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VISUAL PROCESSING AND DRIVING SAFETY

Final Report

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16. ABSTRACT

The normal aging process appears to be associated with a progressive decline in information processing capabilities necessary for safe driving. In order to improve highway safety, the roadway system should be adjusted to accommodate older drivers with diminished capabilities, and driver licensing instruments should be developed to identify individuals with disabilities of a severity to preclude safe driving. These goals require a better understanding of the nature and extent of age-related changes in perceptual and cognitive functioning. This project constitutes an early phase in the research necessary to achieve such understanding. Based on a previously advanced account of age differences in visual processing time, a battery of computer based laboratory tasks was developed and administered to young, middle-aged, and elderly drivers. The tasks differed in the techniques used to assess processing time, the cognitive processes upon which a response was based, and the characteristics of the stimulus set. As expected, aging was associated with longer processing times in most of these experiments. Our attempt to account for the magnitude of the age effect was not successful. The relative age difference varied with both the stimulus and the requirements of the task. In certain tasks, stimulus attributes that had only a small effect upon the performance of young subjects had a large effect upon the performance of elderly subjects. These results are discussed with respect to development of a valid screening instrument for driver licensing, and with respect to improved geometric design and operation standards for the roadway system.

17. KEY WORDS

Aging, Age Differences, Driver Performance; Driver Safety, Dynamic Visual Acuity, Driver License Examination, Driver License Screening Human Factors, Information Processing, Perception, Reaction Time: Visual

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Many traffic accidents result, in part, from limitations in the speed and accuracy with which drivers can process critical information and execute an appropriate response. Some of these accidents could be avoided by improved roadway design, others by ensuring that licensed drivers do not suffer from critical and unremediable sensory, motor, or cognitive disabilities. Both of these solutions require a better understanding of the nature and variability of driving-relevant capabilities.

It is generally accepted that driving requires at least limited sensory (primarily visual) and motor capabilities. Legally blind people, for example, do not typically attempt to drive, and if they were to apply for a license, their disability would be detected by the visual screening tests and would be considered a sufficient basis for denial of a license. Similarly, severe and widespread motor impairment (e.g., quadriplegia) is assumed to preclude driving.

The importance of these sensory and motor requirements notwithstanding, driving is fundamentally a cognitive task: In order to drive safely, an individual must respond appropriately to a complex array of visual information. Although we do not know the exact nature of the information processing capabilities involved in driving, or how best to measure them, we can be assured that they vary substantially from person to person. Moreover, an individual's capabilities will vary from one time to another: (a) Temporary reductions in processing efficiency frequently accompany intoxication, fatigue, and stress; (b) lasting impairment may result from diseases and accidents that cause neurological damage; and (c) a progressive decline in processing capabilities appears to be a consequence of the normal aging process.

The association between advanced age and information processing deficiencies is of particular concern because elderly people represent a large and growing proportion of the population. If the roadway system is to accommodate older drivers and if screening procedures are to identify individuals with deficiencies of a severity to preclude safe driving, a much better understanding of age-related changes is needed.

More specifically, characterization of the elderly driver and development of screening instruments for driver licensing will both be greatly facilitated if a few general factors can account for the changes in processing capabilities that accompany advancing age. In this regard, it has been hypothesized that aging is associated with a reduction in processing speed, which results in a constant relative increase in processing time across a variety of tasks, and with an increase in neural noise, which results in a disproportionate increase in processing time for difficult discriminations. This research project was designed to test these hypotheses and, thereby, to provide information that could help to create safer driving conditions.

Methodology and Results

Ten men and ten women in each of three age groups (young, middle-aged, and elderly) participated in nine different laboratory experiments. The tasks differed in the techniques used to assess processing time, the cognitive processes upon which a response was based, and the characteristics of the stimulus set.

As expected, aging was associated with longer processing times in most of these experiments. Our attempt to account for the magnitude of the age effect was not, however, successful. The relative age difference varied with both the attributes of the stimulus and the requirements of the task. In certain tasks, stimulus attributes that had only a small effect upon the performance of young subjects had a large effect upon the performance of elderly subjects. On the other hand, elderly subjects were not affected disproportionately by high stimulus similarity.

Age differences in response latency are frequently attributed, at least in part, to age differences in cautiousness. We found no evidence of such a relationship, but there were indications that cautiousness is related to subject gender, with women being the more cautious. Since the ratio of women to men increases with age in our society, gender differences would translate into age differences in the population and in research where age and gender covary. Nonetheless, the primary determinant of the age-related decline in performance on information processing tasks appears to be a more fundamental change in nervous system functioning.

Conclusions and Suggested Research

A major, national research effort should be initiated to meet the transportation-related needs of elderly adults. Basic research that examines the nature and extent of age-related differences in driving-relevant capabilities is necessary for the development of a screening instrument and would provide guidance to the applied work required for specific engineering questions. In the applied area, to ensure that the roadway system accommodates old as well as young drivers, estimates of driver characteristics (e.g., perception-reaction time) should be based on the performance of elderly people in realistic field situations. Moreover, since the effects of certain stimulus attributes are much greater for elderly adults than for young adults, elderly people should also be tested in investigations of alternative sign formats and pavement markings. Finally, studies of the relationship between information-processing-task performance and driving capability should employ elderly people.

In light of the present findings, it is suggested that subsequent ADOT supported research (a) investigate the stimulus attributes that affect processing time and the nature of age differences in sensitivity to these attributes; (b) assess age-related differences in visual attentional capacities; (c) compare the processing capabilities of drivers grouped according to their driving records; and (d) develop and evaluate potential screening instruments.

INTRODUCTION

Problem Statement

> If we cannot design our highways to accommodate the 70 year old man with a blood alcohol content of .05 to .06, then our qualified legal requirements should be changed by NHTSA. (Anderson, 1979, p.23)

Driving requires complex visual information processing. Moving objects (e.g., pedestrians and vehicles) as well as stationary objects (e.g., signs and obstacles) must be processed rapidly and responded to appropriately. Both research and experience indicate that there are substantial individual and age-related differences in information processing efficiency and, therefore, in the ability to handle driving demands. Nevertheless, current procedures for reissuing a driver's license are based on the implicit assumption that all neuromuscularly normal adults who have adequate visual acuity and can pass the written exam are capable of driving safely. In addition, transportation design standards are based on limited tests of quite restricted samples of subjects. These standards may not be appropriate for a large segment of the driving population.

It is well known that elderly adults tend to respond more slowly than young adults on most if not all behavioral tasks. In the past this slowness was attributed to relatively peripheral sensorimotor limitations. Recent research indicates, however, that it reflects an age-related decline in central nervous system efficiency. Perceptual, decision, and response times are all relatively long in the elderly. Moreover, age-related differences in processing time increase with the cognitive complexity of the task.

In an apparent attempt to reduce the rate with which information must be processed, elderly people frequently drive more slowly than the prevailing traffic. Driving record data indicate, however, that this strategy is sometimes insufficient or inappropriate: The rate (number per miles driven) of traffic citations and the rate of accidents are both substantially higher for elderly than for middle-aged adults (Burg, 1971).

Prior to his retirement as FHWA's Associate Administrator for Safety, Howard L. Anderson (1979) addressed the National Highway Advisory Committee. He argued that, if we are to improve highway safety, highways and vehicles must be designed to be compatible and must be based on a better understanding of human abilities and limitations. He emphasized that the "design driver" (i.e., the prototypical driver upon which design standards are based) should be representative of the less competent drivers -- that we should accommodate 95% of the elderly drivers who drink in moderation and have no better than 20/40 vision, not 95% of the young drivers who have served as subjects in most past research. He went on to assert that drivers who cannot be accommodated should not be allowed to drive.

Although we support this view, it is important to recognize that there are many driving situations in which the demands placed upon the driver are largely independent of design parameters. Improved design standards would undoubtedly reduce the accident rate, but improving standards (when possible) to accommodate the least able members of the potential driving population would not make these people safe drivers. Such individuals are unlikely to be able to handle the aspects of driving that can not be controlled by design. Design and operation standards should accommodate all licensed drivers; driver-license screening should ensure that licensed drivers have the capabilities necessary for safe driving.

With regard to highway design and operations, there is much to be learned about the distributions of capacities upon which standards are based. In addition, there are many questions concerning how stimuli in the driving environment (e.g., signs and signals) can be optimized for speed and accuracy of processing.

Although laboratory studies have much to contribute to an understanding of stimulus effects and human capacities, accurate estimates of driver characteristics for computing design standards will also require studies that adequately duplicate actual driving conditions, either on-the-road or with a realistic, interactive driving simulator (as yet, nonexistent). Sophisticated simulators will be necessary to answer questions concerning an individual's ability to handle emergency or complex processing situations.

Such a simulator would also be the ideal device for screening potential drivers, if neither money nor time were an issue. Not one such simulator exists, however. If one were developed in the near future, it would be far too costly to be used for routine screening. A realistic alternative is to develop a relatively inexpensive screening instrument (battery of tests) that assesses the basic capacities necessary for safe driving. Before such an instrument can be developed, however, research is needed to determine what capacites to measure, how to measure them reliably, and "how much" of each capacity driving demands.

The laboratory studies reported here constitute an early phase in the research necessary to improve highway safety. Based on previously advanced theoretical accounts of age-related changes in cognitive functioning, a battery of computer-based information processing tasks was developed and administered to young, middle-age, and elderly drivers. Our primary goal was to achieve a better understanding of age-related differences in basic visual processing capabilities and, thereby, to contribute to the creation of safer driving conditions. In terms of specific applications, our objective was to provide information relevant to the following goals:

1. Development of a more adequate screening instrument for driver licensing.
2. Development of improved geometric design standards.

3. Development of standards for signing and pavement markings, specifically, for
    a. format and lettering style of sign messages;
    b. sign spacing and placement;
    c. center-line segment-to-gap ratios; and
    d. edgelines.
4. Identification of transportation situations which are likely to be difficult for elderly people because of age-related changes in capabilities.
5. Identification of future public transportation needs.

Issues concerning geometric design standards and screening for driver licensing are discussed in the following sections.

Design Standards and Perception-Reaction Time

The execution of safe maneuvers on highways and at intersections depends heavily on two factors, namely, the sight distance (length of roadway ahead visible to the driver) and the time necessary for the driver to process information and execute an appropriate response (the driver's "perception-reaction time"). Minimum sight distance specifications for design standards are based, in part, on estimates of a driver's perception-reaction time. The estimated values are supposed to meet the needs of "most" drivers, but are in fact based on very little research. Low estimates will result in highways that are not safe. The magnitude of the effect of misspecification depends, as will be discussed in the following sections and in the Appendix, on the design standard under consideration as well as on design speed and other characteristics of the highway environment.

The next sections address four applications of perception-reaction time estimates to the geometric design of highways. The first application is stopping sight distance on highways, the second application is sight distance on horizontal curves, the third application is passing sight distance for two-lane highways, and the fourth application is sight distance at stop-controlled intersections.

Stopping Sight Distance

> The minimum sight distance available on a roadway should be sufficiently long to enable a vehicle traveling at or near the design speed to stop before reaching a stationary object in its path. . . . Stopping sight distance is the sum of two distances: the distance traversed by the vehicle from the instant the driver sights an object necessitating a stop to the instant the brakes are applied and the distance required to stop the vehicle from the instant brake application begins. These are referred to as brake reaction distance and braking distance, respectively.
> (AASHTO, 1984, p.136)

Stopping sight distance (SSD) is the basis for many geometric design standards. As specified in the above quote from the 1984 AASHTO manual, A Policy on Geometric Design of Highways and Streets (1984 AASHTO Policy), SSD is composed of "braking distance" and "brake reaction distance." For a given vehicle speed the latter distance is determined by the driver's "brake reaction time." The specification value for this driver characteristic is 2.5 seconds.

What is termed "brake reaction time" in the 1984 AASHTO Policy is more commonly referred to as "perception-brake-reaction time," and that term will be used in this report. Some authors and design manuals (e.g., AASHO, 1965; Anderson, 1979) specify that the 2.5 second perception-brake-reaction time is composed of a perception time of 1.5 seconds and a brake reaction time of 1.0 seconds. Although there is considerable inconsistency in the use of these terms, perception time is usually taken to include detection, recognition, and decision times. Brake reaction time is taken as the time between completion of perception and brake pedal contact.

Much concern has been expressed about the appropriateness of the 2.5 second specification value for driver perception-brake-reaction time. The percentages of the driving population accommodated under various driving conditions are not known. Indeed, there has been little relevant research.

Anderson (1979) argued that the specified perception-brake-reaction time should be at least 3.5 seconds. He illustrated the importance of this change by determining the speed at which the design driver, with a perception-brake-reaction time of 3.5 seconds, would be traveling when he reached an object which first became visible at the beginning of the current design stopping sight distance. For design speeds between 50 and 60 mph, he calculated that the impact speed would be 28-30 mph.

Scott (1979) argued that the perception-time specification value should increase with the distance between the driver and the object -- and, therefore, with design speed. He reasoned as follows: In order to provide the necessary stopping sight distance, the minimum acceptable length of a crest vertical curve increases with design speed. Therefore, if a driver is on a crest vertical curve, which has the limiting value for the design speed, and an object begins to be visible over the crest, the distance between the driver and the object will be a positive function of design speed. According to Scott's calculations, a consequence of this relationship between design speed and distance is that the rate at which an object comes into view for limiting crest curvature values varies inversely with design speed. For example, if a driver were driving at design speed on a curve of minimum length for that design speed, a 6-inch object, which would be entirely in view in 1.2 seconds at a 30 mph design speed, would not be entirely in view until 1.9 seconds had elapsed at a 60 mph design speed.

It should also be noted that the visual angle subtended by an object of a given size varies inversely with its distance. Thus, under the conditions described above, both the rate at which an object comes into view and the visual angle subtended by any portion of an object will vary inversely with design speed. Objects that subtend a small visual angle are, in general, processed more slowly than objects that subtend large visual angles. Objects subtending a sufficiently small angle (depending upon other characteristics of the object, environmental conditions, and the acuity and contrast sensitivity of the driver) can not be detected. Thus, there is a limit to the sight distance at which an object can be perceived. Although consideration of visual angle strengthens Scott's argument that the specification value for perception time should increase with design speed (because objects that subtend a small visual angle require longer processing times), it also illustrates both the limits of design solutions (particularly for high speeds, because object perception requires a visual angle of some minimum size) and the importance of considering more than one driver characteristic in the computation of design standards.

Based on the addition of estimates of hypothetical components of perception-brake-reaction time, Hooper and McGee (1983) concluded that the perception-brake-reaction time specification values for SSD design standards are, in general, too low. Furthermore, they reported on the sensitivity of SSD to incremental changes in perception-brake-reaction time. The results of the sensitivity analysis are documented in the Appendix.

Stopping sight distance is a linearly increasing function of perception-brake-reaction time. In terms of additional distance traversed before stopping, the effect of perception-brake-reaction time increases with vehicle speed, and the effect of speed is greater at longer perception-brake-reaction times (see Figure A1).

The sensitivity analysis, reported in the Appendix, determines the percentage change in stopping sight distance that results from a one percent change in perception-brake-reaction time (see Equation [2]). As shown in Figure A2, sensitivity, so defined, is a decreasing function of vehicle velocity and an increasing function of perception-brake-reaction time: For example, at a velocity of 30 mph, a one percent change in perception-brake-reaction time yields a .54 percent change in SSD for a perception-brake-reaction time of 2.3 seconds and a .70 percent change in SSD for a perception-brake-reaction time of 4.6 seconds. (Hooper and McGee considered 2.3 and 4.6 seconds to represent the perception-brake-reaction times of the 50th and 99th percentiles of the driving population.) The sensitivity values for 2.3 and 4.6 second perception-brake-reaction times decrease to .29 and .45, respectively, at a velocity of 70 mph.

