, and driving in high-speed and high-density traffic (Goodenough, 1976). In driving studies that did not consider age differences, field-independent drivers were found to have lower crash rates (Harano, 1970), have quicker braking reaction times (Olson, 1974; Barrett and Thornton, 1968), have higher deceleration rates during simulated emergency situations (Barrett, Thornton, and Cabe, 1969), and show better headway maintenance patterns and better control of a skid-prone car after an initial trial (Olson, 1974) than field dependent drivers. Arthur, Barrett and

Alexander (1991) included field dependence as part of a meta-analysis examining the roles of cognitive, personality, and demographic factors on vehicular crash involvement. Their research resulted in 12 correlation coefficients related to field dependence. These authors determined field dependence to be a weak predictor of crash involvement, and attributed this to be a result of the use of three different assessment tests that were used across studies (e.g., the Group Embedded Figures Test, the Portable Rod and Frame Test, and the Hidden Figures Test).

Two studies have directly examined age differences in conjunction with field dependency and driving performance. Mihal and Barrett (1976) examined the relationship between several perceptual and information-processing abilities and crash rates of utility company drivers. One ability was field dependence, measured by the Portable Rod and Frame Test and the Embedded Figures Test. Both measures were significantly correlated with the number of crashes over a 5-year period. As an additional statistical manipulation, the sample was divided into a younger group (ages 25 to 43) and an older group (ages 45 to 64). For every significant predictor variable (i.e., Rod and Frame, Embedded Figures, complex reaction time, selective attention), the relationship with crashes was greater for the older group.

Shinar, McDowell, Rackoff, and Rockwell (1978) examined the relationship between field dependence and on-the-road visual search behavior. They noted an age-related decline in the time needed to identify information. Field-dependent drivers were characterized as needing longer eye fixations to gather relevant information. In addition, they were less able to adapt to changing perceptual requirements involved in curve negotiation. Although there appears to be some support for a relationship between field dependence and driving performance, the small number of studies in this area, and the diverse methods and measures used, limit the confidence of this assertion, and make it impossible to conduct a meta-analysis with the research conducted to date. A summary of the research findings is presented in table 10.

DRIVER AGE DIFFERENCES IN MEMORY AND COGNITION

There has been frequent speculation in the literature on driving, that some of the age-related increases in accident rates are due to decreased cognitive function in older adults (Arthur, Barrett, and Alexander, 1991; Staplin, Breton, Haimo, Farber, and Byrnes, 1986). Despite the frequent speculation, there are few studies that directly link aging, cognitive function, and driving errors. Driving is a complex behavior that clearly has many cognitive aspects, yet a clear understanding of how age-related changes in cognitive function affect driving behavior is elusive. There are several reasons to explain this difficulty. First, driving is a highly contextual, dynamic behavior with cognitive requirements that are not easily described, and which can change dramatically in a matter of seconds. Cognitive requirements of driving are also influenced by a driver's familiarity with a given situation, traffic flow, and weather. To characterize someone as a good or bad driver with adequate or inadequate cognitive resources to drive, without taking into account the context in which the driving occurs, is naive. The role of context has been largely ignored in the driving literature but will be an issue that arises frequently in this review. This emphasis occurs because the

Table 10. Summary of research findings for field dependence.

AUTHORS	RESEARCH FINDINGS
Barrett and Thornton (1968)	Found braking reaction times were significantly correlated with field dependence; field-independent drivers had quicker braking reaction times than field-dependent drivers.
Barrett, Thornton, and Cabe (1969)	Found that field-independent drivers were able to decelerate faster than field-dependent drivers, while driving in simulated emergency situations
Harano (1970)	Found field-independent drivers had lower crash rates than field-dependent drivers (age differences were not considered).
Mihal and Barrett (1976)	Found that field dependency, in a sample of utility company drivers, was significantly correlated with crash frequency over a 5-yr period. This relationship was greater for older drivers (ages 45 to 64) than for younger drivers (ages 25 to 43).
Olson (1974)	Found braking reaction times were significantly correlated with field dependence; field-independent drivers had quicker braking reaction times than field-dependent drivers.
Olson (1974)	Indicated that field-independent drivers were able to maintain better headway patterns and control a skid-prone car than fielddependent drivers.
Shinar, McDowell, Rackoff, and Rockwell (1978)	Indicated that field-dependent drivers required longer eye fixations to gather relevant information, and demonstrated less adaptive eye fixation patterns in response to changing roadway conditions than field-independent drivers.

context in which driving occurs dictates the mental effort or cognitive resources required to negotiate one's way through a situation and to be an effective driver. Thus, an understanding of cognition and driving cannot occur without factoring in the contextual demands of the driving situation.

Second, there are problems with dependent measures of driving, as the primary dependent measure of accident rate (crashes) likely does not provide a sensitive enough measure to capture the relationship of different aspects of cognitive function and aging to driving performance (Charness and Bosman, 1994). Unfortunately, from the point of view of a statistician, accidents are relatively infrequent so that the majority of individuals will have no accidents, with a large majority of the remainder having only one. Thus, due to this limited variance, the dependent measures will not be very sensitive to what is likely a relatively subtle, but potentially very important, independent variable like cognitive function. If the interest lies solely in adopting a functional approach to predict crashes and accidents, then the lack of a sensitive dependent measure for driving performance may not be a primary concern. However, to understand the mechanisms that underlie good performance versus poor performance in driving, it is essential that more sensitive measures of performance be collected. The use of driving simulators with high visual (contextual) fidelity, which permit a range of dependent measures to be collected, including: steering accuracy; visual fixation and processing of relevant information; braking speed; errors in turning; maintenance of following distance; etc., may permit us to elucidate which cognitive variables are most related to performance on the different aspects of driving performance, as well develop a careful assessment of what aspects of age-related decline most affect the components of driving behavior.

Before beginning a discussion of aging, cognition, and driving, it should be noted that Arthur, Barrett, and Alexander (1991) conducted a meta-analysis on the relationship of cognitive variables to accident involvement for the cognitive components of selective attention, speed (complex choice reaction time), and perceptual style. They were able to find only 13 *r* values for selective attention and five for choice reaction time with which to conduct the me&analyses. Using these data, they reported that the average mean correlation for the selective attention studies to accident rates was 0.26, and for the reaction time results it was 0.05. Thus, the results of the meta-analysis suggest that selective attention may indeed be an important factor in predicting crashes, but that choice reaction time does not account for much variance in predicting automobile accidents. The authors themselves acknowledge that they had an inadequate amount of data with which to conduct meta-analyses and they also suggest that predictive rather than retrospective studies for the accident data would be useful. Moreover, there are serious problems with the accuracy of an accident data base collected for nonresearch purposes.

The data base for such a me&analysis with respect to aging is even more seriously lacking. Interest in cognitive variables and aging does seem to be growing, however. In the past few years, there have been a sufficient number of studies performed on the role of aging and divided attention in driving simulation studies to allow a meta-analysis to be conducted (which is discussed in the present review). With respect to the other component areas of cognition, the focus will be more on reviewing existing findings in the literature, and relating these findings to driving.

Component Behaviors of Driving

The issue of how cognitive function relates to driving is a global one that cannot be addressed in an effective manner without defining the component behaviors of cognition, determining how to measure these components, and then relating the cognitive components to specific aspects of driving behaviors. Areas of cognitive function that have typically been discussed in the driving literature as being important are briefly described below, followed by comments regarding existing meta-analyses on cognition and driving.

Selective Attention/Vigilance. This refers to the ability to allocate attention to relevant target information effectively (Plude and Hoyer, 1985). Because of the vast quantity of information that is available in the driving environment, the ability to selectively attend to information that is of primary relevance for maintaining driving function is viewed as an important aspect of driving.

Speeded Responding. This refers to how quickly an individual is able to respond to a relevant target. Braking quickly when one recognizes that the car ahead is stopped is an obvious example of a driving situation where a quick reaction time can make the difference in whether or not there is a crash. Thus, reaction time-the ability to respond quickly to a stimulus-is often viewed as a critical aspect of successful driving.

Working Memory Capacity. Working memory is the amount of cognitive resource available to both process new information as well as retaining and manipulating information in the cognitive system (Baddeley, Logie, Bressie, Della Sala, and Spinner, 1986, in Hartley, 1992). Working memory capacity is a limiting factor in how much information an individual can process at any given moment. Thus, individuals with limited working memory are able to process and extract less information in the driving situation than individuals with larger working memory capacity. In situations where there is much relevant information from multiple sources to be processed, an individual with a limited working memory would be disadvantaged.

Reasoning/Decision Reasoning is the ability to discover rules or make inferences, and decision making refers to choosing among a range of alternatives, and typically involves reasoning. In the driving situation, the ability to abstract information and make quick decisions about it (e.g., deciding whether an exit is the correct one, while traveling on a busy freeway at high speed) can be important in being successful. Selective attention, speed, and working memory capacity are all factors in how effective an individual is at making rapid decisions. Decision making is a more molar behavior than the others discussed thus far; it will not be discussed separately, but will be subsumed under the discussions of the individual component behaviors.

Divided Attention. Divided attention is a measure of the ability to perform multiple tasks simultaneously. The ability to multi-task is an important aspect of driving, where one must steer, brake, process incoming visual information related to other cars, traffic lights and signs-, attend to information about the vehicle itself (e.g., fuel supply, speed, etc.), and make navigational decisions. The efficiency of divided attention operations is related to a number of factors including familiarity of the operations being performed, working memory capacity, and compatibility of the operations with one another. Because working memory is an important limiting factor in how effectively individuals perform in a divided attention situation, divided attention is discussed within the context of the construct of working memory.

Spatial Cognition and Wayfinding. Spatial cognition refers to the ability of the individual to process location information and use that information effectively to navigate or wayfind. Spatial cognition is particularly important when individuals are attempting to utilize schematics, maps, and environmental cues to navigate a vehicle to a destination, as well as when they are attempting to remember a route that they have previously traversed.

A detailed discussion of age-related changes in the component behaviors of selective attention, reaction time, working memory, and divided attention will follow. Preceding this material, however, it is instructive to consider: (1) theoretical views of cognitive aging, and (2) the relationship between aging, practice, and expertise, as they pertain to the driving task.

The discussion of driver age differences in memory and cognition closes with a consideration of vehicle displays, navigational devices, and wayfinding (spatial cognition), then presents a cognitive model of driving behavior that integrates the current findings and may be useful in guiding future research.

Theoretical Views of Cognitive Aging

This section presents a brief review of the types of cognition where age-related changes are observed, and presents an overview of the major theoretical perspectives on how cognitive function changes with age-the views of Craik, of Salthouse, and of Hasher and Zacks are presented. Additionally, an important new theoretical perspective that integrates sensory function and cognitive function is presented (Lindenberger and Baltes, 1994). The implications of these theories for driving behavior are then discussed. This is followed by a discussion of how expert, highly-practiced behaviors may be somewhat resistant to age-related decline in cognitive function and these data will be extrapolated to driving.

Age-related differences reliably occur on speeded tasks of virtually any type (Salthouse, 1985; Salthouse, 1991; Salthouse, 1993; Salthouse, 1994), on working memory tasks of all types (Salthouse and Babcock, 1991; Cherry and Park, 1993), on measures of free recall (Smith, 1979), and on abstract reasoning tasks (Salthouse, Mitchell, Skovronek, and Babcock, 1989). Although older subjects perform more poorly than younger subjects on divided attention tasks, there is some debate about whether the relative cost of divided attention is disproportionately higher for young persons than for older persons (Hartley, 1992). Similarly, there is ample evidence that spatial memory does decline with age (Light and Zelinski, 1983; Park, Puglisi, and Sovacool, 1983), but there are a few studies and claims suggesting that spatial memory is age invariant, particularly in a naturalistic context (Sharps and Gollin, 1987; Waddell and Rogoff, 1981).

Despite these rather general declines in component processes of cognition, there is also considerable evidence that vocabulary and language abilities do not decline with age (Light, 1992). Moreover, there is good evidence that memory that does not involve deliberate recollection-implicit memory-is age invariant (Park and Shaw, 1992), and that picture recognition is also age invariant (Park, Puglisi, and Smith, 1986). Finally, there is considerable evidence that semantic memory (knowledge about the world) is organized similarly for old and young, and does not undergo any substantive change with age. This conclusion follows from performance on priming studies, a procedure whereby reaction time is decreased when a target item is “primed” by being preceded with a related item that appears to enhance accessibility to the target for both old and young adults; in such studies, differences in response time to various categories of stimuli appear to be similar across age (Howard, 1988; Howard, Heisey, and Shaw 1986).

The findings briefly reviewed above are the findings that any major theory of cognitive aging needs to explain. At present, there are three major views of mechanisms that underlie age-related changes in cognitive function-a processing resource view, a speed view, and a deficiency in inhibitory function view. In addition, a recent new view that sensory decline mediates declines in cognition (Lindenberger and Baltes, 1994) has important implications for driving.

Limited Processing Resources. The processing resource view was initially proposed by Craik and Byrd (1982): They suggest that older adults show deficient cognitive function, and poor memory in particular, because they have limited "mental energy," and because they are deficient in self-initiated processing. That is, older adults are particularly disadvantaged when a task requires them to initiate or extend considerable mental effort. Thus, in a driving situation, older adults would likely be particularly disadvantaged in an unfamiliar situation or in a short-term emergency that required substantial problem-solving and maximal use of mental resources. This would appear to be a plausible explanation for findings in the cognitive aging literature as described above. This pattern of findings can readily be interpreted within a mental effort or processing resource framework as follows. Generally, cognitive measures that rely heavily on processing mechanisms and unfamiliar information (examples of such measures would include reasoning, working memory, speed, etc.) show large age effects, whereas measures that are more knowledge-based like vocabulary and semantic priming do not show age effects. Similarly, measures that require limited amounts of mental effort (e.g., picture recognition and implicit memory) are also age invariant.

The Craik limited resource view has been influential, but until recently, it was considered more of a metaphor than an empirically-testable hypothesis. In recent years, the mental effort view of cognitive aging has been operationalized as a decline in working memory capacity. There is considerable evidence, as mentioned earlier, that older adults have poorer working memory function than younger adults (Salthouse, 1991; Salthouse and Babcock, 1991). Of even more importance is the growing body of literature suggesting that declines in working memory mediate age-related variance on a range of diverse cognitive tasks, including speech comprehension (Stine and Wingfield, 1987), text memory (Hultsch, Hertzog, and Dixon, 1990), spatial memory (Cherry and Park, 1993) and performance of a complex procedural assembly task (Morrell and Park, 1993).

One important aspect of the Craik view of age-related declines in cognitive function is his view of how these declines can be mitigated or repaired (Craik, 1986; Craik and Jennings, 1992). Craik (1986) suggests that restructuring information or the environment to reduce processing demands can result in performance of the old approximating that of the young. Thus, one approach to the aging driver using the Craik (1986) framework would be to ensure that working memory demands are as low as possible in the driving situation, so that the older adult can perform effectively. This issue of environmental support to repair age differences is addressed in more detail later in this review.

Speed of Processing. Overall, the data just presented would seem to support the notion that working memory is the fundamental mechanism that underlies age-related decline in cognitive function, and that working memory should be a primary focus of research on the cognitive aspects of aging and driving. Despite the convincing picture presented above, there are other data that suggest that speed of processing is the fundamental mechanism accounting for age-related decline (Birren, 1965; Salthouse, 1985). For example, Salthouse and Babcock (1991) reported that age-related variance in working memory function was largely accounted for by measures of comparison speed, suggesting that the fundamental mediator of age-related decline is speed, not working memory. In a later study (Salthouse, 1993) found that measures of perceptual speed accounted for 83 percent of the age-related variance in paired associate memory, and Salthouse (1994) reported that measures of perceptual speed accounted for 70 to 80 percent of the variance on measures of spatial rotation, matrix reasoning, and associative memory. The breadth of these findings attests to the generality of the speed mechanism in accounting for age-related decline in cognitive function. Lindenberger, Mayr, and Kliegl (1993) also found that even for a very elderly sample of adults, age-related variance on a range of cognitive tasks that included reasoning, memory, verbal fluency and verbal knowledge was mediated through speed. Finally, Park, Smith, Lautenschlager, Earles, Frieske, Zwahr, and Gaines (1994) measured both speed and working memory and their relationship to three types of memory, using structural equation modeling techniques. They found that age-related variance was mediated through speed, and that working memory exerted a direct effect on other types of memory *only* when the task was highly-resource demanding.