Sight Distance on Horizontal Curves

Sight distance on horizontal curves can be reduced by obstructions. In order to maintain a minimum stopping sight distance, the middle lateral clearance of the curve must be of a minimum value.

As with stopping sight distance itself, this distance is an increasing function of vehicle (design) speed and perception-brake-reaction time. A sensitivity analysis revealed that the percentage change in the middle lateral clearance for a one percent change in perception-brake-reaction time is inversely related to velocity (design speed) and positively related to perception-brake-reaction time (see Equation [3] and Figures A3 & A4).

Passing Sight Distance for Two-Lane Highways

As defined by AASHTO and summarized in the Appendix, the passing sight distance for any two-lane highway is determined from the sum of four distances. The first distance is that which is traversed during the driver's processing time and during the initial acceleration to the point of encroachment on the left lane. This distance is thought to be the only one of the four distances that is sensitive to driver characteristics.

A sensitivity analysis revealed that the percentage change in the first distance due to one percent change in the driver characteristics varied from .153 at 30 mph to .162 at 70 mph.

Sight Distance at Stop Controlled Intersections

The crossing of and the turning on a major roadway at a stop controlled intersection are traffic maneuvers that depend, in part, upon perception time and the time necessary to get the vehicle in gear (perception-gear time). The sight distance needed by the driver to execute such maneuvers safely is also a function of the time required to accelerate and traverse the intersecting highway pavement. Assuming a perception-gear time of 2 seconds, a sensitivity analysis (Equation 7) concluded that a one percent change in this driver characteristic would result in changes of .19 percent and .30 percent in the necessary sight distance for intersection clearance times of 8.5 seconds and 4.5 seconds, respectively.

Research Needs

Appropriate specification of perception-reaction time values for design standards will require extensive field research. Given the difficulty and expense of this type of research, however, laboratory studies of the stimulus and task variables that determine processing time are of great importance. The results of such studies will help define the conditions to be examined in the field. Laboratory research in which subjects span the age range of the driving public will, in addition, provide information concerning the nature and extent of age-related differences in perception-reaction time values.

Our goal in the research reported here was to evaluate a previously proposed account of age differences in information processing time. The results of this research are relevant to questions concerning the constancy of age differences over a variety of stimuli and perceptual tasks and, thus, to questions concerning the variables to be considered in research designed to provide perception-reaction time values for the computation of highway design standards.

Driver Screening

In order for a test battery to serve as a meaningful screening instrument for potential drivers, it must be shown that poor performance on that battery is associated with an inability to handle the demands of driving. The stronger the association the better the instrument.

Vision and Driving

There is growing recognition that the two types of screening instruments used in routine driver licensing (written exams and vision tests) are not strongly associated with driving ability (Henderson & Burg, 1973; Shinar, 1978). Although it is generally believed that good vision is a prerequisite for safe driving, early attempts to demonstrate a relationship between visual acuity and driving performance were largely unsuccessful (Shinar, 1978). In an attempt to establish and evaluate more effective visual-screening procedures, the Institute of Transportation and Traffic Engineering at UCLA, in conjunction with the California Department of Motor vehicles, sponsored an extensive study of the relationship between several tests of visual capacity and driving record (i.e., accidents and convictions for traffic citations). Almost 18,000 drivers were interviewed and tested for a dynamic visual acuity, static visual acuity, lateral visual field, lateral phoria, low-illumination vision, glare recovery, and "eyedness" (preferred eye). Among the vision variables, dynamic acuity was by far the most consistent predictor. Nonetheless, poor dynamic acuity could account for only a small proportion of accidents (Burg, 1971). (In a reanalysis of these data, Hills and Burg (1978) reported that a relationship between driving performance and dynamic acuity was present only for the elderly.)

Based on the small but significant relationship between dynamic visual acuity and driver record, NHTSA sponsored the development of a new vision-testing device for driver licensing purposes (Henderson & Burg, 1973). This effort was directed toward designing an instrument which would be compact, reliable, not too expensive, easy to administer, and capable of measuring the visual functions judged to be most important for driving. The result of this project was the Integrated Vision Testing Device - Mark II, which measures a variety of visual functions. Several of these devices were constructed and subjected to field evaluation: Shinar (1977) tested 890 subjects. Regression analyses were performed with accident rate or frequency as the dependent variable. The multiple correlation between performance on the test battery and accident involvement varied with age group, as did the relative contributions of the individual tests. The correlations were all quite small.

Information Processing Capacities and Driving

Evidence that traffic accident rate is related to information processing capacities has been found in several recent experiments. Fergenson (1971) selected four groups of subjects, matched in driving experience, who differed in their driving records for the previous three years. The subjects were given a simple reaction time task, in which they were required to push a button whenever a red light appeared, and a choice reaction time task, in which they were required to push a different button for each of three lights that could appear. The difference between a subject's simple and choice reaction times was taken as a measure of decision time. Fergenson found that decision time was associated with accident history but not violation history. Drivers who had both high accident rates and high violation rates had the longest decision times; drivers who had no accidents but several violations had the shortest decision times. (There was no mention of subject age in this report.) Treat et al. (1977) also found a positive relationship between decision time (again, the difference between simple and choice reaction times) and accident involvement.

For a group of professional bus drivers, Kahneman et al. (1973) found a relationship between accident rate and performance on a task thought to measure auditory selective attention. Performance on a similar task as well as measures of visual "field dependence" were found to be related to the accident rates of commercial drivers in a study of Mihal and

Barrett (1976). In the latter study, age and accident involvement were positively correlated and, when the sample of drivers was divided into two groups on the basis of age (25 - 43 years and 45 - 64 years), the relationships between accident involvement and information processing performance scores were substantially higher for the older group.

Although these studies suggest that tests of basic information processing capacities may be useful as screening instruments, the selection of tasks and measures has been quite arbitrary. The number of tasks which might discriminate persons who cannot handle driving demands is virtually unlimited. It would be highly inefficient to study the relationships between driving record and scores on a large number of such tasks in order to develop a screening instrument. Rather, prior to validation against driving performance, research is needed to determine the tasks which best assess the variability in information processing capabilities.

In this research project, young, middle-aged, and elderly adults were tested on a battery of visual information processing tasks in order to obtain a better understanding of the nature of age-related differences in visual processing capacity. Such understanding is necessary if we are to construct a screening instrument that can detect age-related disabilities of a severity to preclude safe driving.

Measurement of Processing Time

The most basic questions about visual processing capacity involve _what_ can be detected or discriminated and _how quickly_ it can be done. Standard acuity measures, contrast sensitivity functions, and differential thresholds all describe the former, spatial characteristics of vision. Identification latencies and times to evade backward masking are frequently taken as indices of the temporal aspects of visual processing capacity. Answers to questions concerning these spatial and temporal capabilities are more complicated than they might appear, however, because the accuracy with which an individual performs a spatial task depends upon the time allotted or taken, and the more difficult the task the more time is needed (Vickers et. al, 1972).

The most common method used to assess the duration of mental events involves measurement of the interval between stimulus presentation and subject response. This interval is typically referred to as the _response latency_. The response itself is usually very simple (e.g., a button press) and invariant across levels of processing complexity. Task-dependent differences in response latency are thought to represent differences in the times necessary to perform the required mental operations.

When response latency is the primary dependent variable in an experiment, subjects are typically instructed to respond as quickly as possible without making errors. A subject's response latency is assumed to be the minimum amount of time he or she needed to execute the required cognitive and response processes. Performance is rarely error free, however. In most experiments errors do not occur because the subject can not perform the task correctly (e.g., identify the stimulus) but because he or she does not take enough time to do so. The percentage of errors increases if instructions emphasize speed and decreases if instructions emphasize accuracy. It appears as if subjects choose "speed-accuracy" (response) criteria at which, for the sake of speed, they will accept an occasional erroneous response.

The function relating speed and accuracy is such that, at high levels of accuracy, very small differences in error rate are associated with large differences in latency (Pachella, 1974). Since accuracy is encouraged in most experiments, small differences in response criteria may have significant effects upon latency but nonsignificant effects upon accuracy, resulting in findings that are difficult to interpret. Nevertheless, even though speed-accuracy criteria differences among age groups or conditions can limit the interpretability of experimental results, latency data are invaluable in the study of information processing capacities and demands.

Theoretically, an alternative method of assessing the duration of mental operations would be to measure response accuracy when the time available for processing was controlled. Such a procedure would have the advantage of removing or reducing response criteria effects. There is not, however, a wholly adequate means of restricting stimulus processing time. Limiting stimulus exposure duration is insufficient, because information about a stimulus persists in the nervous system long after stimulus offset. The most effective method appears to be to employ a backward masking procedure, although the mechanisms involved are not well understood.

In a masking task, two stimuli are presented in rapid succession on each trial. The term "backward masking" refers to the situation in which the processing of the first (target) stimulus is impaired by the presentation and processing of the second (masking) stimulus. For a given task, target, and mask, the degree of masking is a function of the time between the onset of the target and the onset of the mask. This interval is referred to as the "stimulus onset asynchrony" (SOA). Backward masking procedures allow one to estimate the time needed to process a stimulus by measuring (a) response accuracy as a function of SOA or (b) the SOA necessary to achieve a specified level of accuracy.

Age-related differences in response latency on discrimination and identification tasks have frequently been attributed to age differences in response criteria (i.e., an increase in cautiousness with advanced age) rather than to differences in processing time itself (e.g., Botwinick et al., 1958). This distinction is of considerable importance, both theoretically and practically. For example, (re)training programs for elderly drivers should emphasize (a) the importance of quick decisions if the elderly are merely overly cautious or (b) age-related limitations if the elderly are characterized by the need for more time to process information. In order to provide data relevant to these alternatives, the test battery developed for this project included both response latency and backward masking procedures.

Stimulus Factors

There are a number of properties of a stimulus and of a set of stimuli that affect the speed and accuracy with which they are processed. The *similarity* of two stimuli affects the time required to determine that they differ (i.e., discrimination latency), and the similarity between a particular stimulus and other members of the stimulus set affects the time required to identify that stimulus (Monahan & Lockhead, 1977; Nickerson, 1962). Moreover, age-related differences in processing time have been shown to increase with stimulus similarity (Botwinick et al., 1958; Lindholm & Parkinson, 1983).

Stimulus similarity can vary in a number of ways, including, but not limited to, the following: First, the similarity of two stimuli can be a function of the magnitude of the difference on a single dimension or attribute. For example, a line 2.5 cm long is more similar to a line 2.6 cm long than to a line 5 cm long. Second, if stimuli vary with respect to several attributes, similarity may be a decreasing function of the number of attributes with respect to which the stimuli differ. For example, if stimuli could differ in orientation, size, and shape, two stimuli which differed in both size and shape would be less similar than two stimuli which differed only in size. Third, similarity can depend upon which attribute differs. For example, two stimuli that differed in size might be either more or less similar than two stimuli that differed in shape, depending on the salience of the relevant attribute and the magnitude of the difference.

Properties of individual stimuli themselves also affect processing time. Two such properties are pattern "goodness" and spatial frequency. Pattern goodness is a rather loose concept, but, as the term is used here, there is evidence that good patterns are processed more efficiently or maintained in memory more easily than poor patterns (Garner, 1978; Garner & Sutliff, 1974). It is not known whether goodness effects vary with age.

The analysis of visual patterns in terms of their spatial frequency is quite new. There is evidence, however, that the visual system can be viewed as a spatial frequency analyzer. Moreover, research indicates that low spatial frequencies, which correspond to the large global aspects of patterns, are processed more quickly than high spatial frequencies, which correspond to the fine details of patterns (Breitmeyer, 1975; Vassilev & Mitov, 1976). Because similar patterns often differ only in their high frequency components, this difference in processing speed could explain some similarity effects. If so, data which have been interpreted as evidence that the elderly are disproportionately affected by stimulus similarity may have resulted from a specific age-related reduction in the speed with which the high spatial frequencies are processed. Support for this interpretation is provided by a recent study in which the age difference in detection latency for high contrast gratings increased as the spatial frequency of the grating increased from 2 to 12 c/deg (Kline et al, 1983).

In the research reported here, stimulus similarity was manipulated both by varying the magnitude of a single-attribute difference and by varying the number of attributes with respect to which stimuli differed. Pattern goodness and spatial frequency were also varied.

Information Processing Efficiency and Aging

Advanced age is known to be associated with deficienies in both spatial and temporal aspects of visual processing (e.g, Lindholm & Parkinson, 1983; Sekular & Owsley, 1982; Walsh, 1982). Little is known, however, about the underlying structure of age-related differences. For example, it is not yet known whether the elderly are characterized by specific and fairly independent processing deficits or whether aging is associated with general deficiencies that affect all aspects of cognitive functioning. The goals of setting design standards to accommodate the elderly and of designing screening instruments to detect individuals with processing deficiencies of a severity to preclude safe driving will be much easier to achieve if age-related differences can be accounted for by a few general factors.

The primary task battery developed for this project was designed to assess the nature of age-related differences in very basic processing capacities. The selection of tasks and stimuli was guided by the hypotheses that aging is associated with a general reduction in processing speed, as has been suggested by Birren (1974), and an increase in neural noise, as has been suggested by others (e.g., Vickers et. al, 1972; Welford, 1977). As conceptualized here, a general reduction in processing speed would affect all stages of information processing, resulting in a constant relative increase in processing time across a variety of tasks. "Neural noise" is thought to determine the variation in sensory effect produced by a stimulus and, in this sense, in synonymous with "processing error." (It is assumed that the nervous system does not transmit information with perfect fidelity; the greater the level of neural noise the greater the variation in processor output given a particular input.) The effects of neural noise are thought to become apparent when "similar" stimuli must be discriminated or identified: A high level of neural noise would result in disproportionately long processing times or, if processing time were limited, low performance accuracy.

Research Approach

Nine experiments were conducted. The tasks differed in the cognitive processes upon which a response was based, the characteristics of the stimulus set, and the method used to assess processing time. Because our primary purpose was to answer questions concerning the nature of age-related differences in visual processing capabilities, analyses of variance were conducted throughout, and group means are reported.

For experiments in which response latency was the primary dependent variable, analyses were conducted on a logarithmic transformation of the median response latency for each condition of interest. Medians rather than means were used because the individual latency distributions tended to be positively skewed, with a few aberrant scores. The medians were subjected to a log transform for two reasons: (1) The distributions of median latencies within an age x condition cell tended to be positively skewed, and the within cell means and variances tended to be positively correlated. The log transform helped to normalize the distributions and to reduce the relationship between the means and variances. (2) As developed by Lindholm and Parkinson (1983), the hypothesis that age is associated with a general reduction in processing speed predicts that the response latencies of old and young will be related by a constant factor across conditions. Therefore, on a log msec scale the difference between old and young would be constant across conditions. Because interaction terms in an analysis of variance test whether the arithmetic differences between levels of one variable vary as a function of another variable, the interactions involving age in an analysis of log msec provide a test of the hypothesis that age differences can be accounted for by a general reduction in processing speed.

EXPERIMENTS

General Method

Subjects

Sixty people served as subjects -- 10 men and 10 women in each of 3 age groups: young (mean age = 21.2 years; range 17 to 27), middle-aged (mean age = 42.1 years; range 37 to 52), and elderly (mean age = 68.8 years; range 65 to 78). All of the subjects were volunteers, and all had active driving licenses. Most of the younger subjects were students at Arizona State University Many of the middle-aged subjects were nonacademic staff at the University. The elderly subjects were members of various church groups and senior citizen organizations. Most of the subjects were paid $40 for their participation; a few of the young subjects received less money in combination with course credit for their participation.