Overall, this body of work strongly suggests that decline in processing speed is the fundamental mechanism mediating most cognitive changes that occur with age. There are several implications for this finding with respect to driving. First, it is obvious that older adults will be disadvantaged in situations that require speeded responding. Second, and perhaps more important, because the loss of speed appears to be a robust and universal finding with age, it is likely due to neurobiological mechanisms, and therefore, attempting to train older people to be faster may not be an effective strategy. What may be more effective is to recognize that the loss of speed appears to have profound implications for cognitive behaviors of all types, particularly those requiring a lot of cognitive effort. As Craik (1986) suggests, the focus should be on relieving the speed and working memory or effort requirements from driving situations through better signage, instrumentation, and other aspects of vehicle and highway design.

Faulty Inhibitory Processes. The third theoretical perspective that has received a lot of recent attention is the notion that older adults evidence cognitive declines due to inefficient use of existing cognitive resources, rather than due to a decline in resource. This is a view advanced by Hasher and Zacks (1988). They argue that older adults are deficient in inhibitory processes, and as a result, they frequently direct attention to irrelevant information at the expense of relevant information. The deficiency observed in working memory function with age is due to information cluttering working memory that younger adults would have effectively inhibited. There is some evidence for the Hasher and Zacks (1988) perspective, in that older adults appear unable to suppress an irrelevant prime in a naming task compared to young adults. Young adults have longer latencies for naming a previously irrelevant item (suggesting that it has been suppressed) when compared to a new item, but older adults do not show longer latencies for recently-irrelevant information. This suggests the item was not inhibited and was active in working memory.

The inhibition point of view has enormous implications for driving behavior. It suggests that older adults will be particularly disadvantaged when they are presented with a lot of information, much of which is irrelevant. This is a good description of a complex driving environment, as it does contain multiple sources of information, a great deal of which must be ignored. Thus, the inhibition view could be an important source of understanding the high accident rates of older adults. At the same time, it is important to recognize that the inhibition effect observed in the laboratory is very small (on the order of 10 ms or less), that researchers in a number of laboratories have been unable to demonstrate it (Park et al., 1994), and that to date, no one has been able to directly link poor inhibitory function with aging to other cognitive deficits. In contrast, measures of speed and working memory have readily been demonstrated to predict deficits on a broad range of other cognitive tasks and appear to be fundamental to cognition. The same cannot **be** said of the inhibition construct. For these reasons, more emphasis will be placed on the speed and working memory perspectives when making interpretations and recommendations regarding aging and driving, as the recommendations will be based on more solid theoretical and empirical ground. More basic research is needed on the inhibition perspective before it can be used effectively and responsibly to understand driving behaviors in aged adults.

Sensory Function as a General Mediator of Cognitive Function. Very recently, Lindenberger and Baltes (1994) have presented an interesting view of cognitive aging, with a strong set of data justifying their approach. They have extensive measures of both sensory and cognitive function from a group of older individuals, ranging in age from 70 to 103. They found that measures of visual and auditory function accounted for 93 percent of the age-related variance on cognitive tasks for these older adults, using structural equation modeling techniques. Moreover, speed did mediate the age-variance on the cognitive tasks, but did not mediate the age differences in vision and hearing. Vision and hearing, however, did account for age-related variance associated with speed. This pattern of findings clearly suggests that sensory function is even more fundamental to cognitive performance in very late adulthood than is speed. The authors note that sensory function typically does not explain variance on cognitive measures in young-old adults, but it does in very late adulthood. They propose the "common cause" hypothesis, arguing that "negative age differences in both domains (sensory and cognitive) reflect an age-associated loss in the integrity of brain physiology. Age differences in intellectual and sensory functioning, then, are seen as the outcome of a third common factor or ensemble of factors, that is, aging changes in the physiological state of the brain."

This view seems to be of particular importance for the aging driver, as there has been a tendency to treat sensory function as a factor that is independent of, or orthogonal to, cognitive function. Lindenberger and Baltes (1994), however, provide evidence to suggest that for the very old, deterioration in both sensory and cognitive function represent an index of global brain deterioration rather than separable, independent factors. The fact that the accident rate increases from old age to very old age suggests that this theoretical view of cognitive aging squares with the reality of accident data of older drivers.

Summary of Theoretical Views. All four theoretical views presented seem to suggest that age-related decline in cognitive function is a given, and that such decline is likely not easily modified. This basic research on cognition and aging would tend to be more congruent with a human factors view of how to support declines in driving behavior caused by diminished cognitive resources with age. That is, efforts need to be focused on understanding what component behaviors decline and how the driving task can be altered or modified to be compatible with the sensory/cognitive changes in the older adult so that mobility can be maintained as long as possible.

Before embarking on a discussion of age trends in the component cognitive behaviors of driving, it will be useful to first consider driving as a highly-practiced, expert behavior, as there is some evidence that expert behaviors may be resistant to age-related decline, despite declines in the component behaviors comprising the highly practiced behavior.

Aging, Practice, and Expertise

There can be little doubt that driving is a complex behavior, given the multiple perceptual, psychomotor, and information-processing requirements associated with this task. It is also the case that for the vast majority of older adults, driving is a highly practiced behavior, with most individuals having logged thousands of hours of experience in the performance of this behavior. There is some evidence that highly-practiced or "expert" behaviors may be resistant to age-related decline, even when there are negative age changes evidenced on the component processes, Perhaps the best example of this is the classic study of age effects and typing speed conducted by Salthouse (1984). Salthouse studied a sample of typists of all ages with the *a prior* characteristic that the correlation between age and typing speed was zero. He measured component behaviors of typing including the interstrike interval between keys, reaction time, and other such measures, and found that older typists showed declines on these measures. Thus, it seemed to be the case that older typists were using some type of compensatory mechanism to maintain typing speed, since there was age equivalence in the typing speed but decline on the component abilities of typing. Salthouse (1984) was able to determine that the older adults appeared to process a larger string of characters in advance than younger adults. This appeared to be the compensatory mechanism that accounted for the equivalent typing performance between older and younger typists in the face of declining efficiency of component processes associated with typing for the older adults. Similarly, in a meta-analysis that examined complex and expert behavior in the domain of work, Waldman and Avolio (1986) found no evidence that there was any systematic relationship between age and job performance, a finding also consonant with a review of the literature on work and aging presented by Rhodes (1983).

The point of introducing these findings with respect to the issue of driving is that these studies isolate two domains of complex, expert, highly-practiced behaviors and present no evidence for age-related decline, despite objective findings that the component processes of these behaviors do decline. Thus, the inference that can be made that is of import to the present discussion is that *just because declines are observed on the component behaviors of a complex, practiced task, these declines do not necessarily suggest that older adults will be poorer or less effective at the task.* It is important to recognize that driving is an expert behavior for the vast majority of older adults and that there is a need to be cautious in concluding that observed declines in speed or working memory function are necessarily the basis for the poorer driving record of the elderly. The increased familiarity and experience that older adults have on the road may have resulted in the formation of some types of compensatory mechanisms that provide some protection against the effects of cognitive declines manifesting themselves at a level that is problematic for driving behavior. At this point, little attention has been paid to driving as a complex, molar behavior and there are not good measures of overall driving effectiveness. Thus, one important issue for future research may be to determine the nature of compensatory strategies that older adults might use to maintain driving behavior to compensate for cognitive decline. These could occur at the level of cognitive function (e.g., paying closer attention), at the level of instrumental activities (e.g., not listening to the radio or talking to passengers to devote all resources to driving). Finally, if compensatory strategies fail, older adults may resort to altering the driving behavior itself to less resource-demanding situations (e.g., not driving in unfamiliar places, heavy traffic, or at night).

Another issue of importance in a discussion of expertise and driving is that many components of driving behavior may become automatized through high amounts of practice. An automatic process is one that requires little or no cognitive resource to maintain (Schneider and Shiffrin, 1977; Shiffrin and Schneider, 1977) and some theorists have argued that automatic processes, because they require little or no capacity, do not show age-related declines (Hasher and Zacks, 1979). Many individuals will report that they are completely unaware of devoting any cognitive effort to driving, or of the information and landmarks that they passed while driving, as they were sufficiently engrossed in other mental activities. This ability to focus on other experiences while driving is likely a result of the highly practiced and automatized nature of driving, particularly when it occurs on an open freeway with little traffic, or on a highly familiar route where there may be few cognitive demands. At the same time, when drivers encounter a demanding traffic situation, they report ceasing an animated conversation with passengers, turning down the radio, or telling children in the car to hold their requests and comments until they maneuver through heavy traffic. This is because in a demanding situation, drivers must shift from an automatic mode of processing to a controlled processing situation that is effortful and resource demanding. In this case, they need to use the resources to drive that they had previously been devoting to processing information not directly relevant to the driving task. Aged adults, despite substantive declines in cognitive processes, may not be particularly deficient in a behavior like driving due to the automatized nature of many aspects of driving performance, because automatized behaviors require few cognitive resources.

It also needs to be recognized, however, that the picture becomes a different one when the contextual demands of the driving task shift from an automatic to a controlled or effortful task. Ackerman (1986, 1987) found that cognitive resource, as measured by high cognitive ability scores, is not important for automatized tasks, but performance on controlled tasks was strongly predicted by cognitive ability scores. Because cognitive ability scores that measure processing efficiency decline with age, the Ackerman data (1986, 1987) provide some evidence that older adults would likely be deficient in driving situations that require a high amount of controlled processing. Such a theoretical framework could account for high accident rates of the elderly if the basis for many of their accidents were disproportionately distributed across situations that were highly resource-demanding situations (e.g., occurred in heavy traffic, at complex intersections, etc.). Holland and Rabbitt (1992) cite a study conducted by Moore, Sedgely, and Sabey (1982) that indicated that elderly drivers had a disproportionate number of accidents at complex junctions, a finding congruent with a cognitive explanation of accident rates. Also, in keeping with the cognitive hypothesis, Lerner, Morrison, and Ratte (1990) reported older adults tended to be disproportionately involved in multi-vehicle as opposed to single-vehicle collisions, except on Interstates, where they are more likely to be involved in single-vehicle accidents. It may be that the requirement for speeded responding and traveling at high rates of speed on Interstates defines cognitively-demanding driving situations, even without the addition of other vehicles. Finally, Treat, Tumbas, McDonald, Shinar, Hume, Mayer, Stansifer, and Castellan (1977) reported that 41 percent of accidents in which older adults are involved are caused by a failure to recognize hazards and problems, and that 18 to 23 percent of their accidents are due to problems with visual search. These causes implicate cognition as a basis for the accidents. In general, while such data are hardly definitive regarding the role of cognitive factors, it does suggest that one important direction for driving research is to determine the cognitive demands of situations in which accidents objectively occur. If the basis for the disproportionate numbers of accidents in older adults is cognitive resources, age would not be normally distributed across accidents but would fall disproportionately in the high cognitive demand situations.

In summary, it is important to understand that the cognitive requirements of the driving situation can shift as a function of practice and expertise, and that the cognitive demands of driving are almost certainly less for a highly experienced driver compared to a less-experienced individual. Because older adults are, as a group, highly experienced, they may be able to maintain adequate driving performance due to the automatized nature of the task. It is also important to recognize that there is evidence that older adults, through experience, may develop compensatory strategies that result in an expert behavior remaining intact in the face of declines in the component processes associated with it. Supporting a cognitive interpretation of accidents in older adults is evidence that older adults are disproportionately represented in accidents that occur in situations with high cognitive demands, in particular, at intersections.

Selective Attention

Selective attention is the ability to direct and focus attention on relevant information. It is believed to be an important cognitive component of driving behavior due to both the visual and auditory complexity of the driving environment. Of particular importance is the fact that much of the information in the visual or auditory environment is irrelevant to the driving task, so that the individual must be able to suppress attention to irrelevant information and rapidly select and attend to information that is important for accident avoidance and safe driving. The driver must be able to ignore, for example, many types of signage but attend to signs signaling warnings or relevant route information. The driver must pay attention to certain moves on the part of other drivers, the sounds of horns, sirens, and other warning noises, attend to his or her rearview mirror, as well as be aware of the relationship of his/her vehicle to other vehicles on the road. At the same time, information irrelevant to successful driving is also present in abundance, including information and music from the radio, and most of the static visual environment along the road side.

<u>General Findings</u>. There are several studies that have examined the relationship of laboratory measures of selective attention to driving performance or accident rates. The typical selective attention paradigm involves presenting subjects with conflicting information in two ears and cueing the subject that they should attend to the information in only one ear. Thus, the subject must suppress attention to one ear, and selectively attend to the other source of information. In general, these studies have yielded promising results. Indeed, Arthur et al. (1991), in their meta-analysis of selective attention studies reported that the overall correlation resulting from their analysis for selective attention and accident rates was 0.26. Although this is not an extremely strong relationship, it is nevertheless significant, and

given the problems with the outcome measure (accident rate), it is possible that with more precise measures a stronger relationship would be observed.

To briefly review some findings in this area, Kahneman, Ben-Ishai, and Lotan (1973) reported that a laboratory measure of selective attention correlated as high as 0.51 with accident rates. One notable aspect of this study was that the investigators selected 29 bus drivers with known accident rates and matched control subjects to these other subjects. The fact that they observed such a high correlation may well be related to the fact that they had a better distribution of accident behaviors in their dependent measure so that there was actually significant variance to predict with the predictor measures. The relatively convincing, high correlation that they observed could be a result of this relatively uncommon refinement of experimental technique.

Avolio, Kroeck, and Panek (1985) conducted a study where they measured both visual and auditory selective attention and its relationship to automobile accidents in a group of utility workers. They reported three types of error data for each measure: (1) omission errors (not reporting an item); (2) intrusion errors (reporting a nonpresented item); and (3) switching errors (not changing to the other channel when directed by a cue to do so). They found differences among the groups for all three types of errors in the auditory modality, with the accident group having a higher rate of errors. In the visual modality, omission and switching errors, but not intrusion errors, differentiated accident from no-accident subjects. Of the three measures, the switching measure had the strongest relationship to accidents, suggesting that inflexibility in directing attention may be a particular cause of accidents.

Finally, Arthur and Doverspike (1992) examined the relationship of an auditory selective attention task to accident rate, using both a predictive and retrospective design. In both cases, they reported a significant relationship between accident rates and selective attention measures.

Next, there is considerable literature on the issue of how selective attention changes with age. An important aspect of the attention literature is whether the process of selecting new stimuli is automatic or controlled. This is a critically important issue with respect to aging, because there is considerable evidence that automatic processes are age-insensitive, that is, do not show an age decrement. In contrast, controlled processes require effort and drain cognitive resources, and this is a particular concern for their elderly due to the strong evidence that they have more limited cognitive resources than young adults.

One important finding in the selective attention literature with respect to driving is that older adults respond much more slowly to stimuli that are unexpected (Hoyer and Familant, 1987), suggesting that older adults might be particularly disadvantaged when an unexpected hazard appears in the road (e.g., a deer running in front of the car), compared to a more expected situation such as a car going through an intersection after the light has just turned red.

There is also substantial evidence that older adults are very slow to automatize new behaviors, as reported in work on consistent mapping paradigms where older adults receive hundreds or thousands of trials in attention situations, where similar responses are required across many trials (Fisk, McGee, and Giambra, 1988; Fisk and Rogers, 1991; Rogers and Fisk, 1991). The underlying mechanism appears to be that younger adults are better at unitizing responses, and that targets gain strength and distracters lose strength for them faster when compared to older adults. Because these effects are observable only after extensive practice, the findings do not suggest that older adults who have been driving for a period of time and have highly automatized driving behaviors when they were younger would be disadvantaged. Rather, the primary implications of these findings for driving would seem to be that older adults who were nondrivers and attempted to learn to drive might have a relatively hard time automatizing behaviors like steering and braking and other component behaviors associated with driving. These behaviors would likely require controlled processing for a prolonged period of time, using up the limited capacity information-processing system of the older adult for behaviors that would be automatized in a younger adult. Thus, there would be less cognitive resources available to attend to other aspects of driving, presenting a potential hazard. Similarly, these data suggest that making changes in any aspect of vehicle design or road design that subjects respond to in an automatized fashion (e.g., the shape and color of yield signs, the meaning of yellow pavement markings, etc.) would be more problematic for older drivers compared to younger drivers.

Finally, laboratory research on attention appears to indicate that the vigilance aspect of attention does appear to operate similarly for old and young individuals (Hartley, 1992; Parasuraman, Nestor, and Greenwood, 1989). Vigilance refers to the ability to monitor one's environment for detection of a target and to make a response when the target appears. This is an important aspect of driving, because a driver who fails to maintain vigilance for even a brief period of time will be at high risk for an accident. The finding of age invariance for vigilance is an encouraging one. Overall, the basic literature on attention and aging suggests that older adults will be at particular risk when a response is required to an unexpected stimulus.