A brief interview and a personal history questionnaire were used to ensure that the final sample of subjects included only people without known ocular pathology or damage to the central nervous system. In addition, each subject's acuity was measured with a standard Snellen chart under normal indoor lighting. With the exception of one elderly man (whose acuity was 20/40), all of the subjects had corrected binocular acuities of 20/30 or better.

This sampling procedure did not result in random samples of young, middle-aged, and elderly Arizona drivers, and it is unlikely that the samples were equally representative of their respective populations. The levels of performance shown by a group of subjects can not, therefore, be assumed to be accurate estimates of the performance capabilities of Arizona drivers of that age. Nor are the observed differences between groups necessarily good estimates of age-related differences in the population. On the other hand, a variety of sampling techniques have been used in the study of age-related differences in sensorimotor and cognitive capacities, and performance differences, in favor of the young, have been found with great consistency. Thus, age effects are robust: Although the magnitude of an observed age effect is likely to be somewhat biased, the direction of the difference is unlikely to be affected by the nonoptimal sampling procedure. Moreover, our interest was in the pattern of results within and across experiments, that is, in the interaction of age and task or stimulus variables. These interactions should be relatively bias free.

Procedure

Subjects were tested individually for six sessions. Each session lasted from 1 to 1 1/2 hours. To prevent fatigue, the sessions were scheduled on different days and, within a session, a short break was scheduled after every block of trials. The blocks varied somewhat in duration but were usually less than 8 minutes.

At the beginning of the first test session, the general nature and purpose of the research were fully explained, and the subjects were given a University approved consent form to sign. With the exception of Experiment 1, for which the instructions were presented orally, the subjects were given typed instructions at the beginning of each experiment. For Experiments 2 to 8, the instructions were accompanied by photographs of the stimulus patterns. Questions were answered as fully as possible before testing began.

The subjects participated in Experiments 1 and 2 during Session 1, Experiment 3 during Session 2, Experiment 4 during Session 3, Experiments 5 and 6 during Session 4, Experiments 7 and 8 during Session 5, and Experiment 9 during Session 6. The experiments were presented in numerical order, with two exceptions: (a) Half of the subjects in each age x gender group were tested with the procedures of Experiment 8 before they were tested with the procedures of Experiment 7, and (b) some of the subjects participated in Experiment 9 before they had completed the rest of the test procedures.

Experiment 1:

Dynamic Visual Acuity

Most acuity tests measure the minimum angular distance between two contours that a person can detect. In standard (static) tests the stimuli are stationary, whereas in a test of dynamic acuity the stimuli move. Response latency is not measured in either type of acuity test. The time available for processing does, however, vary as an inverse function of stimulus speed in the dynamic acuity test. Ocular pursuit accuracy and peripheral acuity also contribute to discrimination accuracy when the target moves (Brown, 1972).

Method

Apparatus and stimuli. The test apparatus for the dynamic visual acuity experiment was developed by Burg (1965) and donated for use in this project by the University of California - Los Angeles. The acuity targets were projected onto a 180 degree cylindrical screen, 4 feet in radius. The projector was mounted in a rotatable cradle driven by a variable speed motor. Checkerboard targets of the type used in the Bausch & Lomb Ortho-Rater served as stimuli (see Figure 1). The squares of the projected target grids varied in size from 10.0 to .67 minutes of arc, in 15 steps.

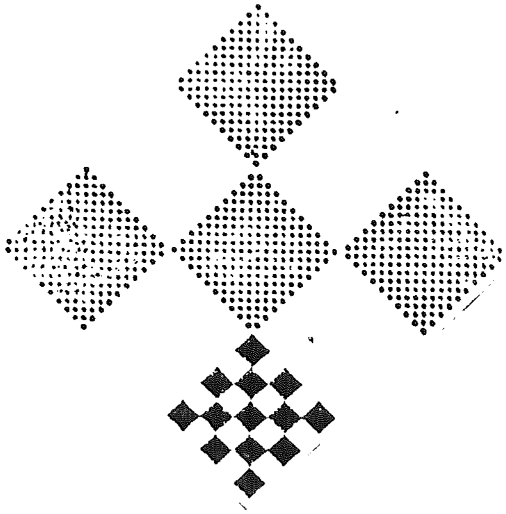

Figure 1. Sample stimulus for Experiment 1.

Procedure. In Burg's (1966) study, acuity was assessed for targets moving at 0, 60, 90, and 120 degrees of arc per second. These tests were given in ascending order of speed. For each test, targets were presented in sequence, from largest to smallest, until the subject responded incorrectly to two successive slides.

In order to increase the reliability of the acuity measures, we modified Burg's procedure by the addition of a second slide of each target size for each test. We also added a second test at each speed to provide a control for and a measure of practice effects.

Two sets of 30 slides each were constructed. Each set contained two slides of each grid size. Each of the four possible grid locations was used once for every grid size, as a partial control for response and projection biases.

A static acuity test and three dynamic acuity tests (60, 90, and 120 degrees per second) were presented to each subject, first in ascending and then in descending order of speed. The two sets of slides were presented alternately. Thus, each set was presented once at each presentation speed. The slides within a set were presented in sequence from largest to smallest.

The subjects were instructed to indicate the position of the target grid by saying "top," "bottom," "left," or "right." They were advised that they were free to move their heads and were cautioned that they would have to respond very quickly during the higher speed tests. Testing continued until the subject gave an erroneous response to both of the slides of a given target size.

Results

In Burg's study, a subject's acuity score for a given speed was based on the target preceding two consecutive errors, i.e., the smallest target for which a correct response was given. In the present study, because there were two slides for each target size and subjects were tested until they responded incorrectly to both, acuity scores could be based on either a) the target preceding the first two consecutive errors or b) the target preceding the size for which both responses were in error (i.e., the smallest target for which a correct response was given). Since statistical analyses indicated little difference between the two scoring criteria, only the results based on the target preceding the first two consecutive errors will be reported. This is the more conservative criterion and, thus, closer to the one used in the prior study.

In Burg's study, a subject's score for each speed corresponded to the visual angle subtended by the checkerboard squares in the smallest target for which a correct response was given. He found that acuity declined as target speed increased and as age increased. In addition to these main effects, the magnitude of the age-related decline was found to increase with target speed. In other words, the deleterious effect of target speed was greater for elderly than for young adults.

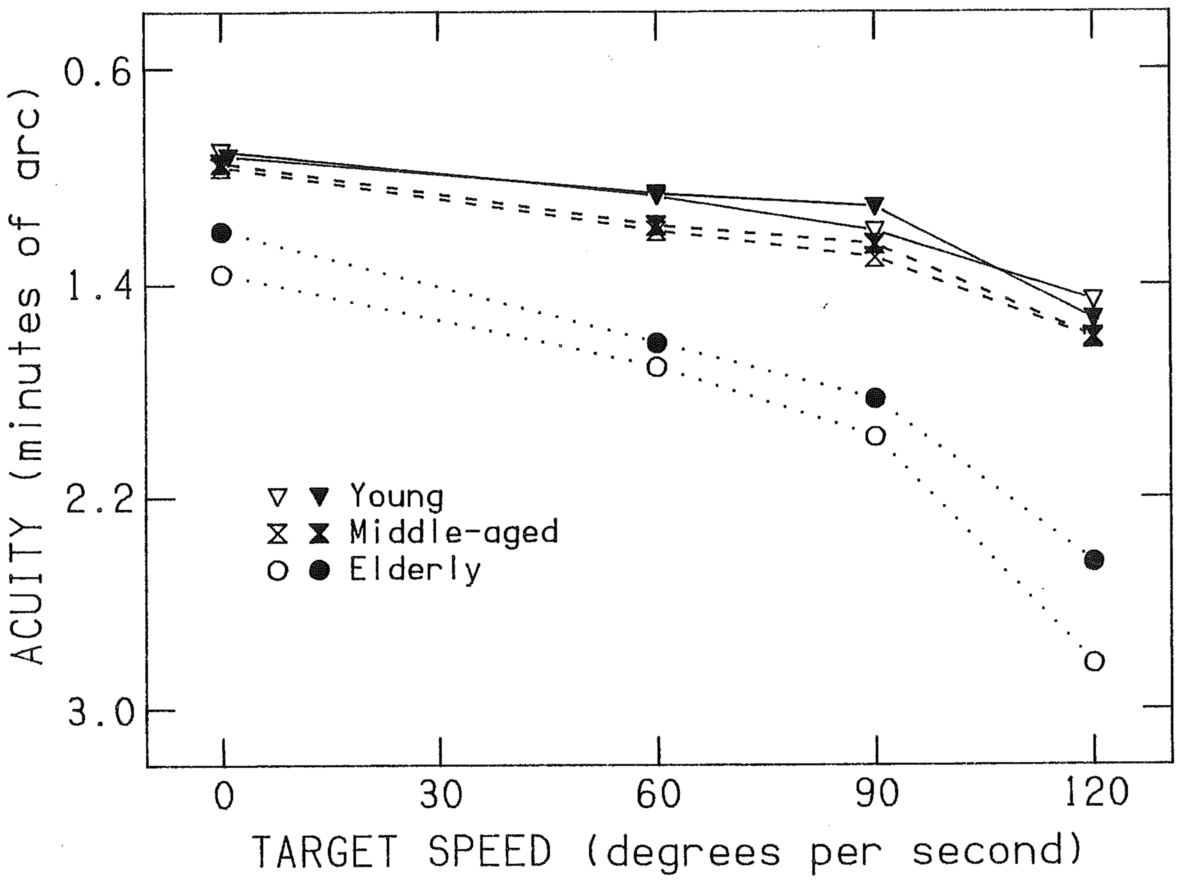

Figure 2. Acuity (minutes of arc) as a function of target speed, for the three age groups in each test series (open symbols = series 1; closed symbols = series 2).

Figure 2 presents the results of the present experiment when the visual angle of the squares in the target preceding two consecutive errors was used as the dependent variable. Each point in the figure represents the average visual angle for the subjects in one age group for one test speed and test series. The first, ascending test series is represented by open symbols; the second, descending test series is represented by closed symbols. Statistical analysis supported the observation that acuity declined with target speed and with age. In addition, acuity scores for the elderly were significantly higher on the second, descending test series. Thus, the age difference was reduced by a small amount of practice. Finally, the decline in acuity as target speed increased was greater for the elderly than for the young and middle-aged groups. There were no significant effects associated with subject gender.

These findings essentially replicate those of Burg, although he found better acuity scores for males than for females (at all ages) and somewhat lower scores, in general, than those in the present study. At least one other study with a large number of subjects, The Framington Eye Study (reported in Pitts, 1982), found that males had better acuity than females, although in the latter study the difference was confined to people older than 65 years (people younger than 52 years were not tested). This concordance suggests that the gender effect in Burg's study was not merely an artifact of the testing procedure. Our failure to replicate this finding can probably be accounted for by the relatively small number of subjects we tested.

The tendency for acuity scores to be higher in our study than in Burg's could have resulted from a variety of factors: (a) Our sample was undoubtedly a more select group; (b) the procedure in the present study differed from Burg's in that we presented two rather than one slide for each target size; and (c) our instructions emphasized that there would be very little response time at the higher speed and that a better score would be obtained if a response was given on every trial, even if the response was just a guess.

Interpretation of these findings (and those of Burg) is complicated by two issues with respect to the visual acuity scale used. The more basic issue concerns the proper scale for measuring visual "capacity." For example, is a drop in acuity form 20/20 to 20/40 functionally equivalent to a drop from 20/40 to 20/60, as is assumed with a visual angle scale? Given different static acuities, the magnitude of the decline in acuity resulting from target movement will depend upon the scale used. Since the static acuity of elderly adults is, on the average, poorer than the static acuity of young adults, the acuity scale will determine the form of the age by speed interaction.

With respect to the present experiment, the question of scale is further complicated by the Bausch & Lomb stimulus set. The 15 target sizes ranged from 10.0 to .67 minutes of arc, but the step sizes were not equal on a visual angle scale. For example, the squares of the fourth largest target size, No. 4 of the Ortho-Rater sequence, subtend an angle of 2.5 minutes of arc. (This corresponds to a Snellen acuity of 20/50). The squares of No. 5 (Snellen acuity = 20/40) subtend an angle of 2.0 minutes. This difference of .5 minutes is to be compared to a difference of only .09 minutes between No. 10 (20/20) and No. 11 (20/18). The larger the visual angle the larger the step size between successive targets. At the high end of the scale, acuity differences as small as .05 minutes of arc can be distinguished. In contrast, target sizes 1 and 2 differ by 5 minutes. If a person could resolve a visual angle of 5.2 minutes but not one of 5.0 minutes, his score would be 10 minutes, the next larger visual angle tested. This nonlinearity may have contributed to the finding that age differences in acuity increased with the speed of the target stimulus.

In order to test the importance of these considerations for the results of the present study, a second analysis was conducted, with spatial frequency (cycles of dark and light per degree of arc) as the dependent variable. The Ortho-Rater target sizes are equally spaced with respect to spatial frequency: Successive target sizes differ by three cycles per degree.

Figure 3 presents detectable spatial frequency as a function of target speed for each of the three age groups. In accord with the analysis of visual angle, the effects of age and speed were both significant. With spatial frequency as

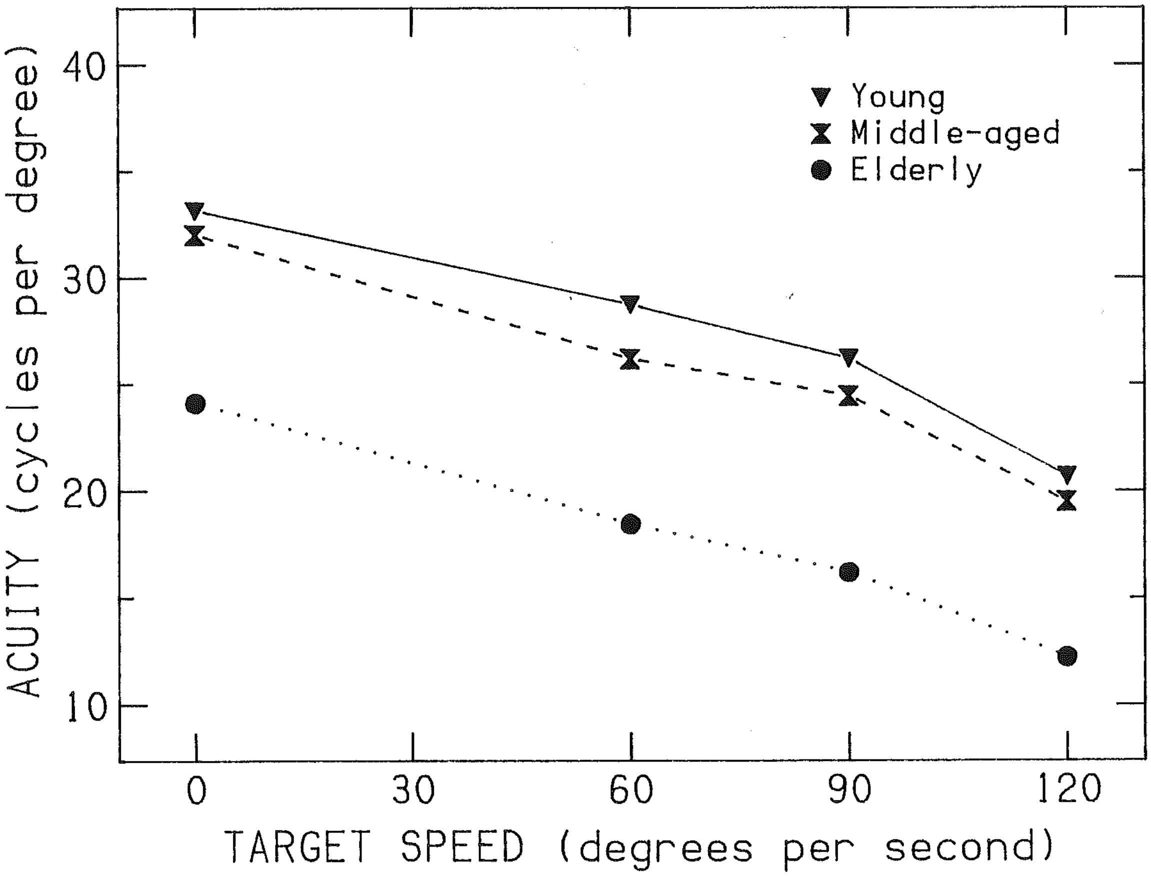

Figure 3. Acuity (cycles per degree) as a function of target speed for each age group.

the dependent variable, however, there was no tendency for age differences in acuity to increase with increases in target speed. Moreover, although acuity scores were somewhat higher on the second test series than on the first, the magnitude of the practice effect did not vary significantly with age in this analysis. Thus, when acuity is defined as the spatial frequency resolvable, it appears that, for the groups sampled in this study, age is not a determinant of the magnitude of the decline in acuity associated with target speed. Nor is the magnitude of the age difference a function of practice.

Apparatus for Experiments 2 to 8

A Digital Equipment Company PDT 11/150 microcomputer was programmed to control all aspects of Experiments 2 to 8. With the exception of the device handlers, which were written in assembly language, all of the programs were written in FORTRAN.

The stimuli consisted of dark lines against an illuminated background. They were presented on a Hewlett-Packard 2648A Graphics Terminal. This terminal is a raster scan device with a refresh rate of 60 Hz and P4 phosphor, which decays to 10% in 60 microseconds. Patterns can be generated and stored in the graphics memory, while the display is off, and presented subsequently, fully formed, in one raster scan.

A millisecond clock attached to one of the input/output channels of the computer was used to measure response latencies and to control the intertrial intervals (which were fixed at 3 seconds, measured from the subject's response). A photocell mounted on the upper left corner of the graphics screen provided the computer with precise information regarding the onset of the stimulus display.

The subjects viewed the graphics screen from a distance of approximately 68 cm. This distance was maintained by a "viewing tunnel" which was affixed to the front of an enclosure for the terminal. The tunnel was opaque and painted black to limit the visual field and to minimize reflectance. Wearing their normal corrective lenses, subjects rested their foreheads against a plastic rim attached to the end of the tunnel. Behind the rim a pair of oversized lenses, mounted at their focal distance (66.7 cm) from the screen, placed the display optically at an infinite distance from the subject. The horizontal positions of the lenses were adjusted for each subject.

The subjects were seated in a modified barber's chair, which contained a hydraulic lift that allowed the vertical position of the subject to be adjusted over a wide range. An adjustable headrest was used to stabilize the subject's head. A response switch was mounted on each arm of the chair.

Experiment 2:
Length Discrimination

The capacity of interest in the length discrimination task was not the resolving power of the visual system, but the processing time necessary to make such discriminatory judgements. Discrimination difficulty was varied by manipulating only one dimension of the stimulus -- line length.

Method

Stimuli. The stimuli consisted of two vertical lines, as illustrated in Figure 4. The longer of the lines appeared equally often as the left and right sides of the pattern. The shorter of the two lines varied in length such that the difference in the lengths of the two lines ranged from approximately 1 mm (1 pixel) to approximately 10 mm (10 pixels). When viewed from a distance of 66 cm, 1 mm subtends a visual angle of approximately 5.2 minutes and 10 mm subtends an angle of approximately 52 minutes.

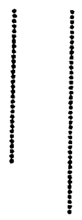

Figure 4. Sample stimulus for easiest discrimination (Experiment 2).

Procedure. The subject's task was to indicate, via a button press, the relative position of the longer line. On each trial a small fixation square appeared for 250 msec, beginning 500 msec before target onset. This "warning" stimulus served to alert the subject and to specify the screen location of the ensuing target.

Lines differing by 10 pixels (the easiest discrimination) were presented for 1 raster scan during the first 24 of 54 practice trials. The 1-scan presentation produced a very low intensity stimulus and was used to insure that subjects did not suffer from ocular pathology that severely reduced the light reaching the retina. The remaining 30 practice trials consisted of 3 trials at each of the levels of discrimination difficulty. These practice trials, as well as the test trials, were displayed until the subject responded, or for 3 seconds.

Two test blocks of 80 trials each were presented. Each block of trials consisted of 8 presentations of each of the 10 differences in line length, 4 with the long line on the left and 4 with the long line on the right. Order of presentation was random with the restriction that each possible stimulus was presented once in each block of 20 trials.

Subjects were instructed to press the button on the side of the longer line, as quickly as possible without making errors. They were told to guess if they could not resolve the difference. If the subject failed to respond within 3 seconds, a "nonresponse" was recorded and the next trial was presented.

Any stimulus to which the subject failed to respond was subsequently repeated.

Results

The data for each subject were reduced by determining the error rate and log median correct response latency for each combination of discrimination difficulty, side of long line, and block.

The main results are presented in Figure 5. For ease of interpretation, in this and subsequent figures, the means of the log median scores were reconverted to milliseconds and plotted on a logarithmic scale. The difference in line length is also plotted on a logarithmic scale, to clarify the shape of the psychometric function.

As shown in Figure 5, discrimination difficulty had a substantial effect upon the response latencies of subjects in all three age groups. On a log-log scale, latency decreased linearly from a difference of 1 pixel (5.2 minutes of arc) to a difference of 3 pixels (15.6 minutes of arc). Additional increases in the magnitude of the difference, out to the maximum difference of 10 pixels (52 minutes of arc), were accompanied by smaller and less regular decreases in latency.

In contrast to our expectation and the results of most previous research examining age differences in response latency, overall response latency did not vary significantly with age in this experiment. Nor did the age groups differ in the increase in response time that resulted from an increase in discrimination difficulty. We suspect that these results

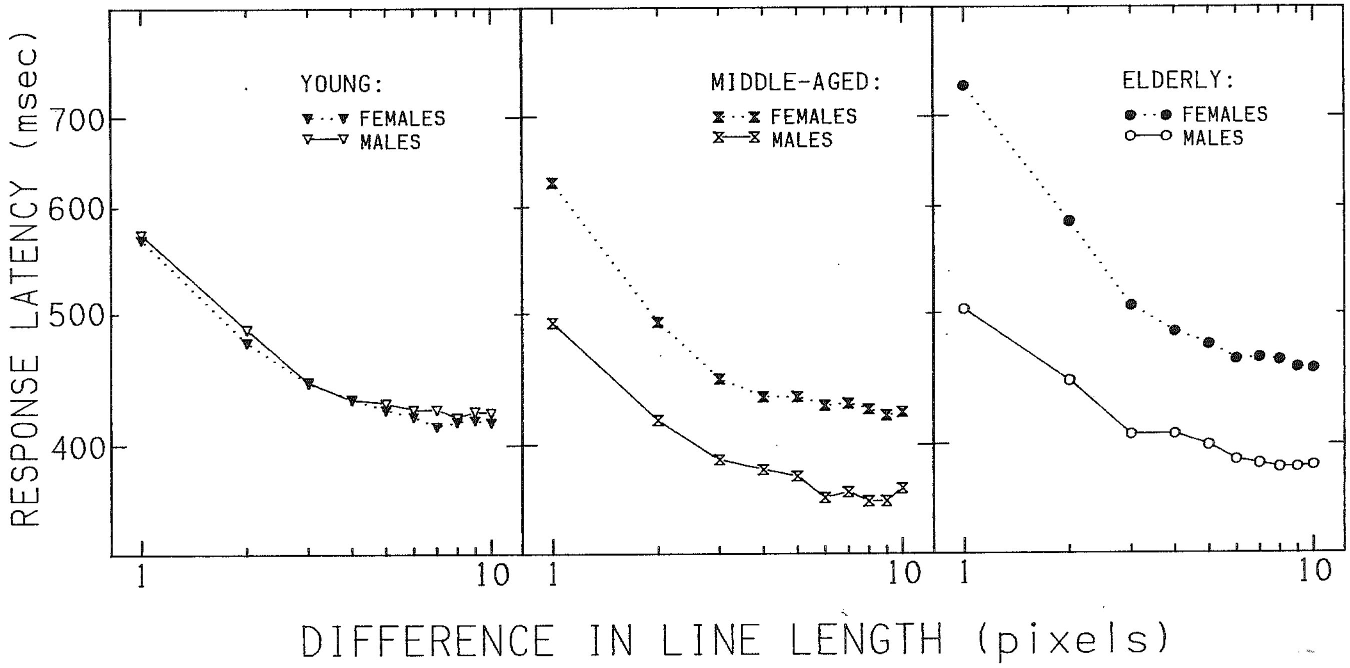

Figure 5. Response latency as a function of the difference in the lengths of the two target lines, for the males and females in each age group (Experiment 2).

reflected both the relatively low level of cognitive processing required by the task and the high degree of motivation and competence of the elderly people in our sample.

Males responded significantly faster than females in this experiment. The interaction of gender and discrimination difficulty was also significant: The difference between males and females was disproportionately large for the more difficult discriminations. Although neither the age x gender nor the age x gender x discrimination difficulty interaction reached statistical significance, inspection of Figure 5 reveals that the gender effect was restricted to the two older age groups. We suspect that the gender difference in response latency resulted from a difference in the relative emphasis on accuracy: Although error rate was low on this task (.71%) and did not vary significantly with age or gender, there was a tendency for middle-aged and elderly females to make fewer errors than middle-aged and elderly males.

Experiment 3:
Backward Masking I

Backward masking procedures were employed in this research project in order to examine age-related differences in processing time under conditions in which response criteria effects were reduced or eliminated. Our goal in the first masking task was to obtain a measure of processing time free of neural noise as well as response criteria effects. Therefore, subjects were presented with a discrimination task of such a low level of difficulty that neural noise should have had no effect (see Vickers et al., 1972).

Method

Stimuli. The target stimuli consisted of two lines which differed in length by 10 pixels (the easiest discrimination in the Experiment 2). Extensive pilot testing was conducted to determine the characteristics of an effective mask for these stimuli. The pattern chosen is presented in Figure 6. When superimposed on either target, this pattern contained lines (8 and 11, from the left) that covered and extended beyond the target lines as well as lines that ended in the same vertical positions as the target lines. (The lower ends of lines 1, 4, 7, 12, 15, and 18 corresponded to the position of the lower end of the longer target line; the lower ends of lines 3, 6, 9, 10, 13, and 16 corresponded to the position of the lower end of the shorter target line.)

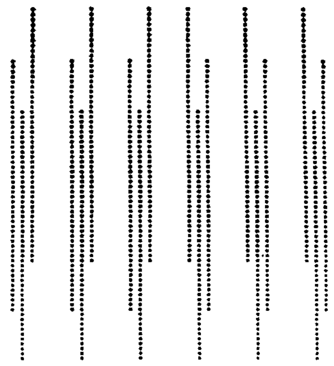

Figure 6. Masking stimulus for Experiment 3.

A ZOOM feature of the Hewlett-Pachard terminal allows different parts of the display memory to be presented on successive scans. Thus, the target and mask stimuli were built and stored with the display off and then presented, successively, in precise alignment. The SOA was controlled by varying the number of raster scans (1 to 20) for which the target was presented. The mask was always presented for 20 scans (333 msec).

Procedure. Two independent estimates of the SOA to evade masking were determined simultaneously. Trials from the two sequences were interleaved at random.

There were 70 practice trials prior to the test trial blocks. During the first 32 trials, SOAs from 333 msec (20 scans) to 217 msec (13 scans) were presented in descending order. The next 54 practice trials started with an SOA of 200 msec (12 scans). Subsequent practice SOAs were determined by an adaptive rule: If an error occurred on a trial the SOA was increased by 1 scan on the next trial. Three successive correct responses for a given SOA caused the SOA for the next trial to be decreased by 1 scan.

Three test blocks of 96 trials (+ 6 practice) were presented. The SOA for a given estimate was determined by an adaptive rule which converges on 84.1% accuracy (SOA_{84}): If an error occurred on a trial the next longer SOA was presented on the following trial. Four correct responses in succession for a given SOA caused the next shorter SOA to be presented on the following trial.

The subjects were instructed in indicate the position of the longer target line by the appropriate button press. It was explained that the computer was programmed to present SOAs near their thresholds and that, therefore, they would frequently have to respond with their "best guess." The importance of responding on every trial was stressed.

Results

The data were reduced by determining the median of the "peak" and "valley" SOAs for each of the two estimation sequences. (A "peak" is the first SOA for which the subject is correct four times in succession following an error on a shorter SOA. A "valley" is an SOA for which an error is made following a run of at least four correct responses.) The two median estimates were subjected to a logarithmic transformation before analysis.

The results of this experiment were in sharp contrast to those of the length discrimination task. The SOA necessary to evade masking was strongly related to subject age but unrelated to subject gender, as shown in Table 1.

Table 1

SOA necessary to evade backward masking (in msec)

	Gender:	
Age Group:	Male	Female
Young	54.24	51.84
Middle-aged	67.95	68.77
Elderly	88.29	89.11

Note. Each mean is based on 10 subjects. Each subject's score was the average of the logs of two independent estimates of the SOA necessary for 84.1% accuracy. The mean log values were reconverted to msec.

Experiment 4:

Backward Masking II

In the second backward masking experiment we were interested in the function relating performance accuracy and discrimination difficulty when processing time was limited to the time needed for an easy discrimination, i.e., a discrimination in which basic processing speed, independent of the effects of neural noise, would be expected to determine processing time. It has been hypothesized that neural noise determines the increase in processing time associated with an increase in discrimination difficulty. By this reasoning, if processing time is restricted to the time necessary for a discrimination for which neural noise is irrelevant, performance accuracy should reflect internal noise (Vickers et al., 1972).

Method

Stimuli. The first backward masking experiment provided us with an estimate of the SOA necessary for an individual to respond with 84.1% accuracy when lines differed in length by 10 pixels (52 minutes of arc), a discrimination which, presumably, reflected basic processing speed. This estimate was, however, rarely an exact multiple of the raster scan interval of the display terminal (1/60 of a second). Consequently, it was not possible to set the SOA to correspond exactly to the estimated value. Rather than employing some rounding procedure, a subject received the two raster scan values which spanned the estimated value. For example, if the SOA_{84} estimate for an individual was 60 msec (approximately 3.6 raster scans), the SOAs for that individual would have been 50 and 66.67 msec (3 and 4 raster scans, respectively). The two SOAs were presented equally often, randomly interleaved, except for the first four practice trials, in which the longer SOA was presented.

The target stimuli were the same as those used in the length discrimination task (see Figure 4). The mask stimuli, which were similar in form to the mask used in the first masking experiment (see Figure 6), varied with the length of the shorter target line. Variation in the mask was considered necessary because the effectiveness of the mask used in the previous masking experiment was due, in part, to the lines that ended at the same vertical positions as the target lines. In order to maintain this relationship between target and mask for those targets in which the difference in line length was less than 10 pixels, the vertical positions of the highest mask lines were moved down 1 pixel for each pixel increment in the length of the shorter target line. The mask for the most difficult discrimination is shown in Figure 7.

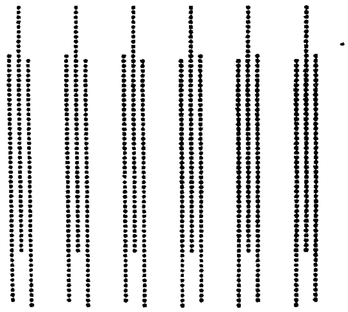

Figure 7. Mask for the most difficult discrimination, Experiment 4.