Aging. Selective Attention. and Driving. There are a few studies that look at the relationship of selective attention in older drivers to driving and accident behaviors. Mihal and Barrett (1976) examined the relationship of an auditory selective attention task to accident data. They found a significant difference in accident rates as a function of selective attention, but more importantly, they reported a stronger relationship for older compared to younger drivers. Unfortunately, this relationship cannot be confirmed, because there is only one other study in the literature. Ranney and Pulling (1990) collected a large battery of cognitive measures as well as 30 min of controlled driving data from a driving course from a group of 44 adults ranging in age from 30 to 83. They reported a general decline in performance on nearly all of the cognitive measures for older adults when compared to younger adults. In terms of driving performance, the older drivers' global rating was lower than that of younger drivers due to more errors in decision speed, route selection, gap execution, vehicle control, and comprehension of instructions. Of interest was the finding that the older subjects performed as capably as the younger subjects in response to an emergency situation. Ranney and Pulling (1989) found no association between the cognitive measures and the driving variables, thus failing to confirm the relationship for selective attention to driving. The failure to find such a relationship, however, may be due to the small sample size of only 50 subjects. This is a notable study in that very precise, detailed quantitative measures of both cognitive function and driving behaviors were noted, so it is somewhat surprising that the cognitive variables failed to predict driving performance in any substantive manner.

Reaction Time

It is important when discussing reaction time and driving, that motor response time and speed of processing be discriminated from one another. Motor speed refers to how rapidly subjects are able to respond to the presence of a target stimulus, and is perhaps best measured by a simple reaction time task. This type of measure of speed would be related to how rapidly a driver brakes or initiates an action once a decision is made to respond. Processing speed is the rate at which one performs mental operations, and it is hypothesized to decline with age (Salthouse, 1985). The best estimate of speed of processing is perceptual speed (Salthouse, 1985, 1993, 1994), a measure of how rapidly subjects can make mental comparisons of digits, figures, or patterns. Processing speed would likely be the more salient aspect of reaction time when attempting to determine how cognitive variables are related to complexity and unexpected information in the driving environment. In a complex driving situation, the rate of processing information, rather than simple ability to respond to a target quickly, would influence how effectively a subject responds to a situation.

The data on the relationship of reaction time to driving behavior has not been clear. Although simple reaction time would seem to play an important role in driving skill, there is not much evidence that differences in this behavior discriminate individuals involved in accidents from those who are not. Fergenson (1971) tested a group of 17 volunteers on simple and complex reaction time, and used the difference score between these two measures as an estimate of rate of information processing. He reported a relationship between slowed information processing and accident rate. However, he also noted that the fastest information processors were in the high violation, zero accident group, the implication being that these subjects might be somewhat reckless, but their superior information-processing skills allowed them to avert accidents.

Aging Reaction Time, and Driving. There are a few studies that look at reaction times and driving performance in older adults. Mihal and Barrett (1976) measured simple, choice, and complex reaction time, by requiring subjects to respond to an actual photograph of a driving scene. They reported that simple and choice reaction time were not correlated with accidents, but complex reaction time was. Moreover, when only older adults were examined, the correlation increased from 0.27 for complex reaction for the total sample to 0.52, suggesting the relationship to be particularly marked for older adults. Ranney and Pulling (1989) found no relationship on overall driving performance on a course as a function of simple reaction time or measures of perceptual speed. However, when only an elderly sample was examined, correlations were significant for simple reaction time and two measures of perceptual speed.

Taking a somewhat different approach, Olson and Sivak (1986) examined the perception-response times for subjects to notice and brake for an object in the road, using actual driving in an experimental vehicle to collect data. The perception-response time is commonly estimated to be 2.5 s, a value that becomes important when designing various aspects of roads and highways. They tested younger and older adults, and found that for both groups, a value of 1.6 s was appropriate for the 95th percentile of subjects. The two findings of note here are that the value of the interval was not different for old and young adults, and that the interval commonly used for highway design was a considerable overestimate. This study does not directly address the relationship of age and reaction time to driving skill and safety, but it does suggest that the millisecond differences that characterize differences between older and younger drivers on measures of speed may not be of importance in assessing a practical response in a real driving situation.

More recently, Lerner, Huey, McGee, and Sullivan (1995) conducted on-road experiments to investigate whether the assumed values for driver perception-reaction time used in AASHTO design equations adequately represent the range of actual perception-reaction time (PRT) for older drivers. Approximately 33 subjects in each of three driver age groups were studied: 20 to 40, 65 to 69, and 70+. Regarding bias caused by self selection of subjects, Lerner et al. stated, "Although there can be no claim that the sample was representative, and while it is likely that those at the extreme lowest limits of ability and confidence tended to exclude themselves, the older group did appear to provide a broadly suitable range, and certainly included many individuals who would have been unlikely to participate without more active recruiting strategies." Drivers operated their own vehicles on actual roadways, were not informed that their response times were being measured, and were naive as to the purpose of the study (i.e., they were advised that the purpose of the experiment was to judge road quality and how this relates to aspects of driving). The Case III PRT study included 14 data collection sites on a 90-km (56-mi) route. The Case III (stop controlled) intersection sight distance experiment found that older drivers did *not* have longer PRT than younger drivers, and in fact the 85th percentile PRT closely matched the AASHTO design equation value of 2.0 s. The 90th percentile PRT was 2.3 s and there were occasional extremes of 3 to 4 s. The median daytime PRT was approximately 1.3 s. Interestingly, it was found that typical driver actions did not follow the stop/search/decide maneuver sequence implied by the model; in fact, drivers continued to search and appeared ready to terminate or modify their maneuver even after they had begun to move into the intersection. This finding resulted in the study authors' conclusion that the behavior model on which intersection sight distance (ISD) is based is conservative.

In the Lerner et al. (1995) stopping sight distance study involving brake reaction times to an unanticipated even (a crash barrel suddenly rolling toward the roadway), there were apparent differences in the distribution of PRT among age groups. Although younger drivers accounted for most of the fastest PRT's, there were no age differences in the 50th or 85th percentiles; all observed PRT's were encompassed by the current AASHTO design value of 2.5 s. The median brake RT was approximately 1.4 to 1.5 s, and the 85th percentile brake reaction time was 1.9 s.

Neuman (1989) argues that a PRT of 2.5 s for stopping sight distance (SSD) may not be sufficient in all situations, and can vary from 1.5 s to 5.0 s depending on the physical state of the driver (alert versus fatigued), the complexity of the driving task, and the location and functional class of the highway. Overall, the relationship of speed to driving behavior is equivocal, as is the role that age-related slowing might play in driving behavior. It should also be noted that, at present, there are insufficient studies to conduct a meaningful me&analysis on this topic.

Working Memory and Divided Attention

Working memory refers to the amount of cognitive resource available at a given moment to manipulate, retrieve, and store information (Baddeley et al. 1986). As reviewed earlier, there is considerable evidence that working memory resources become more limited with increased age. One consequence is that older adults have fewer resources available to perform multiple operations, as is frequently required in driving. In fact, driving is a good example of a divided attention task-a situation where an individual must distribute limited resources across a number of tasks and perform them simultaneously. In the case of driving, multiple ongoing tasks would include steering, braking, processing complex visual input, making navigational decisions, and often additionally includes carrying on a conversation or attending to music, audio taped discourse, or internal musings. Before addressing whether older people are particularly disadvantaged in divided attention tasks, it is important to reiterate the difference between controlled and automatic processes.

Recall that controlled processes are processes that require effort, which uses up limited working memory resources. Automatic processes on the other hand, due to high amounts of practice, require little effort and require little or no working memory capacity. Thus, the effects of age on dual task performance or divided attention tasks must be interpreted within the controlled/automatic framework.

Aging and Divided Attention. It is typically the case, except for highly automatized processes, that the addition of a secondary task affects performance negatively on a primary task. This is the case for both old and young adults. A question of primary interest in the cognitive aging literature is whether the "costs" to the primary task of adding a secondary task are disproportionately large for older adults compared to younger adults. In other words, the question is usually not whether secondary tasks depress performance, but whether the magnitude of the decrease in performance with the addition of a dual task is greater for older adults compared to younger adults. There are numerous studies addressing this issue in the divided attention literature, and determining whether or not there is a disproportionate cost of dividing attention for older adults turns out not to be a simple question.

Hartley (1992) reported the results of a meta-analysis conducted by Kieley (1991) on the nature of age effects associated with divided attention tasks. A total of 24 studies were reviewed, and the results were not homogeneous, so that no clear conclusion was possible. This suggests that the effects in the dual task studies associated with age had different underlying causes. The results, taken from Hartley (1992), appear in table 11. Kieley (1991) attempted to group the studies into smaller, homogeneous groups, but was nevertheless unable to come up with any definitive conclusions about magnitude of processing costs. Hartley (1992) reviewed methods and procedures, as well as the meta-analyses, and warned that any simple conclusion is probably wrong; however, he states: "Accepting that caveat, the most plausible interpretation of the findings from dual-task studies is that younger and older adults do not differ in the ability to allocate attention across conditions."

Table 11. Divided attention studies included in meta-analysis of simultaneous task performance including sample sizes and effect sizes (D), (Taken from Hartley, 1992).

Study	Sample Size		Effect Size
	Older	Younger	D
Baddeley, Logie, Bressie, Della Sala, and Spinner (1986)	28	20	0.31
Craik and McDowd (1987)	15	15	0.82
Craik, Morris, and Gick (1988)	16	16	0.37
	16	16	0.37
Duchek (1984)	32	32	0.26
Gick, Morris, and Craik (1988)	18	18	0.34
Guttentag and Madden (1987)	14	14	0.96
Kirchner (1958)	12	9	3.88
Kolbert (1985)	6	6	0.63
	6	6	2.86
	6	6	1.99
Light and Anderson (1985)	25	25	0.67
	20	20	0.46
Lorsbach and Simpson (1988)	18	18	0.87
Macht and Buschke (1983)	48	48	1.34
Madden (1986)	20	20	1.27
	18	18	2.41
	20	20	1.14
	16	16	1.55
Madden (1987)	24	24	1.36
McDowd (1986)	6	6	1.28
McDowd and Craik (1988)	16	16	1.28
	18	18	1.01
Morris, Gick, and Craik (1988)	24	24	0.30
Park, Smith, Dudley, and La Fornza (1988)	60	59	0.37
Salthouse and Somberg (1982)	16	16	0.53
	16	16	4.08

Table 11. Divided attention studies included in meta-analysis of simultaneous task performance including sample sizes and effect sizes (D) (Continued).
(Taken from Hartley, 1992).

Study	Sample Size		Effect Size
	Older	Younger	D
Penner (1982)	24	24	0.45
	24	24	0.71
	24	24	0.53
Salthouse, Rogan, and Prill (1984)	24	24	0.78
	16	16	0.59
	16	16	0.93
Somberg and Salthouse (1982)	16	16	0.25
	16	16	0.50
Talland (1966)	35	36	0.88
	35	36	1.10
Teece (1982)	38	23	0.62
Wickens, Braune, and Stokes (1987)	10	10	0.37
Wright (1981)	12	·12	0.81

Thus, based on the meta-analysis reported, and Hartley's thorough review, it seems likely that generally, older adults are not unduly disadvantaged when a secondary task is added to a situation.

Aging, Dual Task Performance, and Driving. Because of the particular concerns about aging and dual-task performance that occur in the context of driving, there are actually a number of studies on this topic. This is the only area in the literature on driving and cognition where there are more than two or three studies. The results of a meta-analysis of four of the five studies is presented in table 12, following a review of the individual studies.

Ponds, Brouwer, and Van Wolffelaar (1988) used a tracking task as a primary task in a laboratory setting. They likened the tracking task to steering an automobile. Performance was measured on the primary task and then a secondary task was added. In this case, it was a dot-counting task that required subjects to determine whether there were exactly nine dots in an array. This is a task that probably places a moderate demand on working memory capacity, as the quantity of dots is sufficient that active processing would be required to answer correctly. The relative emphasis the subject was to place on tracking vs. dot-counting was varied across blocks. Using single task performance as a covariate, Ponds et al. (1988)

reported an age effect for divided attention, indicating that the cost of dividing attention was greater for older adults compared to younger adults. This primarily occurred due to the substantially greater decline on the tracking task of old subjects when performing the dot task. Ponds et al. (1988) determined that this finding suggested that older adults are particularly disadvantaged when they are required to use executive function in working memory to manage multiple tasks.

In a later study, Van Wolffelaar, Brouwer, and Rothengatter (1990) introduced the notion that performance breaks down under divided attention conditions when responses are both tapping into the same subsystem. They argue that when one response is vocal and the other manual, that there will be smaller costs than when the response modes are compatible, presumably because the tasks may draw upon different resource pools. They also suggest that maintaining some information visually on a screen that is necessary to make a response will limit costs of dual tasks, particularly for older adults. This is consonant with the Craik (1986) view of environmental support for declining cognitive resources, as the presence of the information at all times on the screen would support working memory. In their study, they presented subjects with a total of three tasks-the tracking (steering task), a second task which required subjects to monitor peripheral events in their visual field, much as in a driving situation, and a third task ("RTI"), which required the subject to perform the dot-counting task or a serial addition task, as described earlier. This third task was viewed as analogous to attending to route information and an in-vehicle navigational device. This may not be a very good analogy because an in-vehicle navigational system provides relevant information to the driver that supports some aspects of driving, whereas the RTI task in this experiment is an irrelevant, distracting task. In any case, the addition of the two tasks resulted in a substantial interaction of number of tasks with age, such that the older subjects were most disadvantaged on tracking relative to the younger subjects, when both additional tasks were being performed. On the peripheral task, age was not interactive for response time, but there was a dramatic increase in nonresponses for the older subjects when the third task was added. Similarly, more nonresponding of older adults occurred on the RTI task in the three task condition. In addition, older drivers rated the multiple task conditions as more effortful than younger adult drivers, a rating that mirrors their actual performance. Van Wolffelaar et al. (1990) concluded that there is a disproportionately greater problem for older adults in divided attention situations. and directly link this to a higher accident rate for older adults in time-pressured, complex traffic situations.

Brouwer, Waterink, Van Wolffelaar, and Rothengatter (1991) conducted another tracking study with visual analysis of dots as the secondary task. In this case, however, they varied the response requirements for the secondary task. Subjects either responded with a button press or a vocal response. The main new finding from this study was that for tracking, older adults were more disadvantaged when the response was manual than when it was vocal. For the dot-counting task, although older adults made more errors, there was no evidence that older adults were unduly disadvantaged in their error rates relative to younger adults when the second task was added. Thus, the cost appeared to be solely on the tracking task. Brouwer et al. (1991) argue that difficulties in response integration in divided attention account for the findings, particularly because of the conflict the manual responding created with the manual task of tracking or steering for the older subjects.

Korteling (1992) conducted an interesting study where he examined both automatized and controlled aspects of driving behavior in a simulator. The automatic behavior was steering, and the controlled behavior was maintaining an appropriate following distance. He also examined the novelty of the following task by varying whether the brake in the simulator was inverted, so that pushing it resulted in acceleration and releasing it was equivalent to braking. There were no age effects on the steering task in single-task performance, providing evidence for automaticity. There was, however, an age-by-novelty interaction for the car-following task, with older adults showing particular difficulty in the inverted pedal condition. In the dual-task conditions, steering performance deteriorated substantially when subjects were required to perform the car-following task with the novel brake pedal. On the car-following tasks, both groups were similarly affected by the dual-task condition. Korteling (1992) suggested that these findings provide evidence that automatic tasks can be disrupted by dual tasks that have not been highly practiced (as in the inverted pedal condition). He suggests that in demanding situations, subjects will sacrifice automatic performance and give a higher priority to controlled processes. Korteling (1992) argues that the problems older drivers encounter are not due to the highly-practiced responses associated with driving the car, but with handling the vehicle in unfamiliar situations or when driving a new car.

Finally, Crook, West, and Larrabee (1993) conducted a study where they measured subjects' reaction times in a simulated driving task, where computer keys acted as an accelerator and as a brake pedal, for a traffic scene depicted on a computer monitor. The secondary task was information about weather and traffic that the subjects were to remember. Crook et al. (1993) reported that costs of the dual task situation were higher for older adults for lift time (removing finger from key) but not travel time (moving finger over to the other key), so the results of this divided attention situation is equivocal.

Meta-Analysis and Driving Simulations of Divided Attention. Because the results presented above are somewhat mixed with respect to the costs of a secondary controlled processing task on the primary task of steering or tracking, a meta-analysis was conducted that combined the results of four different studies that were found to be suitable for meta-analysis. Table 12 presents the studies that were included and the nature of the primary and secondary tasks. In every case, the primary task was an automatized tracking task that simulated steering, and the secondary task was a controlled processing task that involved dot counting in a visual display or maintaining a following distance via a computer simulation. Thus, both the primary and secondary tasks were sufficiently homogeneous that a me&analysis of these results was quite appropriate. The issue that the meta-analysis addressed was whether the pooling of the difference scores across the divided attention studies shown in table 12 resulted in a significant difference. The results of the meta-analysis, using procedures outlined by Mullen (1989) and Mullen and Rosenthal (1985) are presented in table 13.