<u>Procedure</u>. Sixty-four practice trials were presented at the beginning of the test session. During the first 24, the target lines differed by 10 pixels. During the next 20, one

trial at each of the 10 levels of discrimination difficulty was presented for each SOA, in ascending order of difficulty. During the last 20, a second trial at each level of difficulty was presented, for each SOA, in random order. Each of the 5 test blocks consisted of 80 trials, 4 for each of the 10 differences in line length for each SOA. The longer line occurred equally often on the left and right sides for each of the combinations of discrimination difficulty and SOA. Restrictions on the random sequence ensured that practice effects were controlled for the two SOAs and 10 differences in line length.

The nature of the task was fully explained to the subjects. They were instructed to indicate the side of the longer target line by the appropriate button press and to guess if they could not resolve the difference. The importance of responding on every trial was emphasized.

Results

For each subject, the error rate was determined for each combination of discrimination difficulty, side of the long line, and SOA. These values are presented in Figure 8, averaged over subjects within an age group and side of the longer line.

As shown in Figure 8, the error rate declined as the difference in line length increased, for all three age groups. In contrast to the latency data for the length discrimination task, the decrease in error rate was essentially a linear function of the log difference in line length, throughout the

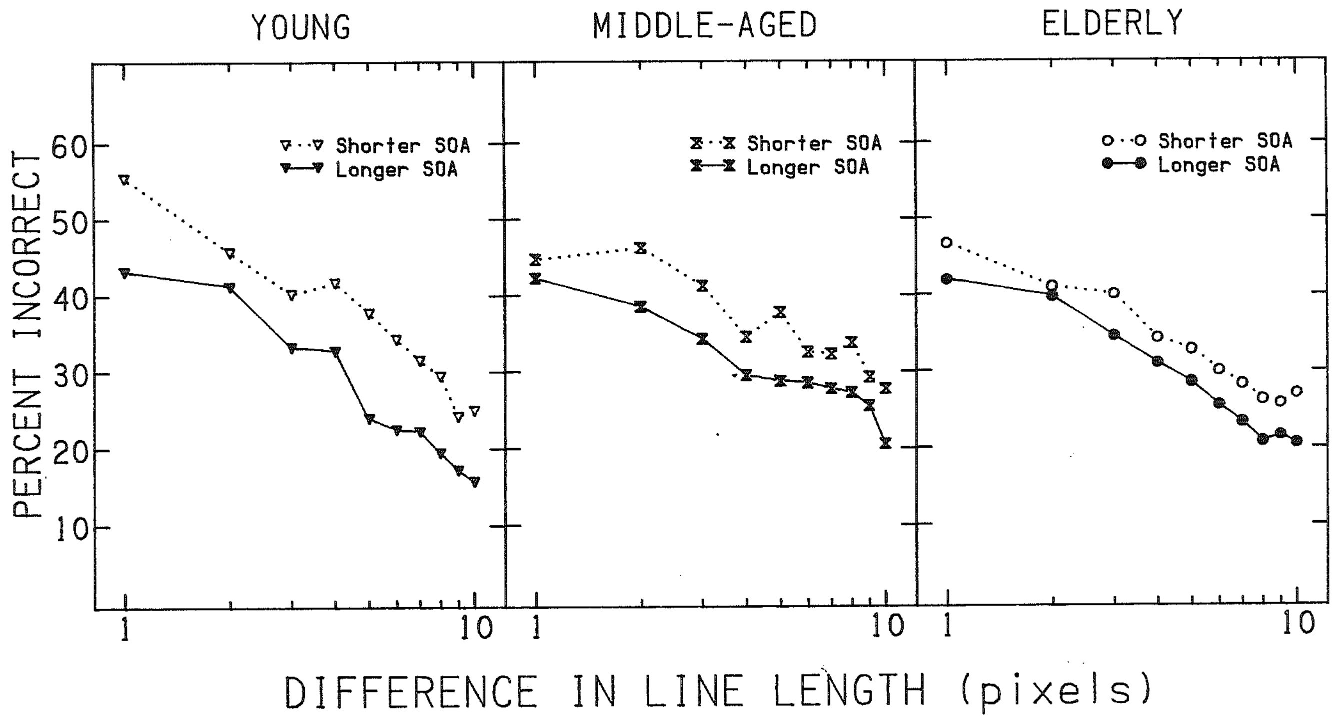

Figure 8. Percentage of incorrect responses as a function of the difference in the lengths of the two target lines, for each age group and SOA (Experiment 4).

range of differences studied. In addition, performance was significantly better for the longer of the two SOAs, at all levels of discrimination difficulty. Although the magnitude of this difference did not vary with discrimination difficulty, it did decline with age. In addition, the average percentages of correct responses for the two older groups were all less than 84%, even for the 10 pixel difference at the longer SOA.

Interpretation of these data is complicated by the fact that the group functions were not representative of the functions for the individual subjects. There were subjects, in all three age groups, who performed at chance for all levels of discrimination difficulty at both SOAs, whereas other subjects performed with close to 100% accuracy on the easier discriminations at both SOAs. Some of the subjects who performed most poorly showed high accuracy during the practice trials with a difference of 10 pixels. Other subjects, who performed well on the test trials, performed poorly on these initial practice trials. The heterogeneity of results suggests (a) that good performance on a task with trial-to-trial variation in discrimination difficulty (and mask form) may require somewhat different strategies or capacities than good performance on a task with trial-to-trial variation in SOA (and a constant mask) or (b) that within-subject variation in processing efficiency or strategy may be of sufficient magnitude that masking procedures can provide only a rough estimate of processing time.

Multidimensional Stimuli

The stimulus patterns for the next four experiments were constructed by combining two states of each of three different perceptual attributes: spatial frequency, shape, and orientation (see Figure 9). These stimuli were chosen because the attributes themselves are of interest and because stimulus dissimilarity is frequently defined in terms of the number of attributes with respect to which two stimuli differ.

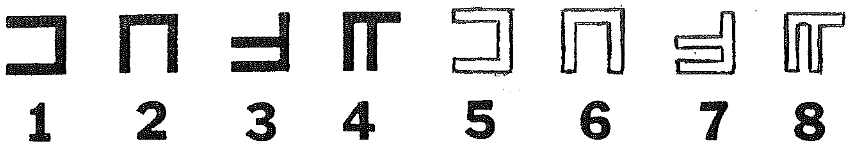

Figure 9. Stimuli for Experiments 5 to 8.

Pattern orientation is a very important attribute in many highway signs, and it has been suggested that the elderly find orientation information particularly difficult to process. As discussed the Introduction, low spatial frequencies (which are prominent in the patterns numbered 1 to 4) are processed more quickly than high spatial frequencies (which define patterns 5 to 8). In addition, there are data which suggest that processing time is inversely related to pattern goodness. Pattern goodness has been shown (Garner & Clement, 1963) to vary with the size of a pattern's rotation and reflection (R & R) subset (i.e., the number of possible orientations that can be assumed by a pattern as a result of a reflection or 90 degree rotation): The smaller the subset size, the better the pattern. By this definition, the C-like shape (with an R & R subset of size 4) is a better pattern than the F-like shape (with an R & R subset size of 8) and should be processed in less time.

Experiment 5:
Simple Reaction Time

In a simple reaction time task subjects are directed to respond to the onset of a stimulus. A minimum of processing is required, in that the subject need only detect the stimulus and execute a response. Stimulus dependent differences in response latency indicate that stimulus attributes differentially affect detection latencies.

Method

In the simple reaction time task used in this study, each of the 8 stimuli in Figure 9 was presented to each subject 20 times, for a total of 160 trials. The first 32 trials were considered practice. Subjects were directed (via a message on the display) to switch response buttons every 16 trials. The order of stimulus presentation was random with the restriction that each of the 8 stimulus patterns be presented once in each set of 8 trials and that each pattern be presented once as the first trial after a hand switch during the test trials. Subjects were instructed to respond as quickly as possible to stimulus onset.

The stimuli were displayed until the subject responded, or for 3 seconds. If the subject failed to respond in 3 seconds, a "nonresponse" was recorded and that trial was repeated at a later time.

Results

A subject's performance was represented by his or her median response latency for each target in each block. An analysis of variance was conducted on the logs of these values.

Response latency varied significantly with gender (males were faster than females) but did not vary significantly with age in this experiment. Spatial frequency was the only within subject variable to have a significant effect upon reaction time. As shown in Figure 10, latencies were shorter for the stimuli containing low spatial frequencies than for the stimuli containing only high spatial frequencies. Although this difference increased significantly with age, the magnitude of the spatial frequency effect, even for the elderly group, was of no practical importance.

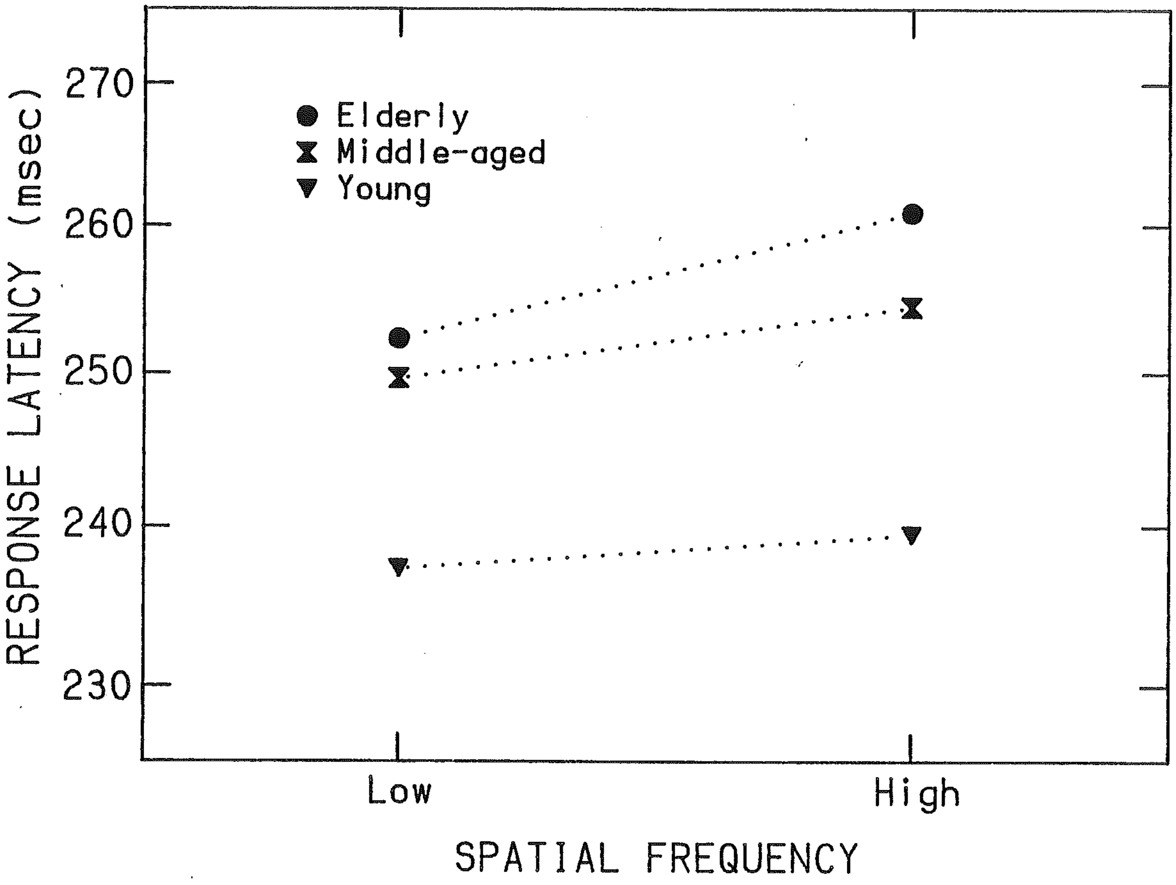

Figure 10. Response latency as a function of spatial frequency for each of the three age groups (Experiment 5).

Experiment 6:
Perceptual Matching

In a perceptual matching task two stimuli are presented on each trial and the subject must judge whether they are the same or different. In addition to the detection and response processes required in a simple reaction time task, perceptual matching requires encoding, comparison, and decision processes. Reflecting the increased processing demands, response latencies in a perceptual matching task are longer than in a simple reaction time task. Discrimination latency (the time to decide that two stimuli differ) tends to increase as a function of the similarity between the two stimuli.

Method

Stimuli. We used all of the 8 possible "same" pairs (2 exemplars of a stimulus) and 56 possible "different" pairs (exemplars of 2 different stimuli) that could be constructed from the stimulus set shown in Figure 9. The two stimuli in a "different" pair differed in 1 of 7 ways defined by the number and type of differing attributes. Specifically, they differed with respect to 1 attribute (spatial frequency, shape, or orientation), 2 attributes (spatial frequency and shape, spatial frequency and orientation, or shape and orientation), or all 3 attributes.

Procedure. Three blocks of 112 trials were presented. The first block was considered practice. Each block of 112 trials consisted of one instance of each "different" pair and seven instances of each "same" pair. The order of stimulus presentation was random with the restriction that, in each subblock of 16 trials, each stimulus was presented once as part of a "same" pair and once as the left member of a "different" pair.

Subjects were instructed to respond with their preferred hand when the two stimuli were identical and with their other hand when they were different. They were encouraged to respond as quickly as possible without making errors.

The stimuli were displayed until the subject responded, or for 3 seconds. If the subject failed to respond in 3 seconds a "nonresponse" was recorded and that trial was repeated at a later time.

Results

A subject's data for the "same" and "different" pairs were reduced separately. For the "same" pairs, the error rate and median correct response latency were obtained by block for each stimulus pattern. For the "different" pairs, the error rate and median correct response latency were obtained by block for each of the 7 types of difference. Except for inequalities introduced by errors, the median correct latencies for the 7 types of difference were equally influenced by the 8 stimulus patterns.

"Same" pairs. The main results for the "same" pairs are shown in Figures 11 and 12. In contrast to the findings for the simple reaction time task, overall response latency varied significantly with age as well as gender when the subjects

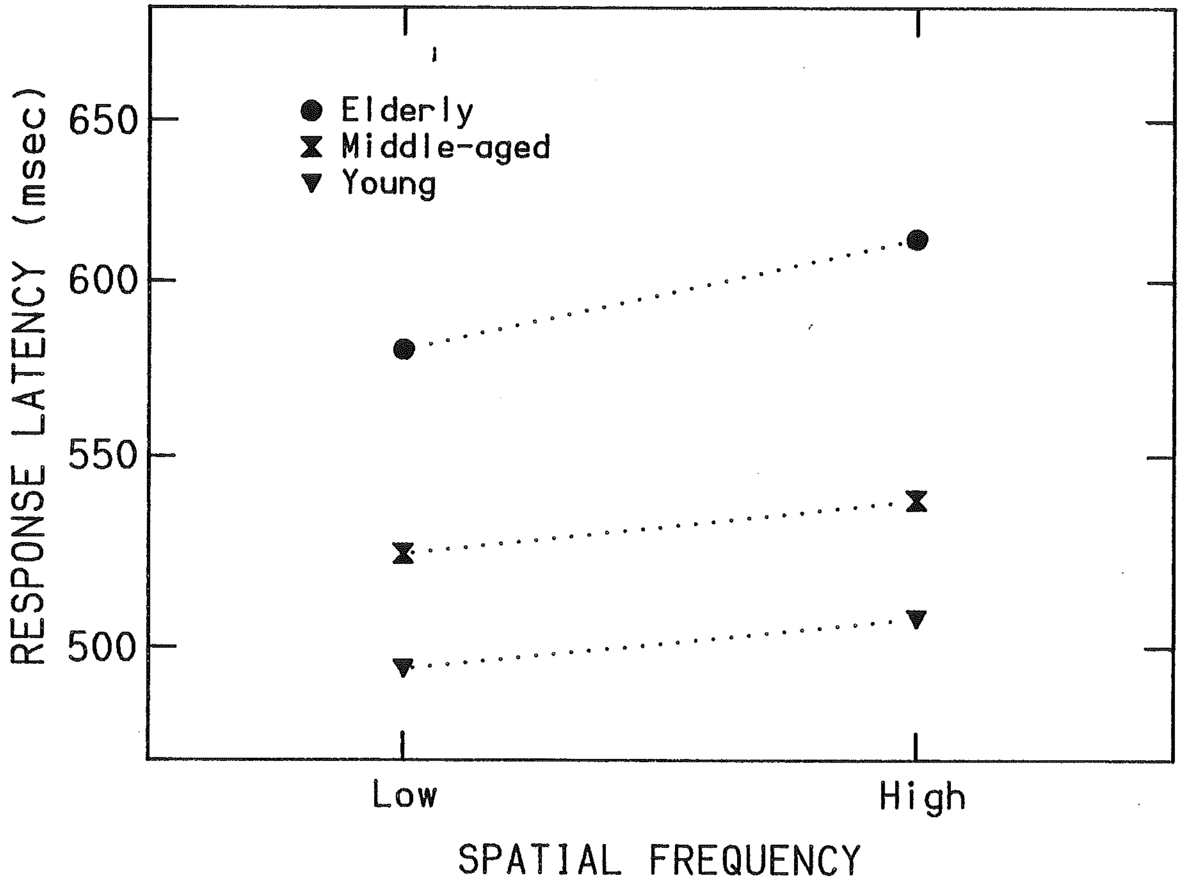

Figure 11. "Same" response latency as a function of spatial frequency for each of the three age groups (Experiment 6).