Table 12. Summary of studies included in meta-analysis.

Study	Driving/Primary Task	Secondary Task
Brouwer, Waterink, Van Wolffelaar, and Rothengatter (1991)	Tracking (steering simulation)	Visual display (dot counting)
Kortelling (1992)	Tracking (computer steering simulation)	Car following (computer simulation)
Ponds, Brouwer, and Van Wolffelaar (1988)	Tracking (computer steering simulation)	Visual display (dot counting)
Van Wolffelaar, Brouwer, and Rothengatter (1990)	Tracking (computer steering simulation)	Visual display* (dot counting)

* Note: three tasks were utilized, but this analysis focused only on the results for the dual task conditions.

As can be seen in table 13, the results of the meta-analysis yielded an overall *z* of 5.93, a value that is highly significant, beyond the 0.0001 level. A fail safe number was calculated which is an estimate of the number of additional studies that would need to be conducted for the results to become nonsignificant, and that value was estimated to be 47.93 studies. Thus, the meta-analysis leaves little doubt that older adults are more disadvantaged in dual-task situations when compared to the costs evidenced by young adults.

Table 13. Results of me&analysis: are there larger costs of divided attention in a driving simulation for older adults?

Study	F (df)	N	Associated Z
Brouwer, Waterink, Van Wolffelaar, and Rothengatter (1991)	6.77 (1,20)*	24	2.384
Kortelling (1992)	1.40 (1,20)***	24	1.149
Ponds, Brouwer, and Van Wolffelaar (1988)	19.07 (1,56)**	57	4.033
Van Wolffelaar, Brouwer, and Rothengatter (1990)	22.92 (1,48)**	48	2.489

* Significant at 0.05 level

** Significant at 0.001 level

*** Study only reported *p* (0.20 level), F is estimated

Cognitive Processes in Wayfinding: Use of Vehicle Displays and Navigational Devices

There is growing interest in the effect of electronic navigational devices and in-vehicle signing on driving behavior. It is becoming feasible and cost-effective to outfit automobiles with in-vehicle electronic displays that provide the driver with varying degrees of information for wayfinding, as well as for traffic management. Such navigational aids can be viewed as a type of cognitive/environmental support for providing route information and relieving the cognitive burden of wayfinding. On the other hand, there is concern that these devices require that visual attention be redirected inside the vehicle, and this may have a negative effect on driving behaviors (Noy, 1990). There are several studies that have examined the effects of in-vehicle navigational devices on various aspects of driving and attention.

General Findings. Labiale (1989) presented subjects with in-vehicle navigational aids that were visual in nature, but had either written or auditory supplemental information. Subjects drove in a low-traffic area, and were required to wayfind using these devices. Labiale (1989) reported that written guidance devices resulted in better memory for the route information than devices with auditory cues. He makes the point that the auditory information could not be maintained or referred to, whereas the visual information was available to the subject to check frequently. Essentially, Labiale (1989) is suggesting that the visual devices provided more environmental support for cognitive processing of the route information necessary to drive. He did note that subjects decreased driving speed while using the devices, but did not measure actual driving behaviors. Thus, this study demonstrates that the visual displays are superior with respect to supporting subjects' cognitive processes due to their ongoing availability, but it is not known from this study how much time was spent gazing at the display, and how much such visual displays detract from attention to driving. It is possible that despite their superiority for providing information to the subject, visual displays drain sufficient attention away from driving, such that auditory systems may prove to be better systems, as they do not conflict with visual processing.

Noy (1990) examined subjects' attentional processes while they were in a driving simulator with an in-vehicle navigational display. He found that subjects spent as much as 50 percent of their time looking at the displays. He was able to demonstrate that the total cognitive workload in a driving task (estimated by difficulty of driving situation and use of navigational devices) had a negative effect on attentional measures in the simulator, but he did not find that cognitive load had an effect on driving. It appears that in most cases, driving may not be such a cognitively-demanding task; even when cognitive resources are drained or used by other tasks, driving performance can still be maintained by younger adults. However, given the cognitive resource limitations of older adults, the same may not be true. It is particularly important, therefore, to examine the usefulness of these devices for older subjects.

Schraagen (1990) examined strategies for wayfinding with maps in an actual driving situation, although he did not study in-vehicle displays. He found that individuals who used street names as their primary strategy for wayfinding were inferior in their abilities, compared to those who used landmarks and road signs. Although women were inferior to men in their wayfinding abilities, this variance was almost entirely explained by their reliance on street signs as their basic strategy. Schraagen (1990) also reported that subjects who received maps with stickers that showed road signs at various critical crossings, performed better. He suggests that road signage may be somewhat unique to particular locations and that use of signage as a wayfinding cue may be an efficient and specific way to provide subjects with additional information that will aid them in wayfinding.

Much work remains to be done on the interaction of in-vehicle display systems with cognitive capabilities and driving performance. The important issue would appear to be how much attention the in-vehicle displays take away from driving performance through diverting attention, and how this affects driving behavior. Of equal importance, is determining what display format is most effective in presenting information so that it can be processed most efficiently and with minimal resource demand.

Aging and In-Vehicle Displays. There are two issues that will be considered. The first will focus on the effect of in-vehicle navigation systems and how older adults utilize these systems. The second issue will be how in-vehicle displays of all types can be designed so that older adults can process the information from the displays most efficiently.

McKnight and McKnight (1992) used a video-based driving simulator to measure driver performance as a function of five types of different navigational displays. They studied young, middle-aged, and older adults. Caution should be used in interpreting their data, however, as their aged sample was adults over the age of 50, with no information provided about the mean age or the distribution of ages within this category. Thus, the subjects described as “old” in this study are almost certainly considerably younger than those included in other studies of aging and driving, as reported earlier. McKnight and McKnight (1992) reported that the most effective system was one that they called the “position-guidance display.” The position-guidance display provided subjects with a simple strip map to give them a sense of where they were, but at the same time had a large arrow on the screen that directed the subject to either continue heading straight or make a turn. A simple audio beep alerted the subject when the arrow changed, signaling the subject to attend to the navigational aid. This system requires minimal attention with respect to navigation decisions, but also provides the subject with information about where he/she is located in a macro-spatial environment, if interested. Neither maps alone nor the guidance system alone were as effective as this system. Of particular interest was the finding that the older adults responded like younger adults to the five types of navigational systems. Overall, they had higher error rates in anticipating turns, despite the fact that they looked for longer periods at the displays, but there was no age interaction with display type. Thus, this initial study provides some evidence that older adults do take more time to process the display information and that, despite this, they continue to have a higher rate of errors. It should be noted, however, that subjects of all ages responded adequately to hazards and driving situations.

The McKnight and McKnight (1992) study, along with the other on navigational aids, suggest that the displays appear to require some cognitive capacity, but do not affect driving behavior. The reason for this may be that driving typically does not require a high degree of sustained attention at all times. Moreover, the navigational systems have typically been tested in less demanding rather than more demanding driving situations. Drivers may be allocating more attention to the displays when there are low resource demands from the driving context and less attention to them when the contextual demands of the driving situation increase.

Other studies evaluating aging and in-vehicle displays have focused on how to effectively present information on gauges and controls inside the car. Laux and Mayer (1991) examined where younger and older adults expected to find displays (e.g., gas gauge, oil pressure) and controls (windshield wipers, hazard lights, etc.), and then measured how long it actually took them to locate these items in three different vehicles. They reported that older and younger adults had similar schemata for where they expected to find these items, but that older adults took substantially longer to locate them in a vehicle. They noted that when controls were in an "expected" location, both older and younger subjects were much quicker at locating them.

In a later study, Mayer and Laux (1992) measured the most effective format for presenting information about oil pressure, present fuel supply, and engine temperature on instrument panels. Subjects performed a tracking task on a computer, and concurrently monitored a range of vehicle displays to which they were to make a response when a critical value was reached. Mayer and Laux (1992) reported that older adults were slower to respond to the displays. Both age groups found a binary display the easiest to monitor. A binary display refers to a display where the subject is presented with information about one of two states (e.g., engine is at a normal temperature vs. engine is hot-a response from the driver is needed). No other display emerged as superior. Various formats for presentation of information in bar graph and analog modalities were roughly comparable. Both age groups responded more effectively when dynamic color was added to the displays. Dynamic color refers to aspects of the display changing, in this case, to red, when a critical value is reached on the monitor. In general, the findings of Mayer and Laux (1992) suggest that old and young respond similarly to aspects of display design, and that features which improve older adults' responses to the displays also improve young adults' responses.

Cognitive Models of Driving Behavior

One limitation of the discussion of driver age differences in memory and cognition, up to this point, is that hypotheses about causes of age-related deficits in driving behaviors have been considered in an independent and serial fashion. The reality is that the deficits in reaction time, selective attention, and divided attention are not independent of one another, and that more than one of these mechanisms is likely acting to reduce driving efficiency in the older adult. Moreover, the issue of sensory deficits and its relationship to driving must also be considered. It seems unquestionable that sensory dysfunction plays a role in the high accident rates of older individuals, given the magnitude of the sensory declines that occur with normal aging. Furthermore, the work of Lindenberger and Baltes (1994) discussed earlier suggests that sensory and cognitive decline are linked and mediated by a global neurophysiological mechanism controlling deterioration of the nervous system. Thus, it becomes important to examine how these different mechanisms might work together and interact with one another to contribute to driving problems in older adults.

One relatively new statistical technique that permits the simultaneous evaluation of both conflicting and complementary theoretical positions is the use of structural equation modeling procedures using a LISREL program developed by Joreskog (1993). Structural equation modeling is ideally suited to determining how different individual difference variables or constructs predict driving behavior. An example of a proposed model appears in figure 1. In this model, the behavior to be predicted is a global measure of driving efficiency (accident rates could be substituted, but due to the limited variability in this measure, the use of driving data would be more appropriate). In this model, it is hypothesized that the effects of age on driving are indirect, that is, the effects of age are mediated by declines in sensory function and speed. Both of these variables then directly predict a certain amount of the variance in driving behavior. If actual structural equation models had been constructed, the strength of the paths to driving efficiency would be available, so the exact quantitative nature of the relationship could be specified.

Note that sensory function is viewed as the most fundamental component in the model. Based on the data generated by Lindenberger and Baltes (1994), one would expect the age-related variance in speed to be mediated through sensory function. Similarly, we know that speed mediates the variance in working memory, but one would also expect that working memory capacity would contribute directly to driving function, and this is also illustrated in figure 1. Selective attention is viewed as a component process of working memory in this model, so it operates through working memory. It is important to note that this model can accommodate the importance of familiarity and contextual demands. The model represented in figure 1 is hypothetical; however, it illustrates the richness of the structural equation modeling approach, and depicts the interrelationships among different constructs and the role they play in explaining driving behavior.

Figure 1 represents a complex model, but driving is a complex behavior. To test the model would require that 200 to 300 people in an age stratified sample be tested, with over-sampling of individuals ages 65 to 74, and 75 and older. Multiple measures of sensory function, working memory, speed, and selective attention would need to be obtained, so that measurement of the behavior at the level of a construct would occur. It is also recommended that subjects' driving behavior be tested in familiar and unfamiliar locations under different conditions of contextual demand. This would permit different models of behavior to be developed for high demand and low demand situations. Figure 1 represents driving in a complex, demanding situation. Figure 2, in contrast, represents a potential model for low traffic volume in highly familiar situations. This model would be constructed from the data collected in the low volume, familiar situation. In this model, it is hypothesized that the automatized, expert qualities of driving would lead to adequate performance and that cognitive variables would not predict driving behavior. Rather, the prediction is that any age-related variance in the behavior would be explained solely by sensory variables, because the task would not be demanding enough for cognitive function to play a role.

It should also be noted that an additional strength of the structural equation modeling techniques is that precise dependent measures could be constructed and used as outcome measures in the model. For example, if one were interested in determining what sensory/cognitive variables predicted left-turn errors, in contrast to erratic steering, different models could be constructed for each variable.

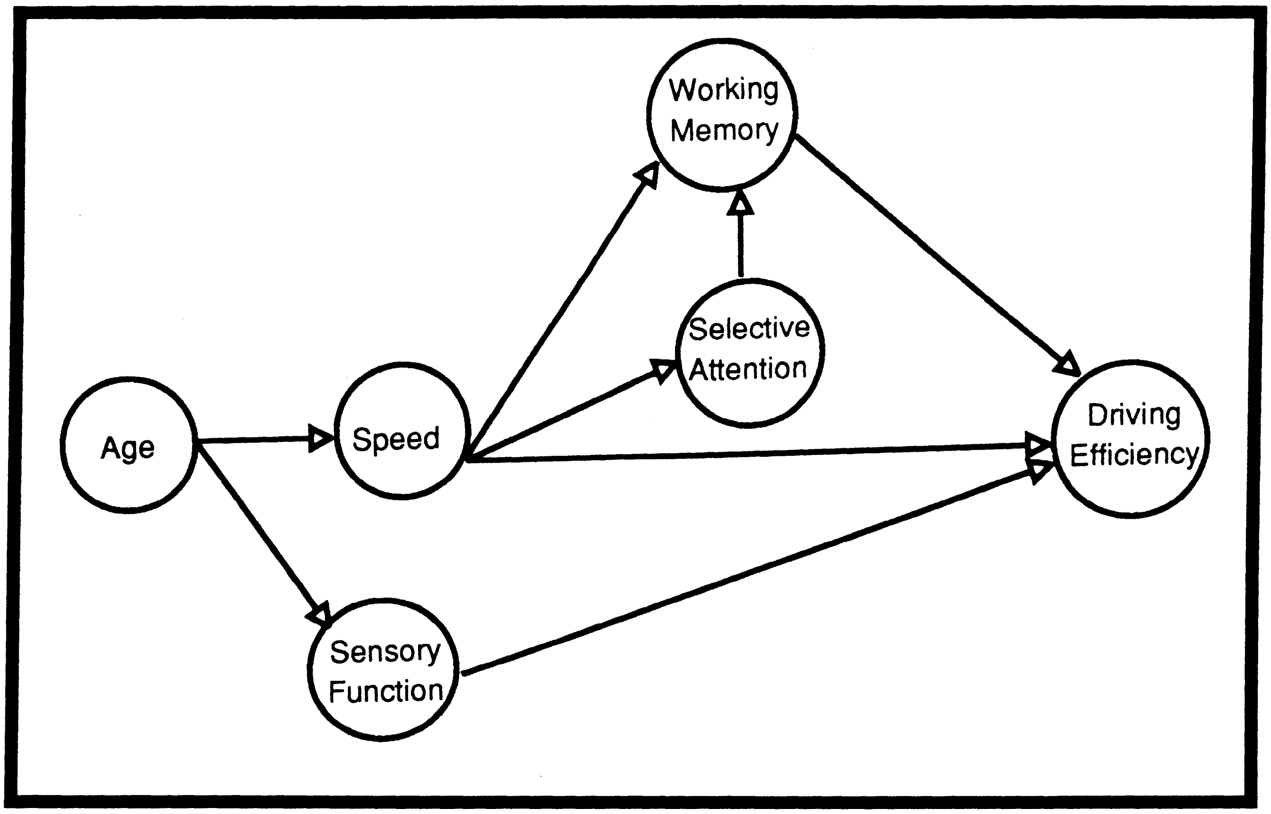

Figure 1. A hypothesized conceptual model relating age, sensory function, speed, working memory, and selective attention to driving efficiency.
[Note: This model assumes relatively high contextual demand in driving conditions.]

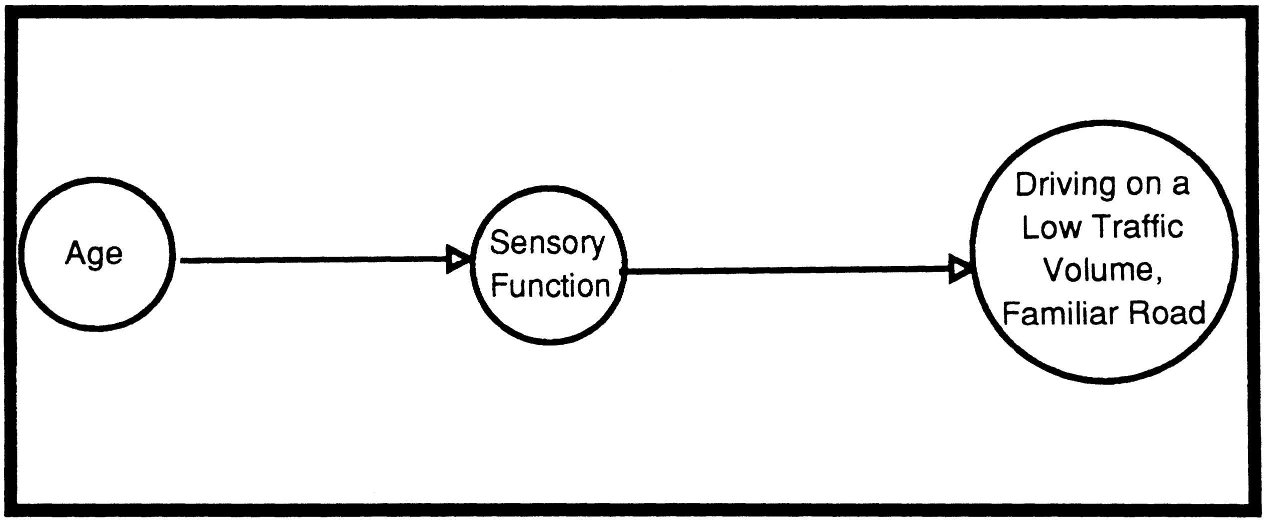

Figure 2. A hypothesized conceptual model for a low-effort driving behavior.
[Note: All age-related variance is hypothesized to be due to sensory function rather than cognitive function.]

Figure 3 represents a hypothesized model for left-turn errors, suggesting that these are caused primarily by sensory variables, speed of responding, and selective attention. Working memory is not hypothesized to play a role, because the driver is typically stopped at the intersection and has time to process all of the information before making a decision to turn. Accident data could be obtained from the subjects. It would be of particular importance in the proposed research to over-sample the elderly and to be certain that a substantial number of subjects over the age of 75 were included. It is clear that cognitive decline is most pronounced in the very old and this is also the group with the highest accident rate. It is essential that sufficient numbers of subjects in this category be tested if the relationship between cognitive function and driving is to be disentangled.

This brief discussion should illustrate the richness of the proposed approach and how, with sufficient sample sizes, an enormous amount of information could be obtained about the mechanisms underlying poorer driving behavior in older adults. Although considerable effort and resources have been directed to understanding driving behavior, virtually every study to date suffers from one of two fatal flaws. First, in cases where large samples of subjects are available, there is typically no data or poor data on cognitive function. Second, the behavior to be predicted is accident data, which is a variable that has insufficient variance to capture the relationships of interest. In the group of studies that utilize simulators, there is a great deal of attention paid to developing adequate simulations and collecting sensitive dependent measures, but typically, extremely small numbers of subjects have been available for testing. There are no studies at this time that simultaneously evaluate the role of sensory function and cognitive function with large samples using sensitive dependent measures.

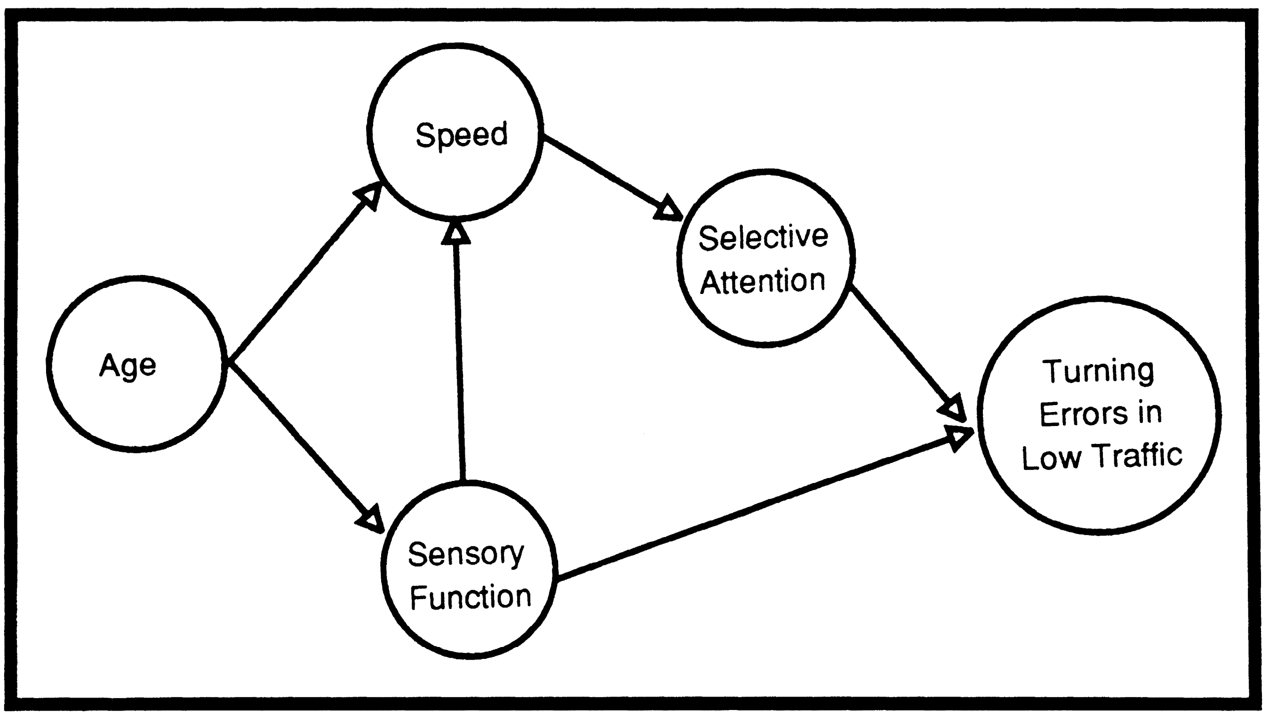

Figure 3. A hypothesized conceptual model that suggests that age-related variance in left-turn errors could be predicted from measures of speed, sensory function, and selective attention.

In the long run, it would be cost-effective to mount such a study. If investigators knew the variables that proved to be powerful predictors, more precise and smaller-scale laboratory research could be conducted in tandem with large-scale population studies. It is only with this type of commitment that a clearer understanding of the role that sensory and cognitive function plays in driving behavior in late life will emerge.

DRIVER AGE DIFFERENCES IN PHYSICAL CAPABILITIES

The physical capabilities (motor functions) needed for driving include: strength; range of motion of extremities; trunk and neck mobility; and proprioception. With the exception of proprioception - the ability of the kinesthetic receptors to determine where one's limbs are at any given moment, resulting in the coordination of movement-it has been well established that physical capabilities decline as a function of age and also as a function of general health. Aging (as well as disease and disuse) brings about changes in the components and structure of the articular cartilage-cartilage near the joints-underlying bones, ligaments and muscles. These changes impair the capability of the musculoskeletal system to perform the driving act. While there is evidence that older individuals have diminished psychomotor abilities (such as visual tracking, bodily flexibility, stability and balance, coordination, strength, reaction force and speed) necessary for the driving task, the extent to which *specific* declines impair driving performance is debatable (Marottoli and Drickamer, 1993; Janke, 1994).

National estimates of the prevalence of age-associated functional impairments for mobility are available from studies such as the National Health Interview Survey (National Center for Health Statistics, 1991), which reported that 4 to 8 percent of persons ages 65 and older have some level of mobility impairment. A self-reported functional impairment study of people ages 65 and older in rural Iowa, found that 13.6 and 17.4 percent of men and women, respectively, reported some level of upper limb flexibility impairment; and 30.2 and 43.4 percent of men and women, respectively, reported having some level of lower limb flexibility impairment (National Institute on Aging, 1986). In a survey of the problems of the elderly by Yee (1985), 21 percent of the older drivers reported difficulty in turning their heads and looking to the rear whendriving. The survey also revealed that 35 percent of the older drivers reported problems with arthritis. In terms of surgical procedures, 19 percent reported having a joint surgically repaired or replaced; 3 percent have had their knee joint repaired or replaced; 3 percent their hip joint; and 3 percent their fingers. In addition, 17 percent stated that painful or stiff joints have interfered, to some extent, with their ability to drive. Because of weak, painful or stiff lower extremity joints, 7 percent of the respondents required a vehicle equipped with automatic transmission; 9 percent needed a vehicle with power steering because of these same difficulties. In addition, 44 percent reported that they had some degree of difficulty getting into and out of vehicles.

In the last 30 to 40 years, there has been an abundance of research in the medical literature that has addressed diminished psychomotor abilities related to the aging process. However, it has only been within the last 15 years that research has begun to examine the relationship between the physical factors related to aging and their effects on driving performance. This section discusses older drivers' psychomotor performance in the areas of reaction time related to movement; strength; range of motion of extremities; and trunk and neck mobility.

Reaction Time Related to Movement

There is nearly uniform agreement among researchers that reaction time (speed) decreases with age, although central-processing changes, as opposed to sensory or motor components, appear to be the major contributor to the slowing. Studies have demonstrated a significant and disproportionate slowing of response for older adults versus young and middle-aged adults, as uncertainty level increases for response preparation tasks. Preparatory intervals and length of precue viewing times appear to be crucial determinants of age-related differences in movement preparation and planning. When older adults are permitted to have longer stimulus exposures and longer interstimulus intervals, they exhibit less slowing of movement (Eisdorfer, 1975; Stelmach, Goggin, and Garcia-Colera, 1987; Goggin, Stelmach, and Amrhein, 1989).

The picture is relatively straightforward for movement execution factors (apart from the issues of response selection, programming, and preparedness) contributing to response slowing in older adults. It has been concluded that movement time-the interval between the initiation of movement and its completion-is significantly slower among older adults than among younger adults. These age-related motor impairments can be linked to decreases in muscle mass and elasticity, arthritic joints, decreases in bone mass, and a deterioration in neural networks (Welford, 1982; 1984). In addition, muscular atrophy and related neural losses during aging disproportionately affect the ability to control movement rapidly and accurately (Larsson, Grimby, and Karlson, 1979). Researchers have also reported findings that show that movement corrections during movement execution are slower and much less efficient (Goggin and Stelmach, 1990). In addition, the synchronous activation of muscles on one side of the body versus the other, as well as the inhibition of inappropriate postural responses, has been shown to be more difficult for older than for younger adults (Stelmach, Phillips, DiFabio, and Teasdale (1989).

Researchers have also investigated limb movement. Early studies that have measured ballistic movement times have shown that older people require 20 to 90 percent more limb movement time than younger people (Szafran, 1952; Singleton, 1955).

There have also been studies on hand movement and coordination. An early study evaluated hand movement response to a four-choice stimulus, to identify the age-related differences in hand movement patterns (Murrell and Entwistle, 1960). They found significant differences in response initiation conditions relating to the magnitude of the initial acceleration and the depth of the deceleration movement between the younger subjects (ages 20 to 25) and the older subjects (ages 60 to 65). A much more recent study by Stelmach, Amrhein, and Goggin (1988) evaluated bimanual coordination to determine whether or not older individuals have difficulty in coordinating two hands in simple motor acts. Older individuals demonstrated differentially greater performance deficits as task complexity increased. Thus, the reaction time and motor time results taken together suggest that the locus of differential aging effects in bimanual coordination at the task level, beyond simple overall latency increase, is in the control of movement execution, rather than in movement preparation. Older individuals were much poorer in compensating bimanual movements compared to the younger individuals. The older group was not as sensitive to the influence of task complexity on compensation as was the younger group. Their study suggested that there are specific aging deficits for movement processes in unimanual and bimanual tasks. These include: poorer preparation of short movements relative to long movements, regardless of task complexity; lessened ability to yoke initiation of bimanual activity; and at a more complex level of motor control, poorer ability to compensate for movement initiation asynchrony so as to terminate movement in a near simultaneous manner, reportedly found in young individuals.

Regarding the possible effect on actual driving performance of known declines in motor ability and reaction speed, the picture needs further clarification. Studies have reported a relationship between longer response time, e.g., depressing the brake pedal in response to a hazard (Olson and Sivak, 1986), or upon seeing a target stimulus (Barrett et al., 1977) for older drivers than for younger ones, in real and simulated driving environments; however, the operational significance of age differences with respect to highway safety cannot be established from these data. Detailed comparisons of motor abilities and driving performances necessary for such conclusions have not been accomplished, nor have reliable and accurate measures of the parameters involved been developed (Marottoli and Drickamer, 1993; Janke, 1994).

Strength

Decreases in muscle strength are due primarily to decreases in total muscle mass, decreases in the number and size or muscle fibers, and a reduction in biochemical activity within the body. While literature in the medical field has reported on the effects of aging and disease on strength, very little research has seriously addressed the relationship of strength (and tests of strength and levels of physical function) and older driver performance. In the 1960s, the United States Public Health Services provided guidelines regarding musculoskeletal ability and driving. The guidelines indicated that to operate a private vehicle, a driver should have at least normal strength in the right lower extremity and both upper extremities, i.e., the muscle should hold the joint against a combination of gravity and moderate resistance (Stock et al., 1970). Gurgold and Harden (1978) assessed the driving potential of persons with disabilities, and reported that a 3.15 kg (7 lb) tangential force is needed for steering, and 60 lbs of force for braking. Many of today’s vehicles have power steering and anti-lock braking systems, suggesting that earlier recommendations may be too conservative.

Studies have evaluated the grip strength required for steering wheel control. A hand dynamometer is used to measure grip strength for each hand. The strength of other muscle groups is similarly assessed by working against a source of resistance such as weights. Strength can also be assessed by manual muscle testing using the Medical Research Council scale (Marottoli and Drickamer, 1993). Retchin, Cox, Fox, and Irwin (1988) examined the grip strength in both the dominant and nondominant hands of over 100 frequent and infrequent male drivers who were age 65 years and older. They found that the strength of the nondominant hand was significantly and positively associated with driving frequency, or continuation of driving by older individuals; that is, the weaker the nondominant hand, the less likely the older individuals were driving.

Flexibility and Range of Motion of Extremities

There is no evidence that age alone is the sole determinant for the declines seen in flexibility and range of motion, since most research links degenerative disease and disuse with loss of flexibility (Adrian, 1981). It is estimated that joint flexibility declines on the average of 20 to 30 percent in the older adult. Decreased flexibility with age is probably the result of combined histological and morphological changes in the components of the joint, including cartilage, ligaments, and tendons (Adrian, 1981; Serfass, 1980). The greater calcification of cartilage and surrounding tissue, the shortening of muscles, increased tension and anxiety, and the prevalence of arthritic and other orthopedic conditions all contribute to reduced flexibility (Piscopo, 1981). Changes in joints and tendons may adversely affect the flexibility and stability of joints. Studies that have made assessments of flexibility in older persons generally support the conclusion of a decline in flexibility in the middle and later years (Walker, Miles-Elkousy, Ford, and Trevelyan, 1984). Motion perception in the lower extremities, metatarsophalangeal joints (those between the toe and ankle bones), decline with age as well (Kokmen, Bossemeyer, and Williams, 1978). It has also been reported that over 50 percent of people over the age of 65 have osteoarthritis in at least one joint.

Joint flexibility is an essential component of driving skill. If upper extremity range of movement is impaired in the older driver, mobility and coordination may be seriously weakened. Older drivers with some upper extremity dysfunction may not be able to steer effectively with both hands gripping the steering wheel rim. Upper extremity movements required for hand control and steering control operation, include shoulder abduction, flexion, extension, internal rotation, external rotation, circumduction, and forearm flexion, extension, supination, and pronation (Gurgold and Harden, 1978).

Roberts and Roberts (1993) evaluated the effects of arthritis on the elderly driver. They reported that arthritis can result in several anatomical changes, including: cervical rotation; weak or painful wrist; painful proximal and distal interphalangeal joint (lower and upper finger area) or first carpalmetacarpal; pain or decreased range in knees or hips; ankle rigidity; pain in metatarsophalangeal joints; and single inflamed digits, either acute or subacute, in the hand or foot. Arthritic conditions can affect entering and exiting the vehicle, as well as positioning and comfort in the vehicle. The following driving tasks are affected: backing up, parking, turning, synergy with peripheral vision defects, turning wheel, gripping wheel, and difficulty stepping on brake. Cornwell (1988) reviewed several techniques used at a mobility center to assess arthritic drivers. The report assessed the type and level of difficulty arthritic drivers experienced, and provided recommendations for vehicle modifications. He reported that 29 percent of the arthritic drivers required power steering (i.e., they could not drive a manual shift) due to shoulder problems alone. Arthritic drivers were also lower in stature than the “able-bodied” population, leading to the recommendation for a seat raise for 30 percent of the arthritic group, and a forward seat tilt for 25 percent of the group. Side supports were recommended for 13 percent of the arthritic group, to reduce fatigue and increase comfort and stability. Many arthritic drivers were recommended to have nearside and offside mirrors together with panoramic rear view mirrors, to compensate for painful or restricted neck and trunk rotation. A steering wheel with a reduced diameter was recommended for one-third of the arthritic group, to accommodate restricted shoulder movement. Finally, almost 40 percent required servo-assistance to aid in braking.