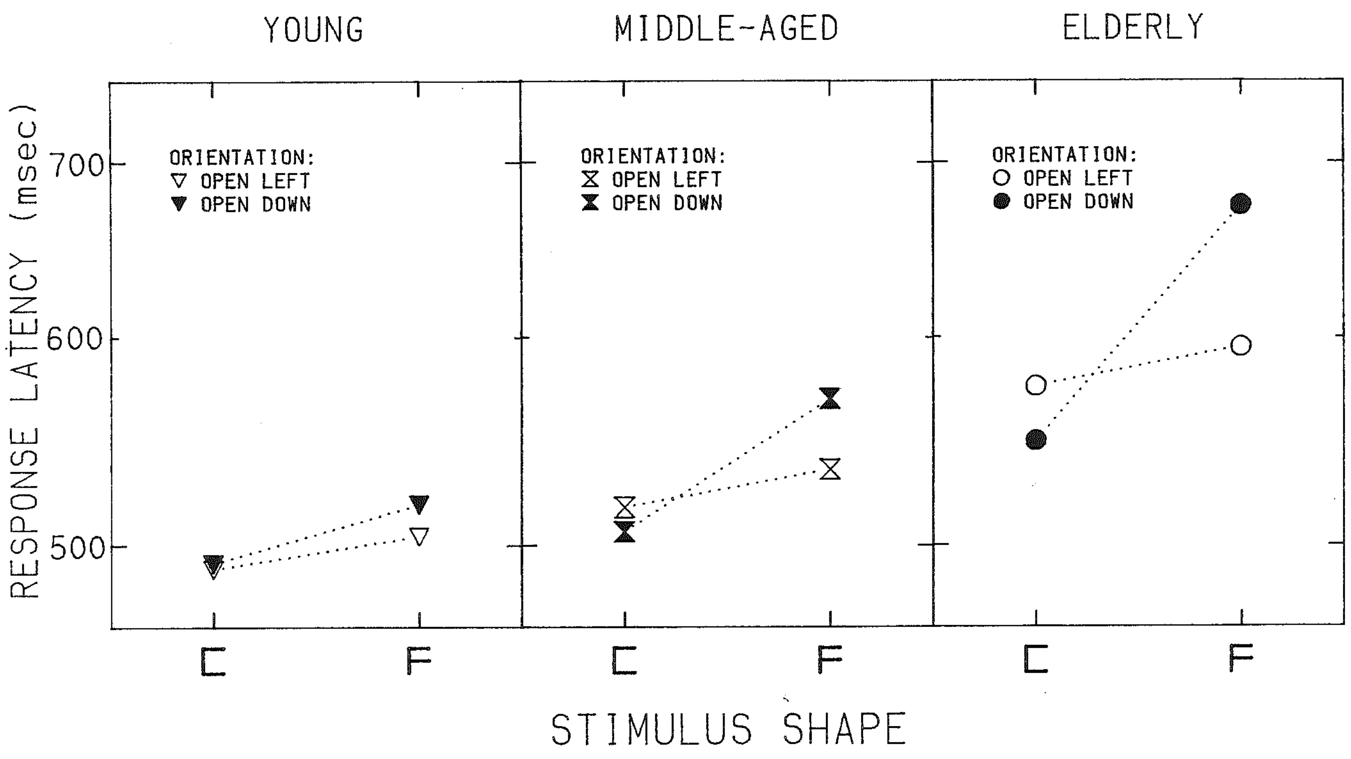

Figure 12. "Same" response latency as a function of shape and orientation for each of the three age groups (Experiment 6).

processed a stimulus pair sufficiently to determine that its members were identical. In addition, the main effect of spatial frequency and the age x spatial frequency interaction were both significant. As shown in Figure 11, stimuli containing only high spatial frequencies were responded to more slowly than stimuli that also contained low frequencies. The magnitude of this difference in latency was disproportionately large for the elderly group.

The main effects of shape and orientation were also significant. It took longer to decide that two F-like shapes were identical than to decide that two C-like shapes were identical. Averaged over the two shapes, latencies were shorter when the open part of the pattern was on the left than when it was down. The shape x orientation interaction was also significant, however. As shown in Figure 12, the effect of orientation was shape specific. Latencies for the C-like shape tended to be shorter when it was open at the bottom than when it was open on the left. The F-like shape showed a larger, reverse effect of orientation: Latencies were shorter when it was open to the left. Finally, both the shape and shape x orientation effects increased with age.

Although the shape effect was expected, the orientation and shape x orientation effects were not. It could be that the shapes appeared more "letter like" in one orientation than in the other, but the form of the interaction does not seem to be consistent with this explanation. Fox (1975) argued that symmetry about a vertical axis is uncharacteristic of "different" pairs and can thus be considered to be "diagnostic" of sameness in this type of task. He presented data that supported the hypothesis that "same" judgements can be made more quickly for pairs with vertical symmetry. In the present experiment, vertical symmetry was present only for the pairs of C-like shapes that were open at the bottom. The relatively short latencies for these pairs could have been due, in part, to this property. Although a full explanation of the pattern of results will require further research, whatever the bases of the shape x orientation interaction, it is important that the magnitude of the effect increased with age.

There was also an effect of blocks in this experiment. Latencies were significantly shorter in Block 2 than in Block 1. The magnitude of this practice effect did not vary with age, gender, or stimulus attribute.

The average error rate for the "same" pairs (i.e., false "different" responses) was only 2%. Differences in the error rates among patterns mirrored, roughly, the latency data. The error rate was comparable across age groups. Although the gender effect was not significant, the average error rate for the female subjects was lower than the average error rate of the male subjects.

In summary, with regard to age differences in information processing capabilities, the "same" data for this experiment indicate that there is an age-related increase in the time necessary to determine the identity of two simple geometric forms and that the relative magnitude of this effect depends upon the attributes of the stimulus.

"Different" pairs. For an analysis of response latency as a function of the number of attributes with respect to which the stimuli differed, the log median correct "different" latencies were averaged to yield three scores per subject, one for each number of differing attributes. As shown in Figure 13, response latency decreased as the number of differing attributes increased from from one to three. The main effects of age (as shown in Figure 13), gender (males faster than females), and blocks (2nd block faster than 1st) were all significant. None of the interactions approached significance.

The error rate for the "different" pairs also varied significantly as a function of the number of attributes with respect to which the two patterns differed. Averaged over groups, the incorrect response rates were 3.47%, .26%, and 1.04%, for pairs which differed on 1, 2, and 3 attributes, respectively. None of the effects involving age or gender approached significance.

The effect of stimulus attribute on the latency of a "different" judgement was assessed by an analysis of the log median correct latencies for the 3 ways in which stimuli in a pair could differ on only 1 attribute. The main effect of stimulus attribute was significant in this analysis: As shown in Figure 14, stimuli that differed in spatial frequency (and, thus, matched in shape and orientation) resulted in the

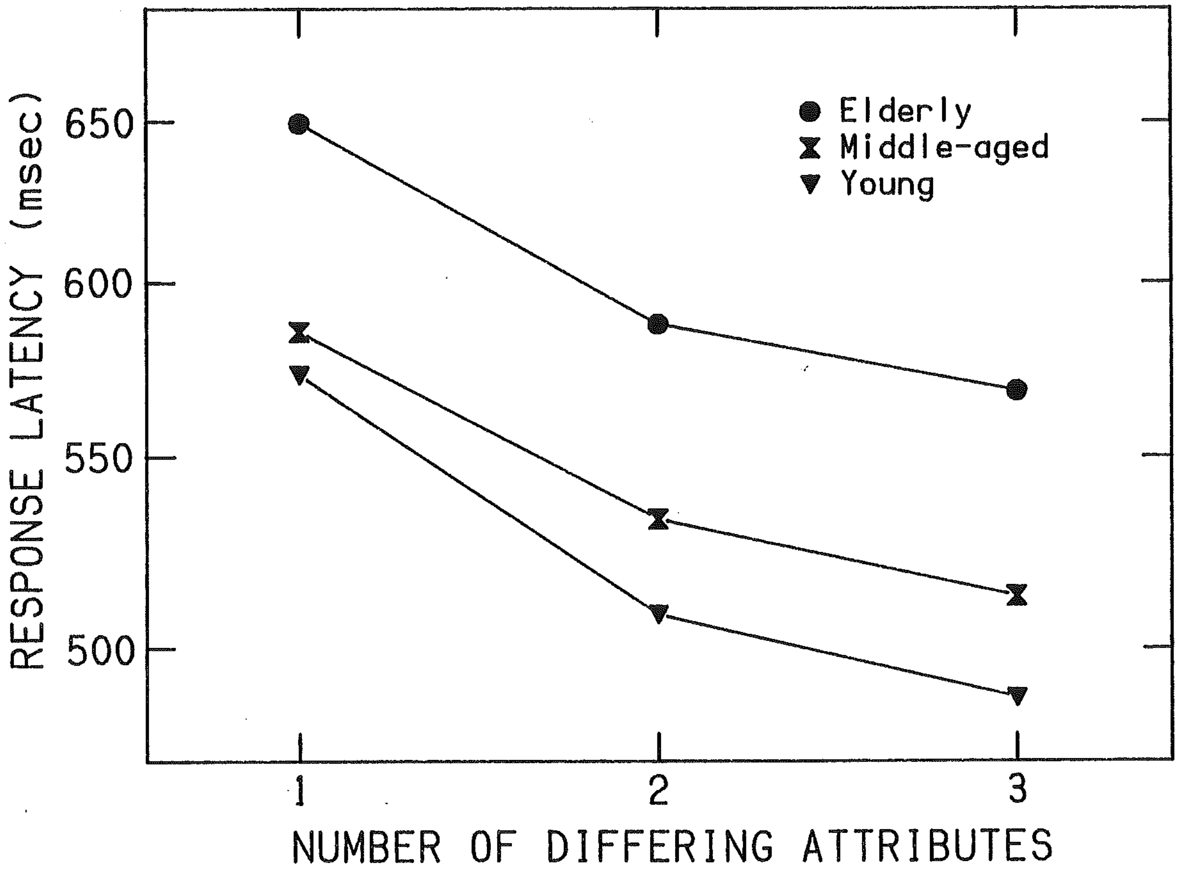

Figure 13. "Different" response latency as a function of number of attributes with respect to which the stimuli differed, for each of the three age groups (Experiment 6).

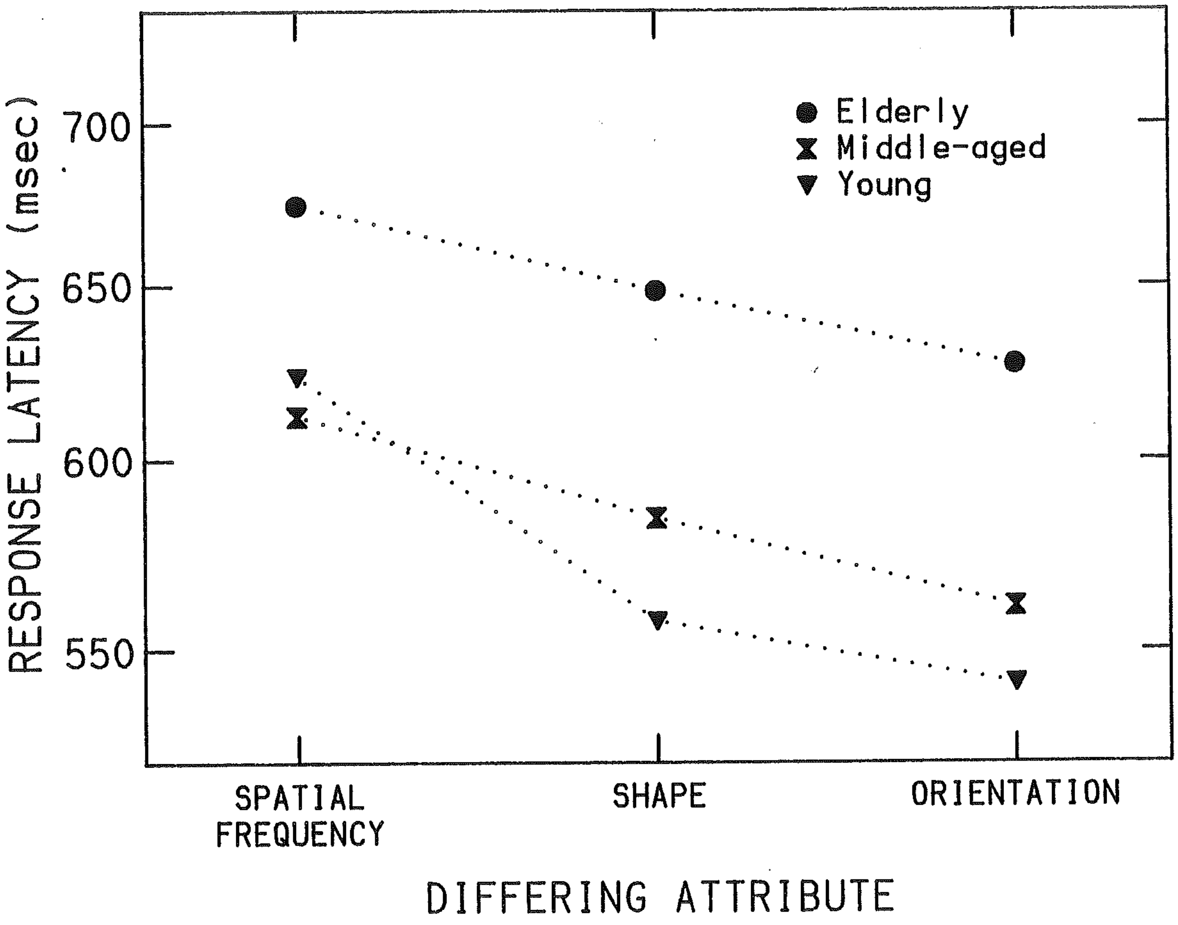

Figure 14. "Different" response latency as a function of differing attribute, for each of the three age groups (Experiment 6).

longest discrimination times, whereas stimuli that differed in orientation (matched in shape and spatial frequency) were discriminated most quickly. Although the age, gender, and blocks effects were all significant, none of the variables interacted significantly with stimulus attribute.

Paralleling the latency results, erroneous "same" responses were significantly more frequent for stimuli that differed with respect to spatial frequency than for stimuli that differed with respect to one of the other two attributes: The error rates were 6.5%, 2.5%, and 1.5% for pairs that differed in spatial frequency, shape, and orientation, respectively. Neither age nor gender had a significant effect upon overall error rate, but the effect of stimulus attribute was significantly greater for the young group than for the middle-aged and elderly groups, and significantly greater for females than for males.

In summary, although "different" latencies increased with age, the relative magnitude of the increase did not vary as a function of the number of attributes with respect to which the stimuli differed. Nor was there any evidence that the elderly were disproportionately affected by the difficulty of a single-attribute based discrimination: For all three age groups, discriminations based on orientation were faster than those based on shape, which were in turn faster than those based on spatial frequency. Combining the latency and error data, spatial-frequency-based discriminations appeared to be disproportionately difficult for the young group.

Experiment 7:

Focusing I

In a standard focusing task, one stimulus is presented on each trial and the subject responds positively to a predesignated "target" stimulus and negatively to all other stimuli. This task differs from the simultaneous perceptual matching task in that only one stimulus is encoded on a trial and, more importantly, the comparison is between that stimulus and an internal representation of the target stimulus, held in memory.

Method

In the first focusing task developed for this research project, each of the eight multidimensional stimulus patterns (Figure 9) served as a target for 14 consecutive trials in each of three blocks of 112 trials. The first block was considered practice. During each set of 14 trials the target was presented seven times and each of the nontargets was presented once. The order in which the stimuli served as the target was controlled to ensure that successive targets were maximally different and that targets composed of both levels of each attribute were presented equally often in the first and second halves of a block.

Subjects were instructed to respond with their preferred hand when the target was presented and with the other hand for all other stimuli, as quickly as possible without making errors. Feedback was given to ensure that the target stimulus was not forgotten: If the subject made an error, the message "Error, the target is" appeared on the display followed by the target stimulus.

Results

For each block, a subject's error rate and log median correct response latency were determined for each target and for each of the seven ways in which a nontarget could differ from a target: spatial frequency; shape; orientation; spatial frequency and shape; spatial frequency and orientation; shape and orientation; and spatial frequency, shape, and orientation.

Target stimuli. In the analysis of the log median correct response latencies for the target stimuli, the age effect failed to reach statistical significance. The main effects of gender (males faster than females) and blocks (Block 2 faster than Block 1) were, however, both significant.

The major effects involving the three stimulus attributes are shown in Figures 15 and 16. Although latencies were, on the average, significantly shorter for C-like targets than for F-like targets, the effect was due solely to the "open down" orientation (see Figure 15). This interaction between shape and orientation is similar to that found in the perceptual matching task, although the actual differences (relative as well as absolute) in latency are much smaller, and neither the age x shape interaction nor the age x shape x orientation interactions approached significance in this experiment.

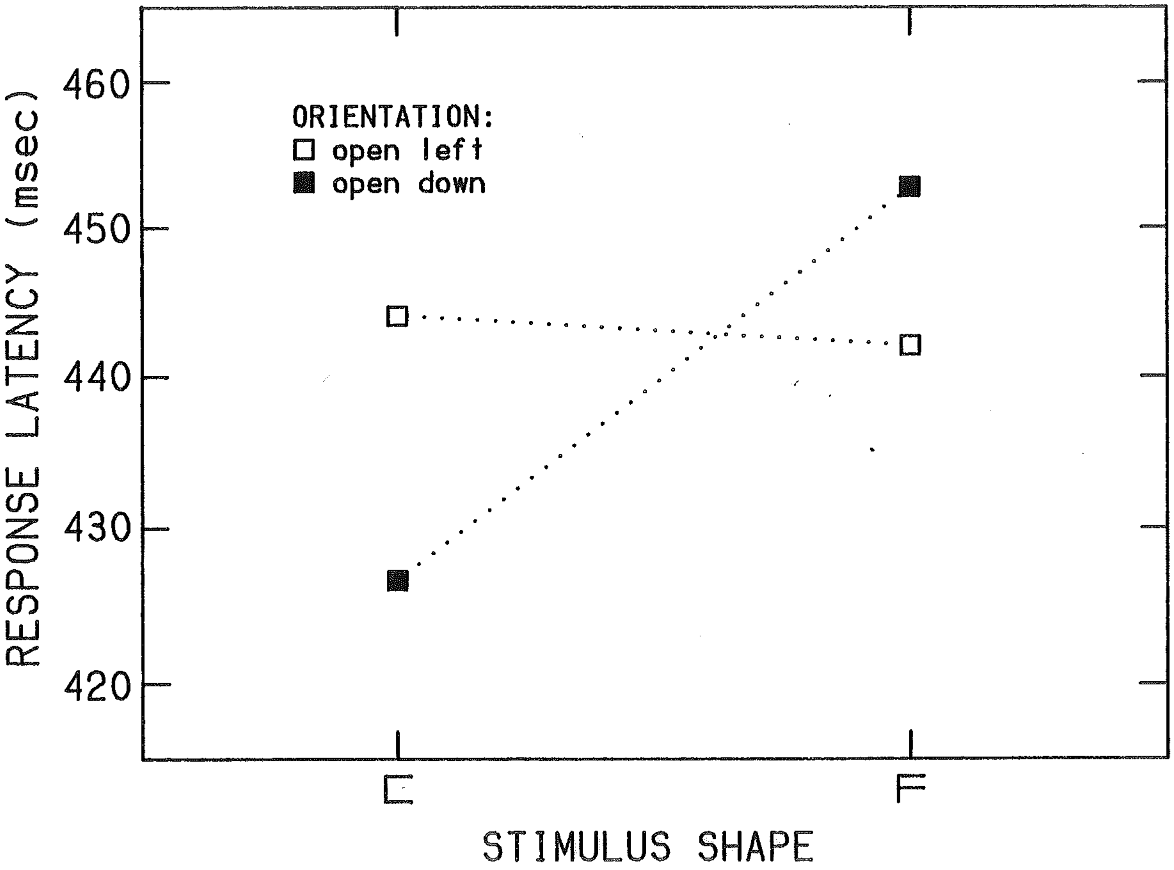

Figure 15. "Target" response latency as a function of target shape and orientation (Experiment 7).

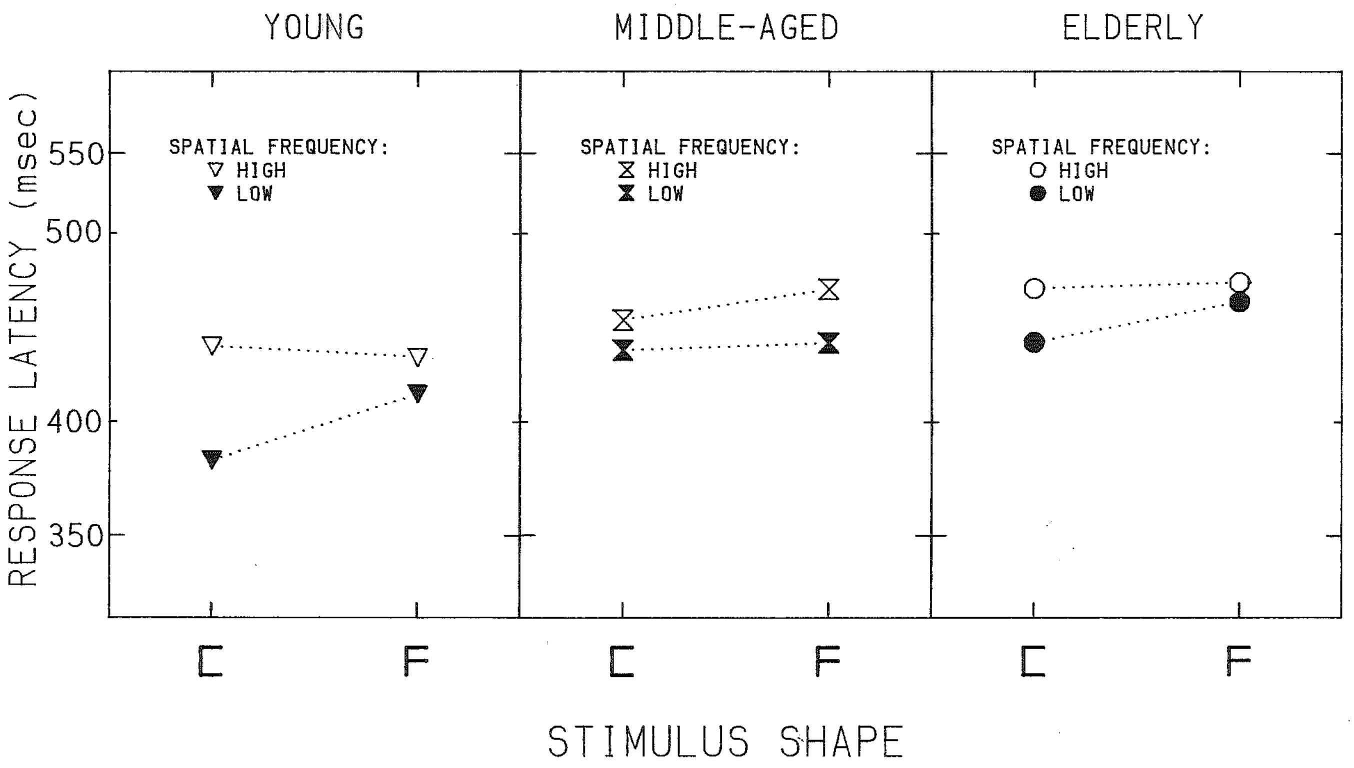

Figure 16. "Target" response latency as a function of target shape and spatial frequency, for each of the three age groups.

Latencies were significantly shorter for targets containing low spatial frequencies than for targets containing only high spatial frequencies. The magnitude of this effect varied significantly with age group (largest for the young) and shape (largest for the C-like shape). In addition to these first-order interactions, however, the age x spatial frequency x shape interaction was significant. The irregularity of this effect, which is depicted in Figure 16, suggests that the interactions involving spatial frequency, in this experiment, would not replicate.

The overall error rate for the target stimuli was only 1.5%. Although neither the age nor the gender effect was significant in the error analysis, there was a tendency for females to make fewer errors than males.

Nontarget stimuli. The seven log median correct latencies for the nontarget stimuli were averaged to yield three scores per subject -- one for each number of attributes with respect to which the target and nontarget differed. These scores, averaged over subjects within an age group, are shown in Figure 17. The effect of the number of differing attributes was highly significant. Although latencies increased with age, the age effect did not reach statistical significance. Males responded significantly faster than females, and latencies were significantly shorter for Block 2 than for Block 1. Finally, the interaction of block and number of differing attributes was significant: There was no reduction in latency over blocks for stimuli that differed from the

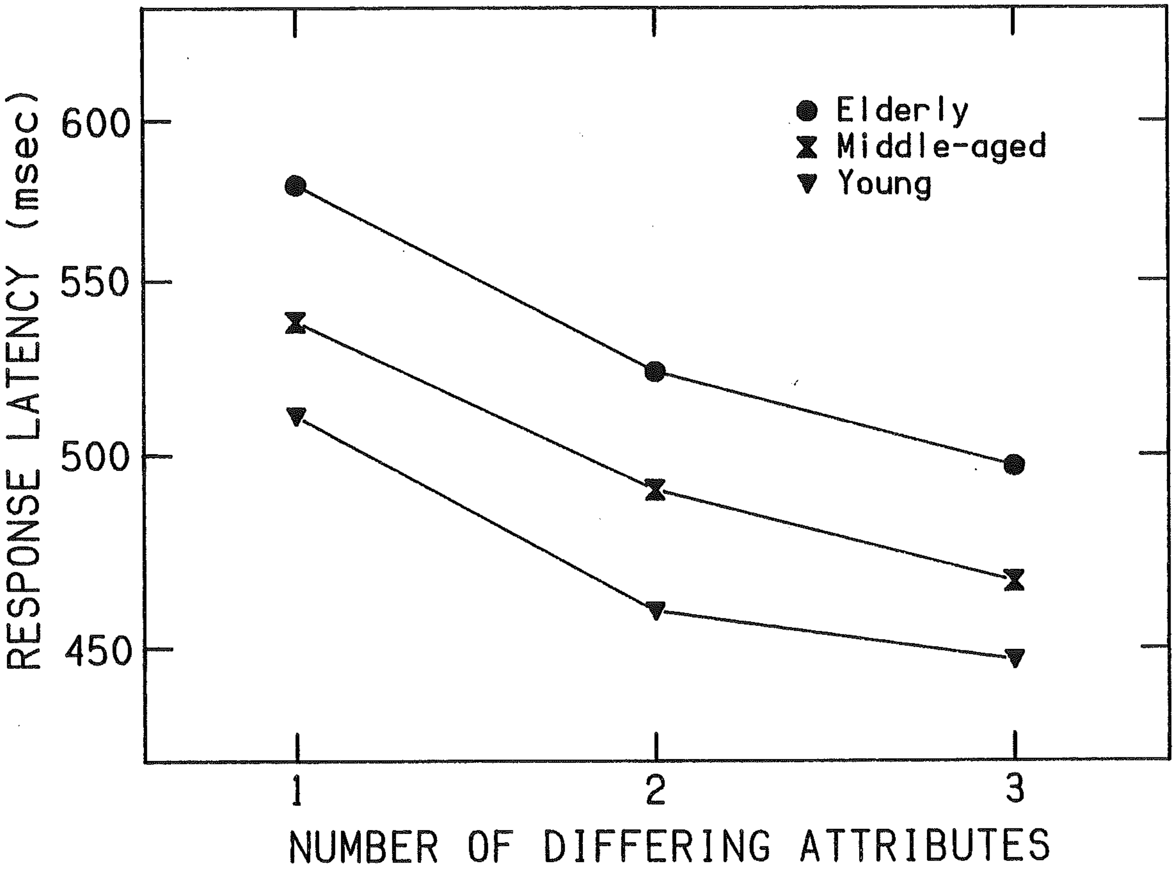

Figure 17. "Nontarget" latency as a function of the number of attributes with respect to which the patterns differed, for each of the three age groups (Experiment 7).

target on all three attributes.

The error rate for the nontarget patterns also varied significantly as a function of the number of attributes with respect to which the target and nontarget differed. Averaged over groups, the incorrect response rates were 3.65%, .80%, and .52% for nontargets that differed on 1, 2, and 3 attributes, respectively. Although error rate did not vary significantly as a function of either age or gender, the mean error rate for the male subjects was greater than the mean error rate for the female subjects and the young group, on the average, was less accurate than the two older groups.

The effect of distinguishing attribute was examined for stimuli that differed from the target stimulus with respect to only one attribute. In contrast to the results for the perceptual matching task, in which latencies were shortest when two patterns differed in orientation, latencies in the focusing task were shortest when the target and nontarget differed in shape (see Figure 18). As in the analysis of the number of differing attributes, the age effect failed to reach statistical significance, although latency did vary significantly with gender and block. None of the interactions were significant.