Movement execution problems associated with age-related losses in flexibility may stem simply from an overall decline in physical fitness among older drivers, and are therefore amenable to remediation. McPherson, Ostrow, and Shaffron (1988) studied the relationship between physical fitness and older driver performance using a driving simulator, and measuring physical and psychomotor characteristics of the subjects. They found that older people had less shoulder flexibility and torso/neck rotation than did younger people. It was also found that among older people, those with less flexibility tended to have lower driving ability than those with more flexibility. The probable cause for the relation of flexibility to driving ability is that the safe operation of an automobile requires freedom of body motion. Restricted joint movement makes driving difficult for the older driver. Basic vehicle control and guidance, such as steering around a corner or observing behind before changing lanes, requires quick body movement and an ample range of joint motion. Using on-road measures, the researchers found that those older adults with less joint flexibility had poorer driving ability than did those with larger ranges of motion. Specifically, older drivers exhibited less range than their younger counterparts in shoulder, torso, and neck joints. The second phase of the study (McPherson, Ostrow, and Shaffron, 1989) found that information-processing speed and range of motion were both related to performance of older drivers. An experimental program to improve trunk rotation and shoulder flexibility; and to manage cognitive stress was successful in changing these attributes, but not in improving the handling skills of older drivers. The program was not successful in improving speed of information processing.

Head and Neck Mobility

With advancing age there is decreased head and neck mobility that adversely affects the older person’s ability to complete driving tasks. A restricted range of motion can reduce an older driver’s ability to operate an automobile, especially for effectively scanning directly and indirectly (mirrors) to the rear and sides of his/her vehicle to observe blind spots, as well as hindering timely recognition of conflicts during turning and merging maneuvers at intersections (Ostrow, Shaffron, and McPherson, 1992). Schroeder, Allen, and Ball (1973) found that restricting the head resulted in more driving errors and fewer long eye movements. They concluded that driving performance is better when drivers are able to move their eyes and head about in an unrestricted manner. Restricting the head may alter where a driver “looks” in the visual environment. Also, the frequency of how often individuals shift their fixations is negatively correlated with errors; that is, more eye movements are related to fewer driving errors.

Older driver limitations in head and neck movement have also been studied. Hauer (1988) reported that intersection angles of 75 degrees or less cause problems for older drivers, since this situation requires extensive head movement. Hunter-Zaworski (1990) studied the effect of restricted head and neck movement on driving performance, by measuring decision time at simulated T-intersections. A fixed-based driving simulator that incorporated video recordings of intersections (180 degree field of view) was used in the study. Subjects were between the ages of 30 and 50, or between the ages of 60 and 80; half in each group had a restricted range of neck movement, where neck impairment was defined as a combined static range of movement of the head, and visual field of less than 285 degrees. The subjects' task was to depress the brake pedal, watch the video presentations of the T-intersections on three screens, and release the brake pedal when it was safe to make a left turn. Results showed that decision time increases with age and level of neck impairment, indicating that younger drivers were able to compensate for their neck impairments, but older drivers both with and without neck impairments were unable to make these compensations in their driving performance. The researcher also noted that skewed intersections are hazardous for drivers with neck impairments.

DRIVER AGE DIFFERENCES IN MOTIVATION AND RISK/HAZARD PERCEPTION

Basic driving abilities are influenced to some degree by motivational characteristics, as well as situational influences of the driving environment. Therefore, during evaluation of driver behavior, not only must the functional abilities of the driver be taken into consideration, but compensatory behaviors, driving strategies, and various aspects of risk-taking must also be considered. Thus, the safety of a roadway is dependent on the driver's ability to perceive and evaluate hazards, and on the degree to which highway design features and operational characteristics conform to these driver perceptions. This section summarizes the current state of the knowledge pertaining to how motivational and situational influences affect driver perception of hazards, and identifies those driver characteristics-with a focus on age-that effect these perceptions. The text below may be referenced against the summary table (table 14) presented at the end of this section addressing driver age differences in motivation and risk/hazard perception.

Risk perception is often defined in terms of the perceived likelihood of a negative event combined with the perceived consequence of the event. It should be noted, however, that when evaluating risky behavior, one must look further than simply evaluating how an individual perceives hazardous situations. A person's acceptance of risk may not only be influenced by the perceived degree of risk, but also by other motives and influences, including personality factors and perceived benefits of the action. Such factors may include enjoying the sensation of speed, wanting to minimize trip time, or possibly not caring sufficiently about the consequences of an accident. Lerner (1988) distinguishes risk perception from risk-taking, noting that risk perception refers to a person's ability to perceive the potential for harm as a consequence of the action, while risk-taking refers to the individual's willingness to accept a certain potential for harm, whatever benefits result from the action.

The vast majority of research in the areas of driver risk perception and risk-taking has focused on younger drivers. Research shows that young drivers generally tend to underestimate the risk involved in certain driving situations, but overestimate their own driving ability. Simpson and Mayhew (1987) also note that the overinvolvement of young drivers in roadway crashes has been attributed to such factors as inexperience, less exposure to dangerous situations, and to a propensity towards risky driving, including speeding and driving while impaired.

Subjective Risk

To determine whether the high rates of traffic accidents among younger persons could be attributed to younger drivers perceiving driving to be less hazardous than older drivers, Finn and Bragg (1986) examined two groups of male drivers: 45 younger drivers ages 18 to 24, and 48 older drivers ages 38 to 50. Three off-road methods were used to compare risk estimates between the two groups: (1) general questionnaire about estimates of accident involvement; (2) rating the riskiness of 10 specific driving situations illustrated in still photographs; and (3) rating the riskiness of 15 videotaped driving situations. For the first method, interview questions indicated that 18- to 24-year-old males were judged by both younger and older drivers to be significantly more likely to be involved in an accident than all other categories of drivers. However, young male drivers perceived ***their own*** risk of accident involvement to be much lower than that of their male peers. Risk estimates for the still photographs of various driving situations (e.g., tailgating, driving at night, speeding, driving on snow-covered roads, driving after consuming six beers within 1 hour) supported questionnaire findings that younger drivers see their likelihood of accident involvement as lower than that of their peers. Additionally, younger drivers did not see their own risk as greater than that of older drivers in any of the situations presented. However, findings showed that older drivers saw younger drivers as significantly more likely to be involved in an accident than older drivers in 8 of the 10 situations presented. For the third method of the study-videotaped situations-only two sequences were rated significantly differently by young and older drivers: the tailgating sequence was rated as more dangerous by older drivers, and the pedestrian sequence was rated more dangerous by younger drivers.

Finn and Bragg (1986) note that these findings are not surprising, considering that the skill involved in avoiding an accident while tailgating is more likely to be indicative of skills assumed to be well-mastered by younger drivers. However, in the pedestrian sequence, the sudden emergence of the pedestrian in front of the driver results in the sense of the driver having less control of the situation. Therefore, younger drivers, who have relatively fewer years of exposure to such experiences, rated this sequence as more dangerous than did the older drivers. The findings of the Finn and Bragg study (summarized in table 14) suggest that the risk misperception of younger drivers may account for much of the disproportionate involvement of young male drivers in traffic accidents. Similar findings were found in a study by Sivak and Soler (1986), in which subjects from the United States and Spain who were ages 18 to 75 years old, were asked to rate risk of various driving situations depicted in slides. Findings showed that, for drivers in both countries, older drivers generally tended to rate traffic scenes as more risky than younger drivers.

In a more recent study, Jonah (1990) conducted a telephone survey in order to evaluate age differences in risky driving and risky non-driving behavior, and in accident and violation involvement. A total of 9,943 subjects, ranging in age from 16 to 69, were interviewed. Subjects were divided into six age categories: 16 to 19; 20 to 24; 25 to 34; 35 to 44; 45 to 64; and 65 to 69. The survey questionnaire included such items as: personal incidence of drinking and driving; riding with impaired drivers; perception of the amount of alcohol that can be consumed before being too impaired to drive; and perception of the likelihood of an impaired driver being cited with a violation. Additional questions included license suspensions, accident and violation involvement, illicit drug use, reasons for drinking alcohol, and frequency of seat belt use. Results showed that risky behavior peaked for both males and females ages 20 to 24, although the peak was not as pronounced for females (see figure 4). Also, the differences in risky behavior between males and females tended to decrease with age, beginning around age 25 to 34. A summary of the statistical findings is presented in table 14.

Another study has attempted to determine whether or not drivers with higher accident rates tend to have certain habits, values, and needs that put them at risk (West, French, and Elander, 1991). The researchers developed and administered two parallel questionnaires to each of 714 drivers: the decision making questionnaire (DMQ) and the driving style questionnaire (DSQ). On the decision making questionnaire, respondents were asked to report the frequency with which they make decisions in particular ways (e.g., ***Do you change your mind?, Do you take the safe option if there is one?, Do you rely on "gut feeling"?).*** In the driving style questionnaire, respondents reported on their own driving style (e.g., ***Do you exceed the 70 mi/h speed limit?, Do you drive cautiously?, Do you plan long journeys in advance?, Do you become flustered when faced with sudden dangers while driving?).*** Subjects responded to both questionnaires using a six-point scale ranging from "never or very infrequently" to "always or very frequently." Correlating DSQ scores and DMQ scores with accident rates showed a significant relationship between age and accident rates, although the relationship was not linear. Results showed a decreasing accident rate up to the age of 60, with an increasing rate for drivers beyond age 60. Additional analysis showed that, for drivers ages 60 and under, speed and age were found to be independent predictors of accident rates, while for drivers over age 60, thoroughness and hesitancy were independent predictors.

Four variables emerged as predictors of speed for drivers age 60 or under: thoroughness, age, gender, and mileage. Faster driving was associated with being younger, male, and having a higher annual mileage. Also, in drivers age 60 or under, accidents are associated directly with driving faster, and younger drivers are more likely to have road traffic accidents. For drivers ***over*** the age of 60, like their younger counterparts, faster drivers have more accidents. However, it was also found that older drivers are less thorough and more hesitant, when compared to younger drivers.

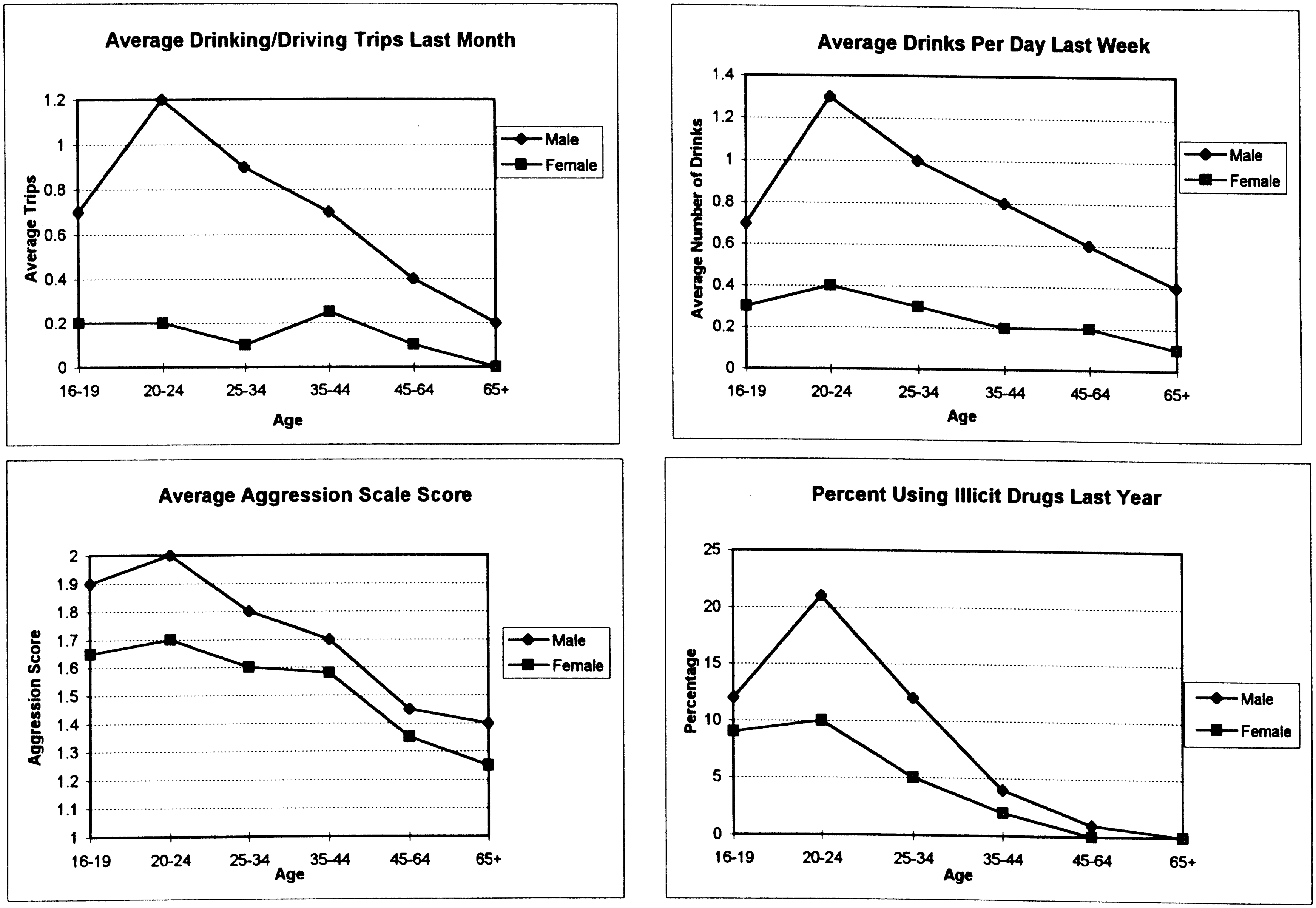

Figure 4. Age differences in risky behavior among males and females (from Jonah, 1990).

Overall, the results of this study indicate that accident rates are attributable, at least in part, to motivational factors. To further examine this, the authors carried out a followup study of a subsample from the original postal survey (n = 122). A variety of questionnaires were administered to obtain a measure of impatience (Bortner's Type A questionnaire), a sociopathy scale developed by the authors, and key questions from Zuckerman's sensation seeking scale. The scores from these questionnaires were correlated with thoroughness, speed, and accident rates from the previous surveys. Results indicate that type-A behavior was correlated significantly with speed (r=0.22, p=0.02). However, type-A behavior did not correlate significantly with thoroughness or accident rate. Sensation seeking also correlated with speed (r=. 17, p<.05), but not with thoroughness or accident rate. Sociopathy, on the other hand, correlated with speed (r=0.29), thoroughness (r=0.23), and accident rate (r=0.19). The authors suggest that it may be that these individuals are at higher risk of an accident because of the way they make decisions. On the other hand, it is also suggested that this may have more to do with the needs and values that go into those decisions. The statistical findings of these two studies are presented in table 14.

Objective Risk

Speed. Several studies have been conducted that have evaluated objective risk, as measured by driving speed, seat belt use, following headway, and minimum acceptable gap. Findings have repeatedly shown that excessive speed is common among young drivers (Galin, 1981; Shinar, McDonald, and Treat, 1978), and that younger drivers are more likely than older drivers to die in roll-over crashes, which are typically associated with high speed (Evans, 1991). The increased likelihood of young drivers driving at high speed may be attributed to the younger driver perceiving less risk for speeding than older drivers.

Seat Belt Use. Relatively consistent findings have also been found for seat belt use as a function of age. Seat belt use peaks for both males and females during the late 20's to mid-30's (see figure 5), with percent usage declining with age (Jonah, 1990; Evans and Wasielewski, 1983).

Headway. In another measure of objective risk, Evans and Wasielewski (1983) attempted to evaluate following headway-the time interval between successive vehicles in a lane-in high-flow, freely-moving freeway traffic. A total of 12,000 observations were made at 2 sites, 1 in Michigan and 1 in Toronto, Canada. A photographic technique was employed that allowed vehicle and occupant characteristics to be recorded, including type of vehicle, driver gender, seat belt use, and presence of passengers. Additional information regarding driver and vehicle characteristics was obtained from accessing the vehicle license number in State files. Information obtained included the owner's age, gender, and driving history, as well as the model year, mass, make, and style of the vehicle. When the owner age and gender from the State files matched the characteristics of the photographed driver, the owner was assumed to be the driver. Data was collected by photographing vehicles from an overpass.

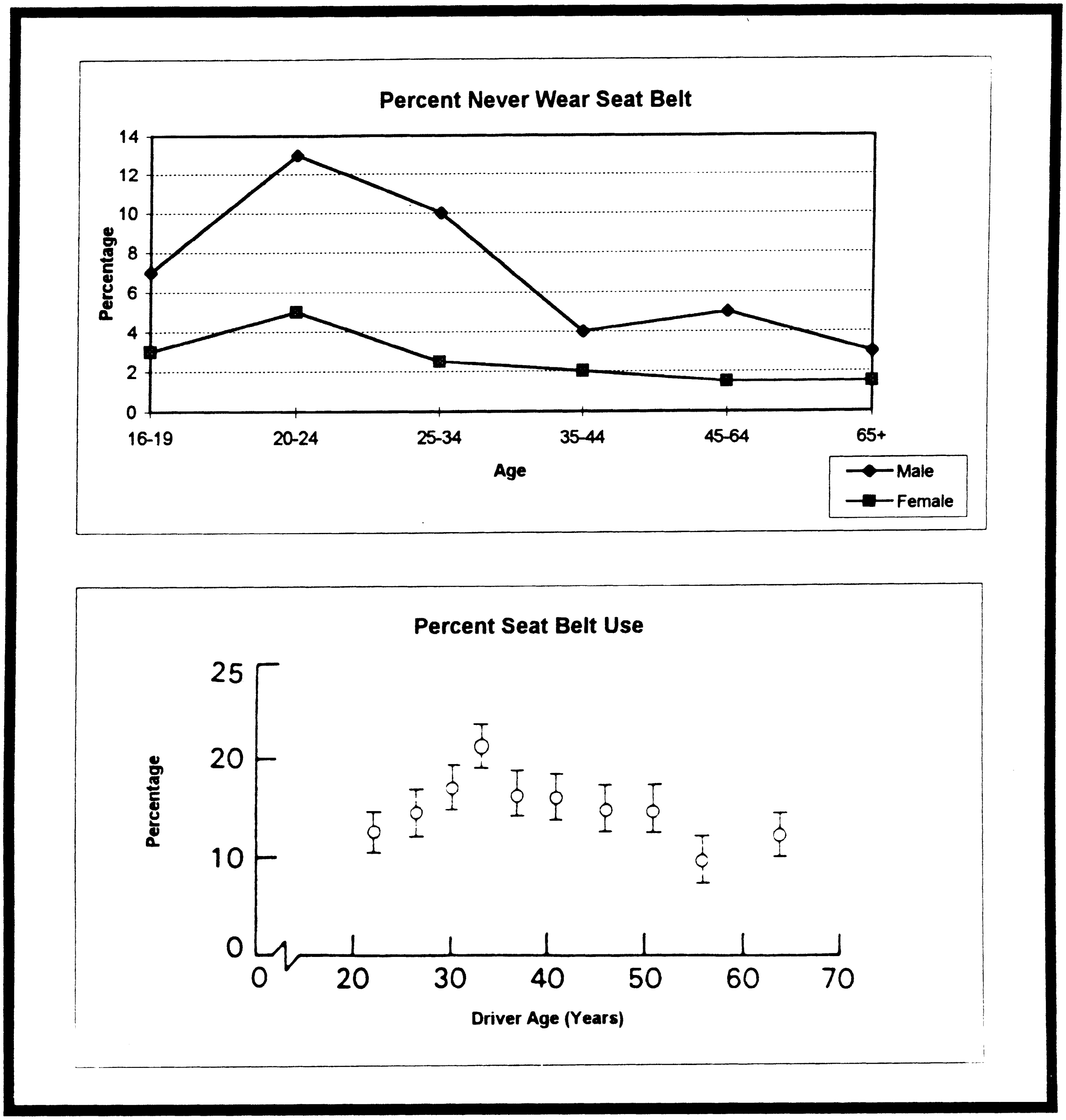

Figure 5. Percent seat belt use as a function of driver age and gender.
[Jonah, 1990 (n=9,943); Evans and Wasielewski, 1983 (n=2,552).]

The researchers concluded that following at a very short headway (i.e., less than 1 s) also appears to be indicative of a driver's willingness to accept risk (Evans and Wasielewski, 1983). Based on their analysis, they also note that measures of risk based on headway should be more sensitive to short headways than to long headways. In fact, the most effective measure in discriminating among driver groups was found to be the reciprocal of the headway. The researchers argue that the reciprocal headway is more sensitive to small headways, which are most indicative of risk, and less sensitive to larger headways, which may be unrelated to risk. A summary of the statistical findings is presented in table 14.

Findings of this study are consistent with other research, showing that when reciprocal headway is plotted as a function of driver age, younger drivers generally appear to take more risk (i.e., accept shorter headways). Additionally, females in all age groups are clearly underrepresented at the shortest, risky headways, but over-represented at more cautious headways of approximately 1.5 s. Also related to these findings, in an analysis of police-reported fatal accident records (1977 to 1986) and nonfatal multiple-vehicle accident records (1984 to 1986) in Pennsylvania, Staplin and Lyles (1991) found that younger drivers tend to be overrepresented in accidents involving improper car following (i.e., tailgating), careless lane changing, and careless passing.

Gap Acceptance Another common objective measure of risk-taking behavior is that of determining the minimum gap that a driver will accept in crossing or merging with traffic. In one such study, measures of risk were examined as a function of speed of the approaching main road vehicle and as a function of main road flow (Darzentas, McDowell, and Cooper, 1980). This study analyzes Hills' data regarding driver behavior when crossing a single lane of traffic at a T-junction. In Hills' study, subjects were asked to judge the last safe moment to cross the main road traffic stream. Subjects were not in vehicles, but were on the roadside, and they did not actually attempt to cross the main roadway. The speed of oncoming vehicles was also measured.

For purposes of analysis, subjects were divided into four groups: young males (YM: ages 31 to 40); old males (OM: ages 61 to 70); young females (YF: ages 31 to 40), and old females (OF: ages 61 to 70). Data showed that gap acceptance behavior was strongly dependent on the speed of approaching vehicles. For each class of driver, minimum acceptable gap (in seconds) was negatively correlated with the speed of the approaching main road vehicles (ft/s). Overall, females showed more conservative judgment than males (i.e., longer acceptable gaps) for all speed ranges. It should be noted that the slopes of the regression lines were significantly different from zero for all four groups. However, the slope of the OF group was much steeper than all other groups, indicating that the judgment of speed of the older females was appreciably worse than that of other classes of drivers. Males showed less variation in minimum acceptable gap than females in each age class. Additionally, younger drivers showed less variation than older drivers for each gender, although at the 5 percent level, the difference between younger and older males was not statistically significant. A summary of the statistical findings is presented in table 14.

Effects of Motivational and Situational Influences on Older Drivers

The effects of motivational and situational influences on older driver behavior have been studied very little, although some studies have focused on elderly pedestrian behavior (e.g., Harrell, 1990, 1991). The vast majority of research in this area has concentrated instead, on adolescent and young adult drivers. Even for those studies that show changes in driving behavior as a function of driver age, these changes can rarely be directly attributed simply to changes in motivational and situational influences. For instance, many studies have shown that driving speed decreases with driver age, and acceptable headways and gaps tend to increase with age. While motivational factors (e.g., sensation seeking, risk taking) have been shown to play a major role in influencing the higher speeds and shorter headways accepted by younger drivers, they seem to play a less important role in older driver behavior. Instead, the relatively slower speeds and longer headways and gaps accepted by older drivers have been attributed to their compensating for decrements in cognitive and sensory abilities (Case, Hulbert, and Beers, 1970; Planek and Overend, 1973).

Unfortunately, the empirical data that currently exists regarding motivational and situational influences on driver behavior does not lend itself well to meta-analysis techniques. Research is surprisingly weak, even for many basic areas of study, and there seems to be little agreement among researchers on the basic methodological issues of measurement. Subjective risk, for instance, has been particularly difficult to measure. However, there seems to be no better agreement among methods of measuring objective risk, which is the most basic measure of this type of research.

Relationship Between Risky Driving Behavior and Accidents

Studies show that drivers who exhibit riskier driving behaviors tend to have higher accident rates. Using headway as a measure of risk, Evans and Wasielewski (1982, 1983) found that for headways less than 1 s, there were more drivers with reported accidents and more drivers with violations than there were drivers who were accident- or violation-free. Also, for headways between 1 and 2 s, there were fewer drivers with reported accidents and fewer drivers with violations. Findings overall showed a general trend for the percent of drivers with accidents and/or violations to increase as headways decrease. Interestingly, further analysis showed that not only do drivers with some points on their driving record follow closer than drivers with no points, but that drivers with many points follow closer than those with fewer points. A summary of the statistical findings is presented in table 14.

Using a different objective measure of risk, Evans and Wasielewski (1983) evaluated seat belt use as a function of accident rate. As expected, the researchers found that for drivers with no accidents, seat belt use was relatively high (approaching 20 percent), with lower rates for drivers with one, two, or three accidents. Surprisingly, for drivers with four or more accidents, seat belt use was actually higher than the rate for those drivers with no accidents (approaching 25 percent). However, the authors caution against drawing strong conclusions from this finding, due to the small amount of data and the resulting statistical uncertainty.

Jonah (1990) evaluated age differences in risky driving and risky non-driving behavior and in accident and violation involvement. Results showed that accident rates and violation rates, controlling for distance traveled, generally decrease with age (see figure 6). Findings also indicate a direct relationship between risky behavior and accident and violation rates. Among the 9,943 subjects interviewed (between the ages of 16 and 69), those drivers between the ages of 16 to 24 were more likely to exhibit risky behavior and more likely to be involved in traffic accidents and have violations than older drivers. A summary of the statistical findings is presented in table 14.

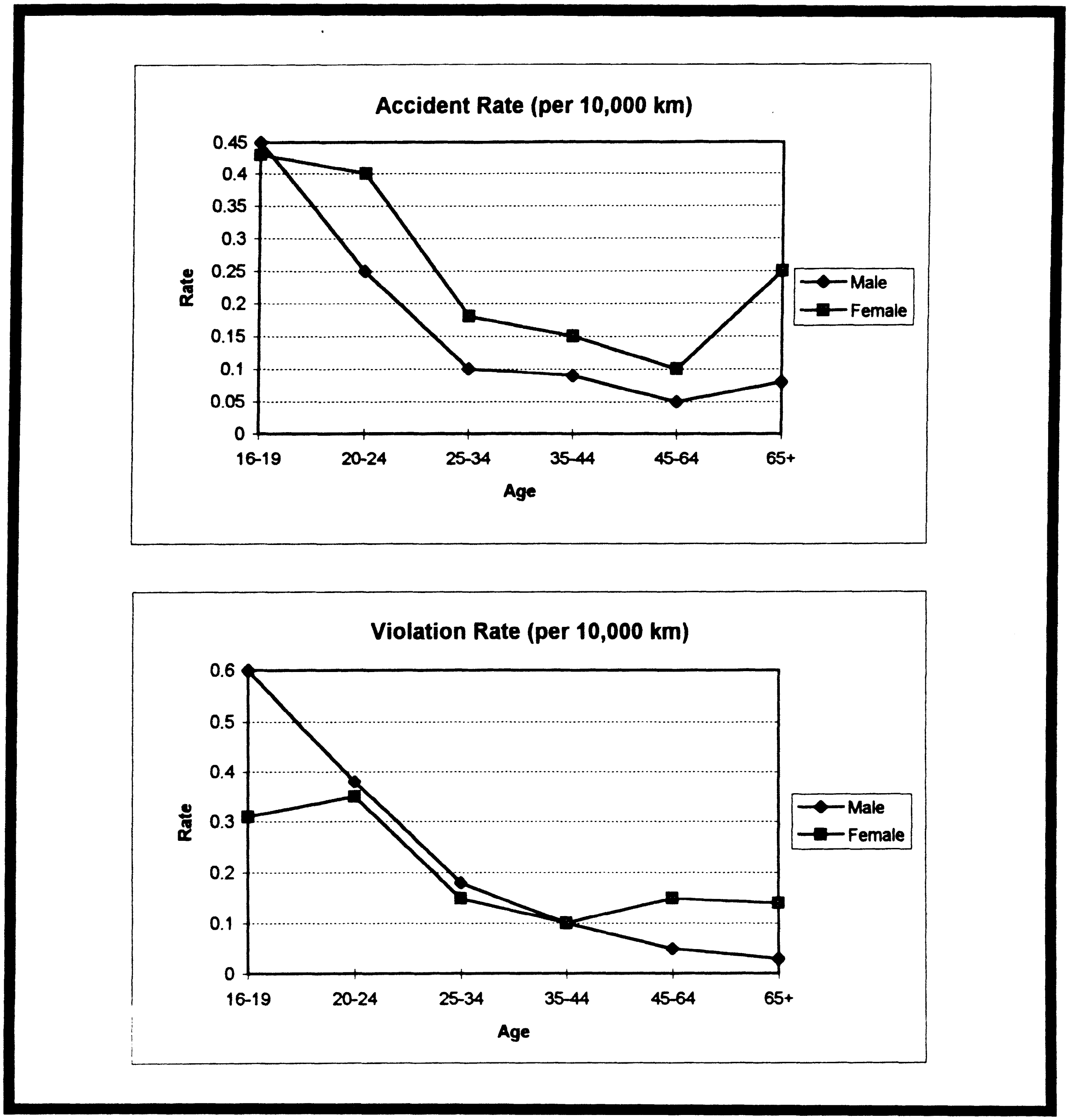

Figure 6. Age differences in accident and violation rates among males and females. (Taken from Jonah, 1990).

Relationship Between Risky Driving Behavior and Roadway Features

The influence of roadway factors, including geometric design and traffic control devices, and environmental factors on motivational influences have been studied very little, and what information is available is not easily correlated. There is also little empirical evidence to show whether small changes in driver perception impact safety over time. For instance, a roadway that has been widened and resurfaced to provide a "safer” and more comfortable ride may inadvertently result in higher mean driving speeds and may actually reduce the net safety benefit.

One roadway design feature that has been shown to affect driving behavior is pavement width. Roads of different widths are actually designed for different travel speeds. Studying another aspect of the effects of pavement width, Troutbeck (1984) examined overtaking behavior on narrow two-lane two-way rural roads. An instrumented vehicle was used to observe overtaking behavior of other vehicles, using video cameras to provide simultaneous views forward, rearward, and to the side of the instrumented vehicle. Time of day, distance traveled by the test vehicle, speed of the test vehicle and output from a radar speed meter were also recorded. The first set of observations was recorded on a stretch of highway that had a pavement width of 7.3 m (24 ft), while the second set of observations was recorded on a secondary road with a pavement width ranging from 5.8 to 6.1 m (19 to 20 ft). In the first set of observations, there were 343 overtakings analyzed, of which 143 were single accelerative overtakings. In the second set of observations, there were 204 observations, of which 89 were single accelerative overtakings. In a single accelerative overtaking, the overtaking vehicle slowed to the speed of the overtaking vehicle before the maneuver was commenced, and only one vehicle was overtaken. From the data collected, values were calculated for 27 overtaking parameters, including overtaking time, overtaking distance, accepted gap, indecision time, safety margin, speeds of overtaken and overtaking vehicles, and headways at start and completion of overtaking.

The mean overtaking time for the 7.3-m (24.ft) wide highway was 8.6 s, increasing to 9.3 s for the 6.1-m (20-ft) wide secondary road. Similarly, overtaking distances were 192 m (630 ft) and 205 m (672 ft) for accelerative overtakings on the highway and secondary road, respectively. Drivers on the narrow roads also showed longer indecision times, and gaps accepted by drivers on the narrow roadway were significantly greater than those on the wider highway observation route. The author notes, however, that this was likely due to the substantially lower traffic volumes on the narrow road.

In order to identify other possible misleading roadway design features that affect driver risk perception and risk-taking, Watts and Quimby (1980) asked subjects to provide on-road risk assessments. As subjects drove along a 25.7-km (16-mi) test route, they were asked to verbally rate the risk associated with each of 45 predetermined locations along the route. Risk was rated on an 11-point scale ranging from “no chance of a near miss” to “good chance of a near miss.” A variety of locations was assessed, including single- and two-lane roadways, suburban and urban settings, and a variety of hazards, including sharp bends, junctions, and locations with poor visibility. Subjects rated risk at each location while they were driving, verbally reporting ratings to the experimenter in the vehicle.

As a comparative measure, objective risk was determined through injury accidents that were reported as occurring in daylight hours from 1973 to 1976 within 100 m (328 ft) of the measurement locations along the route. The authors acknowledge that only a crude measure of objective risk at each location is possible using this method, since accidents are rare events and provide limited data, and accident data for certain locations may be incomplete, especially those locations where single-vehicle accidents are likely to occur (e.g., rural bends). A total of 60 subjects participated in the study, with sampling controlling for age and gender so that the subject group corresponded with national exposure data.

Results showed strong agreement between driver subjective risk rankings of the locations, suggesting that drivers apply the same general criteria when estimating risk levels. There was also strong agreement between rankings of perceived risk and rankings based on the measure of safety margin (r_s=0.88), indicating that the rating technique used was a reasonably accurate method. Although somewhat weaker, there was also an association between rankings of the locations on subjective and objective risk levels (r_s=0.37). However, because of the previously discussed inherent unreliability of the accident data used for the objective risk measure, only a tentative analysis of these differences was possible. The authors noted that at under-rated sites (including a rural T-junction and a rural two-lane roadway near a picnic area) expectancy was a likely contributory factor, since drivers may not have expected vehicles to appear at these sites. Another factor causing drivers to under rate sites was the phenomenon of a "perceptual trap." In the case of the most dangerous site along the route, a rural junction with traffic lights, there had been a total of five injury accidents reported during 1973 to 1976. Vehicles approached this intersection at high speeds along a straight stretch of roadway, and the uninterrupted straight line of the roadway may have led to driver difficulty in judging speeds of oncoming vehicles. Thus, roadway features that go against driver expectancy or mask roadway features should be avoided.

A summary of the statistical relationships for studies reviewed in this section is presented in table 14. In this table, the independent and dependent variables in each study are designated "X" and "Y," respectively, for convenience.

Table 14. Summary of findings related to driver age differences in motivation and risk/hazard perception.

Study	X and Y	Study Statistic	N	df	Expected Direction	One-Tailed P Value
Jonah (1990)	X = Age Y = No. reported violations		9943		+	0.01
	X = Age Y = No. reported accidents		9943		+	0.01
West, French, and Elander (1990)	X = Age (≤ 60 yr) Y = Accident rate	t = -2.4	714		+	0.015
	X = Age (≤ 60 yr) Y = Speed	Corr r = -0.27	714		+	0.025
	X = Age (>60 yr) Y = Speed	Corr r = -0.02	714		+	
	X = Sex (≤ 60 yr) Y = Speed	Corr r = -0.26	714		+	0.025
	X = Sex (>60 yr) Y = Speed	Corr r = 0.15	714		+	
	X = Age (≤ 60 yrs) Y = Speed	t = -6.2	714		+	0.0000
	X = Sex (≤ 60 yrs) Y = Speed	t = -4.8	714		+	0.0000
	X = Type-A behavior Y = Speed	Corr r = 0.22	122		+	0.02
	X = Type-A behavior Y = Accident rate		122		—	0.50
	X = Sensation seeking Y = Speed	Corr r = 0.17	122		+	0.05
	X = Sensation seeking Y = Accident rate		122		—	0.50
	X = Sociopathy Y = Speed	Corr r = 0.29	122		+	0.05
	X = Sociopathy Y = Accident rate	Corr r = 0.19	122		+	0.05
Finn and Bragg (1986)	X = Age Y = Estimate of # people injured in accidents in own State	t = .95	45,48	1		

Table 14. Summary of findings related to driver age differences in motivation and risk/hazard perception (Continued).

Study	X and Y	Study Statistic	N	df	Expected Direction	One-Tailed P Value
Finn and Bragg (1986)	X = Age Y = Estimate of # people injured in accidents in U.S.	t = .98	45,48	1		
	X = Age Y = Estimate of # people killed in accidents in State	t = 2.44	45,48	1		
	X = Age Y = Estimate of # people killed in accidents in State	t = -.66	45,48	1		
	X = Age Y = Risk estimate of driving situation in still photo	F = 0.81	93	9	+	0.6102
	X = Age Y = Risk estimate of driving situation in videotape	F = 1.97	93	14	+	0.0170
Evans and Wasielewski (1983)	X = Sex Y = Recip headway (5-l)	F = 0.20	2552	1	+	0.66
	X = Age Y = Recip headway (s^{-1})	F = 26.22	2522	1	+	0.0001
	X = Accident history Y = Recip headway (s^{-1})	F = 6.99	2552	1	+	0.008
	X = Points on driving record Y = Recip headway (s^{-1})	F = 22.50	2552	1	+	0.0001
Evans and Wasielewski (1982)	X = Drivers w/ and w/out reported accidents Y = Proportion of headways < 1 s	x^2 = 5.5	2576		+	0.02
	X = Drivers w/ and w/out reported violations Y = Proportion of headways < 1 s	x^2 = 11.5	2576		+	0.0007

Table 14. Summary of findings related to driver age differences in motivation and risk/hazard perception (Continued).

Study	X and Y	**Study statistic**	**N**	df	Expected Direction	One-Tailed P Value
Evans and Wasielewski (1982)	X = No. of reported accidents Y = Proportion of headways < 1 s	t = 2.38	2576		+	0.02
	X = No. points Y = Proportion of headways < 1 s	t = 4.88	2576		+	0.0001
Darzentas, McDowell, and Cooper (1980)	X = Speed of main road vehicle (ft/s) Y = Minimum acceptable gap (s)					
	Young Males (31-40)	Corr r = -0.27	200	198	+	< 0.01
	Older Males (61-70)	Corr r = -0.34	200	198	+	< 0.01
	Young Females (31-40)	Corr r = -0.42	200	198	+	< 0.01
	Older Females (61-70)	Corr r = -0.50	200	198	+	< 0.01
Watts and Quimby (1980)	X = Ranking of perceived risk Y = Ranking based on measure of safety margin	Corr r = 0.88	60		+	0.05
	X = Ranking of subjective risk Y = Ranking of objective risk	Con r = 0.37	60		+	0.05

GAPS IN KNOWLEDGE AND ISSUES FOR FUTURE RESEARCH

The results of this research synthesis were directed to two major goals in this project: (1) to provide the rationale and justification for the recommendations subsequently developed for the ***Older Driver Highway Design Handbook,*** and (2) to identify gaps in knowledge and priority issues for future research investigating the relationship between age and driver performance. While the former objective is addressed in a separate project deliverable, recommendations for future research priorities are discussed below.

The strongest emphasis is upon the functional areas of vision and visual attention, and memory and cognition; the greatest promise for application of research findings appears to lie in these areas. A lower probability that research findings in the area of motivational influences will lead to specific design or operational enhancements must be assumed, because of the exaggerated methodological problems that plague this area; and, older drivers' physical abilities are accorded priority only as one among competing influences on response speed in describing a research need in the area of memory and cognition.

The following paragraphs initially describe gaps in the present knowledge that impede progress in the application of research on *vision and visual attention* to highway safety. To address these needs, three priority areas for continuing study with older drivers may be identified.

(1) *Detemine what visual skills are important for safe driving.*

Based on a review of the literature, the relationships between visual function and driving record, although sometimes significant from a statistical standpoint, are not significant from a practical standpoint. In reviewing this literature, many authors have described the relationships that are found as "highly suggestive," "practically significant, " and "useful for pointing the direction for future research on how to screen vision for driving." These putative relationships are used as a basis for deciding what specific visual tests should be recommended for newly-designed vision assessment batteries for driving. Frequent summaries recommend the development of a series of tests of various aspects of vision (e.g., static acuity under different illuminations, dynamic acuity, contrast sensitivity, glare sensitivity) that can be standardized, validated, and normalized so that they can be used for driver screening. They also recommend that the software and hardware for such a device be developed. In evaluating the research, a new battery of visual sensory tests seems unwarranted. However, correlations between these visual function measures and crash involvement are not practically significant for many of the reasons enumerated above.

(2) *Determine the extent to which the visual skills crucial for driving are more likely to be perceptual/cognitive skills, rather than sensory capabilities.*

First, it should be emphasized that the sensory status of the visual system is not irrelevant for safe driving, even though visual sensory tests are not predictive of crash involvement. Of course, some level of visual function must be intact to support the input stage of information processing. The point here is that the strongest relationships to driving performance will be those skills that reflect the complexity of driving behavior. The idea that the, best correlates will not be sensory, but instead will be perceptual/cognitive, is definitely not a new idea. Burg, in his pioneering papers in the 1960's, argued for this very point. Thus, it is somewhat surprising that few researchers in the subsequent 25 years have picked up the banner of this theme in trying to develop better screening measures for driving licensure. Instead, most of the studies in the literature and in government technical reports are heavily concerned with sensory tests rather than perceptual/cognitive tests.

To pursue this issue, it is reasonable to expect that future vision tests for driver screening will have some of the following components. Many, if not all of these features have been mentioned before. These features have been included on this list because they involve the real-world features of everyday driving: (1) dual task requirements; (2) visual clutter, or visually complex stimuli; (3) both a central and peripheral visual field component; (4) dynamic visual arrays; (5) contrast and luminance as stimulus variables to be investigated; and (6) target localization and identification. These stimulus variables are especially crucial when studying an elderly population. Further, with an emphasis on the inclusion of real-world highway features when testing functional capabilities, an approach which incorporates test stimuli into a realistic driving scenario could be particularly effective; the importance of context on driver performance has been noted often in this review. Also, this is not an exhaustive list, and each component is not independent from the others. Researchers have discussed many possible reasons for the weak correlations typically found between vision and driving. Of course, assessing the wrong visual skills is just one of the possible causes. But at least it is an aspect of future research that can be modified.

Finally, it must be emphasized that the design and evaluation of highway information elements, including all manner of traffic control devices, should include specifications that provide for their timely detection and recognition ***in context,*** under multi-task demand conditions.

(3) *Identify dependent measures to link vision to driving that reflect not only the end result (i.e., a crush) of "bad" behavior (i.e., poor driving skills), but rather the behavior itself.*

The primary dependent variable in early work on this topic has been crash rate (or some similar variable like traffic citations). The tacit belief is that this is really the best dependent variable because it is a measure of what we want to prevent. Also, it is a concrete, quantifiable piece of information, and is usually available (albeit with some effort) from each State's motor vehicle/public safety department. It is also a type of data that legislators and other government officials can readily relate to, and rightly so: it is in the public's interest to keep accident statistics minimized. However, in trying to link vision to driving problems, crash rates and similar measures are far from ideal in representing driver performance. The issue here is that if we want to study driving performance, and the mechanisms that underlie it, we cannot merely study the end result of the "bad behavior" (i.e., a crash), but rather must study the behavior itself. As many others in the literature have pointed out, drivers can compensate for poor driving ability in a variety of ways, such that the crash data will not reflect true driving ability. Measures of selected aspects of driving behavior itself are more likely to reflect the subtle yet crucial relationships between safe driving and visual skills. Also, by using these types of dependent measures, researchers will not be trying to predict the occurrence of an improbable event. Therefore, future studies attempting to link vision and driving performance, should also utilize alternative dependent measures such as performance in a simulated driving task, actual driving performance, and reported driving difficulties on validated questionnaires. These types of measures should allow researchers to better pin down the perceptual determinants of safe driving.

The next set of critical gaps in knowledge lead to the identification of future research priorities in four areas of *memory and cognition:* selective attention, divided attention, response speed, and processing demands (workload) of using in-vehicle displays in various driving situations. Specific research needs deemed most pressing to understanding and predicting the performance of older drivers are discussed below.

(1) *Refine methodologies as required to obtain valid and predictive measures of the influence of selective attention on driving behavior.*

The most obvious gap in the broad area of memory and cognition is that there are insufficient data on the relationship of selective attention to driving behavior. Before studies are conducted, however, it seems worthwhile to note that there are only certain aspects of driving behavior that are likely related to the function of selective attention. One problem with the driving literature, in general, is that researchers have not specified general theoretical models with the notion that different mechanisms would underlie performance on the various aspects of driving behavior. The Ranney and Pulling (1990) measures of behavior provide a good model of the multiple dependent measures that one could assess and extract from closed-course driving or driving in a simulator. For example, one might expect selective attention performance to be more related to intersection performance, stop-go decisions, emergency response, and interpretation of signs than to gap performance, speed, and vehicle control. Thus, future studies should focus on areas where selective attention effects are likely to emerge. It is also critically important that adequate numbers of subjects of each age group be tested to address the hypotheses, and that a substantial number of drivers age 75 and older be tested, i.e., the group most at risk of accidents where it is most likely that cognitive factors would play an important role. With respect to selective attention, it would be particularly worthwhile to observe the relationship of this variable to surprise or emergency situations, to performance in visually-complex environments (e.g., approaching a hazard situation where lanes are being defined by traffic cones due to road work, etc.) or in situations where there is a great deal of traffic, signage, and information that must be simultaneously processed.

(2) *Improve the ecological validity of divided attention studies through appropriate driving simulations.*

There are still a relatively small number of studies conducted on this very important topic. One problem with the research is that the work conducted to date is a “far-simulation” of driving behavior. The tracking task is probably a reasonably good estimation of steering, but the secondary task of dot-counting bears little relationship to a task that one might encounter in an actual driving situation. The Korteling (1992) study has the more ecologically valid task of car following for the secondary task, and appears to be a more accurate simulation of driving. More studies with such accurate simulation are needed.

Also, there is no research to date on how older adults respond in a divided attention situation when presented with surprising stimuli, confusing intersections, and other complex aspects of highway design such as warning signs, changing or flashing message signs, work zones, and high density traffic. These are the types of situations that are likely to be most resource-demanding and would be excellent choices for secondary tasks. Moreover, steering, acceleration, and adequate braking might all be viewed as primary tasks that are to be assessed in the context of secondary stimulation of the type described. It also cannot be emphasized enough how important it is to conduct research with sufficient numbers of subjects to determine the actual effects of the manipulations. Finally, it is important to include drivers aged 75 and greater in studies of these types. The cognitive literature shows that at approximately this age, decline becomes more precipitous. This is the group with the highest accident rates and the age group where cognitive deficits are most likely to play an important contributory role to accidents.

(3) *Discriminate more accurately between the effects of motor speed versus perceptual speed on driving behavior.*

The primary problem in this area is that there is an insufficient data base, and the studies that have been conducted to date have had such low numbers of subjects that it is impossible to conclude that neither motor nor perceptual speed have an effect on driving behavior. With respect to age, it is likely that effects of speed may be indirect (that is, affecting selective attention, working memory, and decision-making) and that these in turn affect various components of driving behavior. One serious lack in the driving literature, in addition to the small numbers of subjects tested and the lack of age-stratified samples, is that studies have not been designed that permit the assessment of multiple cognitive constructs simultaneously. With the advent of LISREL techniques (Joreskog, 1993) and the use of structural equation modeling, the effects of multiple variables on the component behaviors of driving can be simultaneously assessed and the interrelationships among these variables measured. In addition, these techniques can be used to model composite measures of overall driving ability as well as accident rates. Examples of how these techniques could be used were presented earlier in the discussion of driver age differences in memory and cognition.

(4) *Quantify the processing demands for use of in-vehicle displays and assess their safety in different driving situations.*

It appears that older adults respond very similarly to younger adults to both navigational devices and in-vehicle displays. Moreover, it also appears that they have a similar mental representation of automobile control and display location as younger adults. Nevertheless, they are consistently slower in using and locating these devices. At the same time, the literature reviewed here appears to indicate that navigational devices and attention to displays use up cognitive resources. Although no one has yet to demonstrate that the attention to these devices affects driving directly, it seems likely that this would be the case in a highly demanding contextual situation. It is of critical importance to thoroughly investigate what types of navigational aids and displays place the lowest demands on cognitive function, but also to determine whether or not older adults are capable of using these devices when they are placed in a highly demanding driving situation. If the older adults are able to ignore the device when the driving demands get high, the devices should not be seriously problematic in highly demanding situations. They may indeed serve as an effective support of wayfinding when the driving load is such that older adults can attend to the navigational aids. It is essential in designing the devices that they be as low in their resource demands as possible. The arrow-based guidance system investigated by McKnight and McKnight (1992) appears very promising, particularly when there are auditory cues directing the driver that a navigational decision must be made. Investigation of the resource demands made by various devices with assorted formats, and how much visual attention they require would appear to be an important and promising direction for future research. The issue of whether such devices help or hinder older persons will be related to how much resource is required to use them and how readily older adults can disengage from them in a demanding or hazardous situation.

Finally, with regard to future research priorities in the area of aging and motivational influences, the largest hindrance is the lack of agreed-upon measures of both objective risk and subjective risk/hazard perception. Until this is resolved, a multivariate approach that relies on a number of convergent measures, each offering strong construct validity, will be unavoidable. Further, future research designed to measure within-subject variability in the performance of risky driving behaviors among (older) drivers as a function of situational factors is a priority, in addition to the more traditional studies of cross-sectional differences between age groups; because of the need to expose subjects to situations with high levels of objective risk in such research, the use of high-fidelity driving simulation seems most likely to yield applicable findings.

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