The results of an analysis of the error rates for nontargets that differed from the target on only one attribute were similar to those for the analysis of the latency data: The effect of attribute was significant, with error rates of 3.54%, 1.88%, and 5.53% for nontargets that differed in spa-

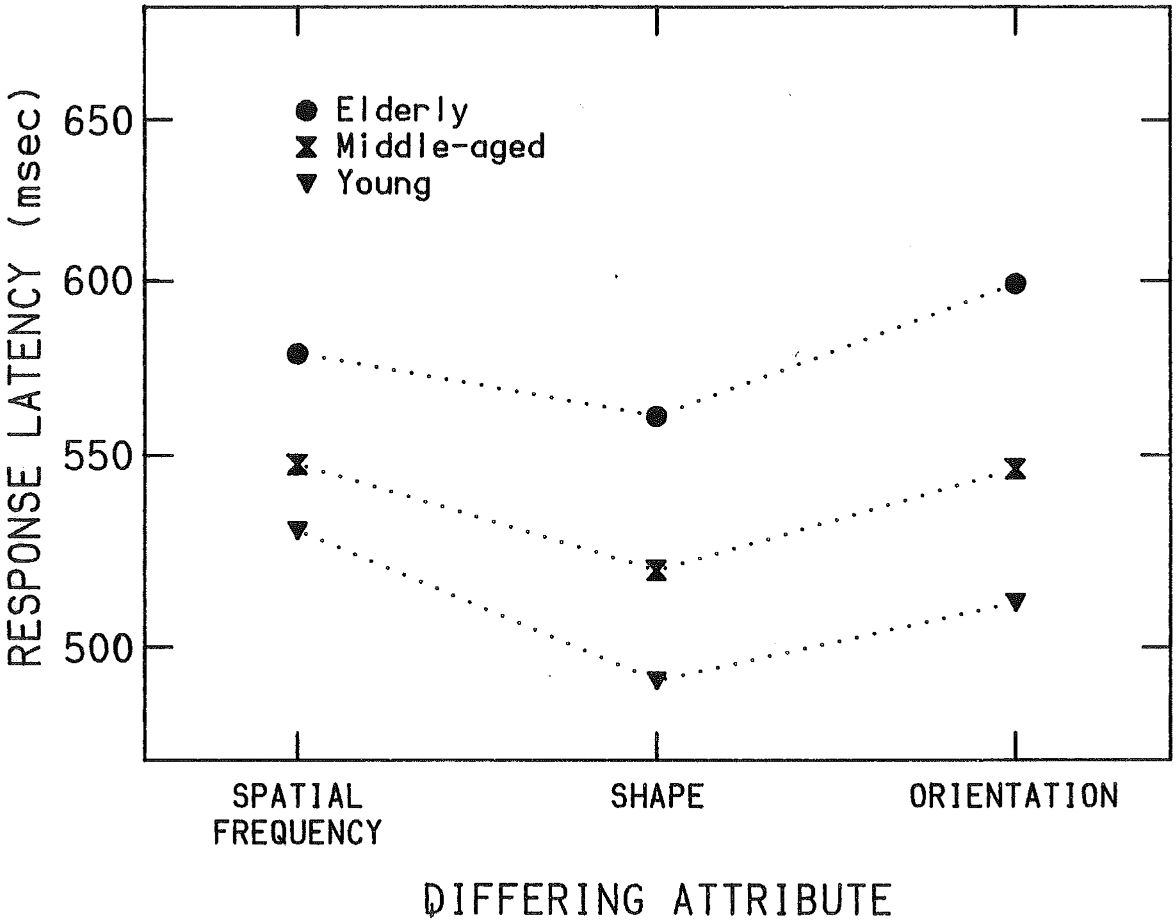

Figure 18. "Nontarget" response latency as a function of differing attribute, for each of the three age groups (Experiment 7).

tial frequency, shape, and orientation, respectively. The age effect was not significant, but the female subjects were significantly more accurate than the male subjects.

The main difference between the findings for the nontarget stimuli in this experiment and the findings for the "different" pairs in the perceptual matching task was the relative difficulty of a discrimination based on orientation. When two stimuli were presented simultaneously, both the latency and error data indicated that orientation-based discriminations were easier than shape- or spatial-frequency-based discriminations. With the successive presentation of the focusing task, orientation-based discriminations resulted in the highest error rate and latencies comparable to those for the spatial-frequency-based discriminations. Although the age x type of difference interactions were not statistically significant, the age effects were largest when the target and nontarget stimuli differed only in orientation. These findings suggest that pattern orientation is a difficult attribute to store or retrieve from memory. The tendency for this difficulty to increase with age deserves further study.

Experiment 8:

Focusing II

Method

In the second focusing task, 12 pairs of stimuli served as targets. The 12 target pairs consisted of all possible (i.e., four) exemplars of three types of pairs: 1) The two stimuli differed only in spatial frequency; 2) the two stimuli differed only in shape; and 3) the two stimuli differed only in orientation. The stimulus attribute with respect to which a pair differed is referred to as the "irrelevant" attribute because the level of that attribute was irrelevant to the target-nontarget distinction.

Each of the 12 pairs served as the target stimuli for a set of 12 consecutive trials in each of two blocks of 144 trials. The first block was considered practice. During the 12 trials associated with a particular target pair, each of the targets was presented three times and each of the nontargets was presented once. The instructions and feedback were comparable to those for the first focusing task.

Results

For Focusing II, subject performance was represented by (1) the log median correct latency for each target stimulus for each pair in which it served as a target and (2) the false negative and false positive error rates for each type of target pair.

The latency of a correct target identification varied significantly with the type of target pair (i.e., which attribute was irrelevant). As shown in Figure 19, latencies were shortest when spatial frequency was irrelevant. Latency also varied significantly with age (young < middle-aged < elderly) and gender (males < females).

The only significant effects involving target attributes were the shape x orientiation interaction (similar to that

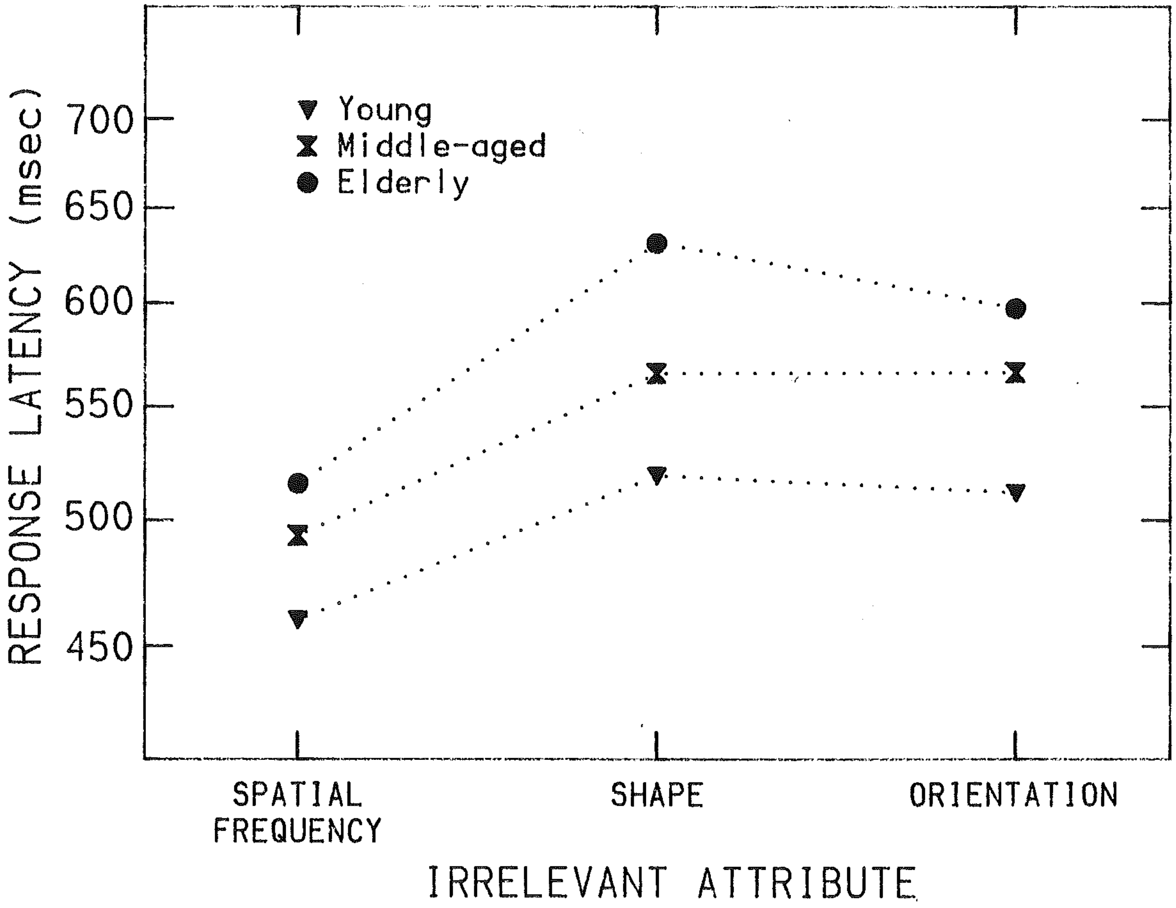

Figure 19. "Target" response latency as a function of the irrelevant attribute in the target pair, for each of the three age groups (Experiment 8).

found in Focusing I) and the type of pair x shape x orientation interaction. Subsequent analyses revealed that the three-way interaction reflected a tendency for latencies to be longer for the left member of a target pair. This finding suggests a "recency" effect, if it is assumed that the targets are encoded and, possibly, rehearsed from left to right. This interpretation is only tentative, however. Because all subjects received the members of a pair in the same spatial order, position and pattern were confounded within each type of pair.

The overall error rate was 3.37% in this task, with the errors equally divided between false negatives (a "nontarget" response to a target) and false positives (a "target" response to a nontarget). As shown in Figure 20, the false negative error rate roughly mirrored the latency data. However, in addition to the main effects of age, gender, and type of pair, the age x type interaction was significant in the error analysis: Elderly subjects made a disproportionately large number of errors when shape was irrelevant. The rate of false positives did not vary significantly with type of pair, age, or gender, but the ordering of the means for the false positives paralleled that for the false negatives.

This experiment was designed to examine age differences in stimulus classification time when only a subset of the attributes had to be remembered and processed. For example, if a target pair consisted of the two C-like shapes of low spatial frequency, one open to the left and one open down, the

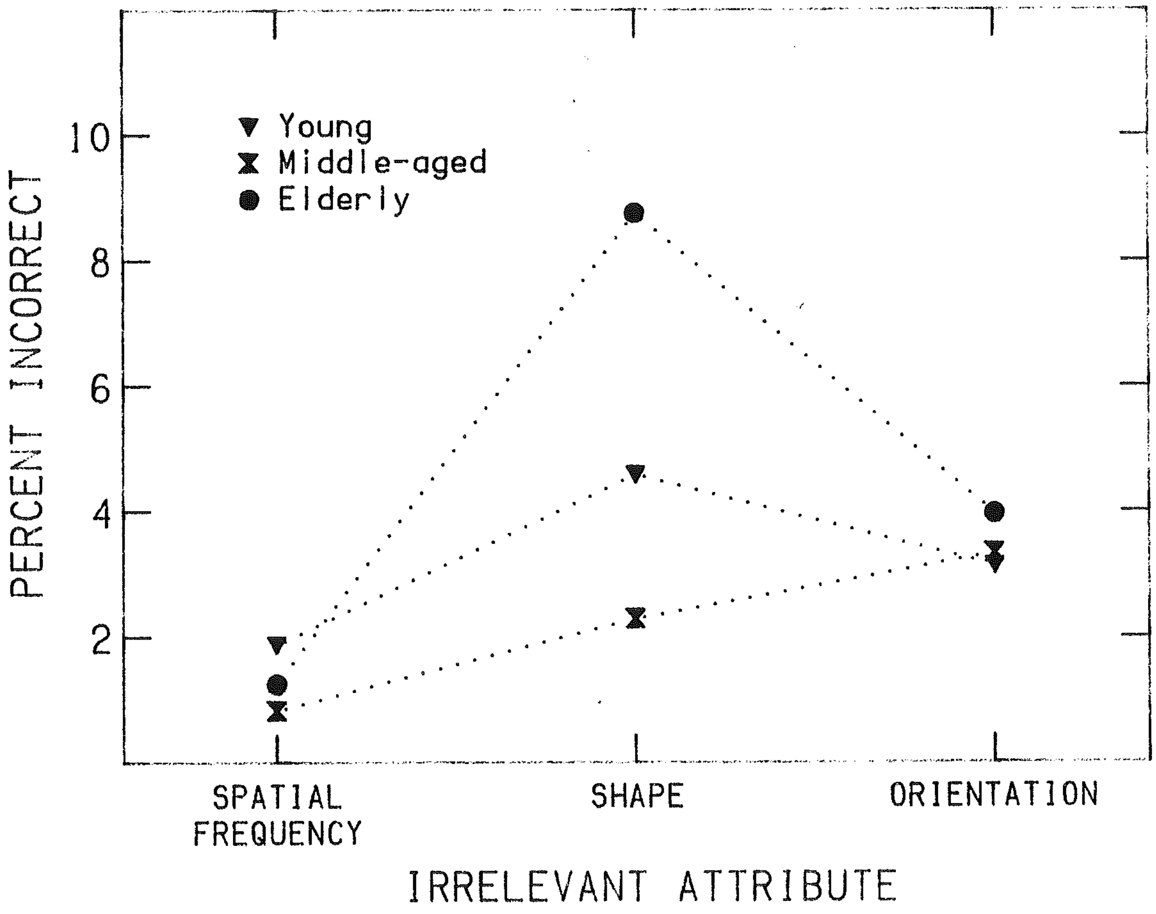

Figure 20. Percentage of false negative responses as a function of the irrelevant attribute in the target pair, for each of the three age groups (Experiment 8).

subject could, presumably, remember "black C" ("black" being the way most subjects seemed to encode the low spatial frequency). The subject would not have to remember anything about orientation because the target pair included both of the two possible orientations. Nor would orientation have to be processed when a pattern was presented for classification. This reasoning assumes, however, that the subjects were fully aware of the structure of the stimulus set (2 orientations, 2 shapes, and 2 spatial frequencies) and that they both could and would selectively process the relevant attributes. This does not appear to have been the case. Response latencies tended to be longer and error rates tended to be higher in Focusing II than in Focusing I. These findings, as well as the verbal reports of some subjects, suggest that subjects treated the target pair as two separate patterns to be remembered: A decision as to whether a particular stimulus is or is not one of two target patterns requires, on the average, more time than a decision with respect to a single target (Nickerson, 1972).

Assuming that attributes were not processed separately, the pair-type effects for the latency and error data probably resulted from differences in the ease with which the stimulus pairs were held in or retrieved from memory. A rather specific age-related memory deficit, that deserves further study, is suggested by the high error rate for the elderly group when shape was irrelevant.

Experiment 9:

Simulated Driving Environment

The goal of this experiment was to measure information processing capabilities in a visual environment as close as possible to that encountered in an actual driving situation.

Method

Visual display and apparatus. Driving scenes were created with a Canon 514XL-S sound movie camera by attaching the camera to the hood of an automobile and driving along specified routes. The camera was aimed at eye level for the driving position. Six 100-foot cartridge films were used to photograph six 3-minute driving scenes. After processing, the films were joined to provide an 18-minute film with short spaced strips between the scenes.

The filmed driving scenes included three roadway environments: (1) a city street with intersections and/or stop lights; (2) a two-lane "country" road with some intersections and/or stop lights; and (3) a 4- or 6-lane freeway with limited access and exits, and normal freeway markings.

Seven "driving events" were generated on a Harris 800 computer with Precisions Visuals Co. DI-3000 graphics language: (1) a regular-sized stop sign; (2) a double-sized stop sign; (3) a yield sign; (4) a 5-foot long pavement marking of spaced, parallel transverse lines; (5) a 20-foot long pavement marking of spaced, parallel transverse lines; (6) a single line; and (7) a child's wagon (see Figure 21). All of the

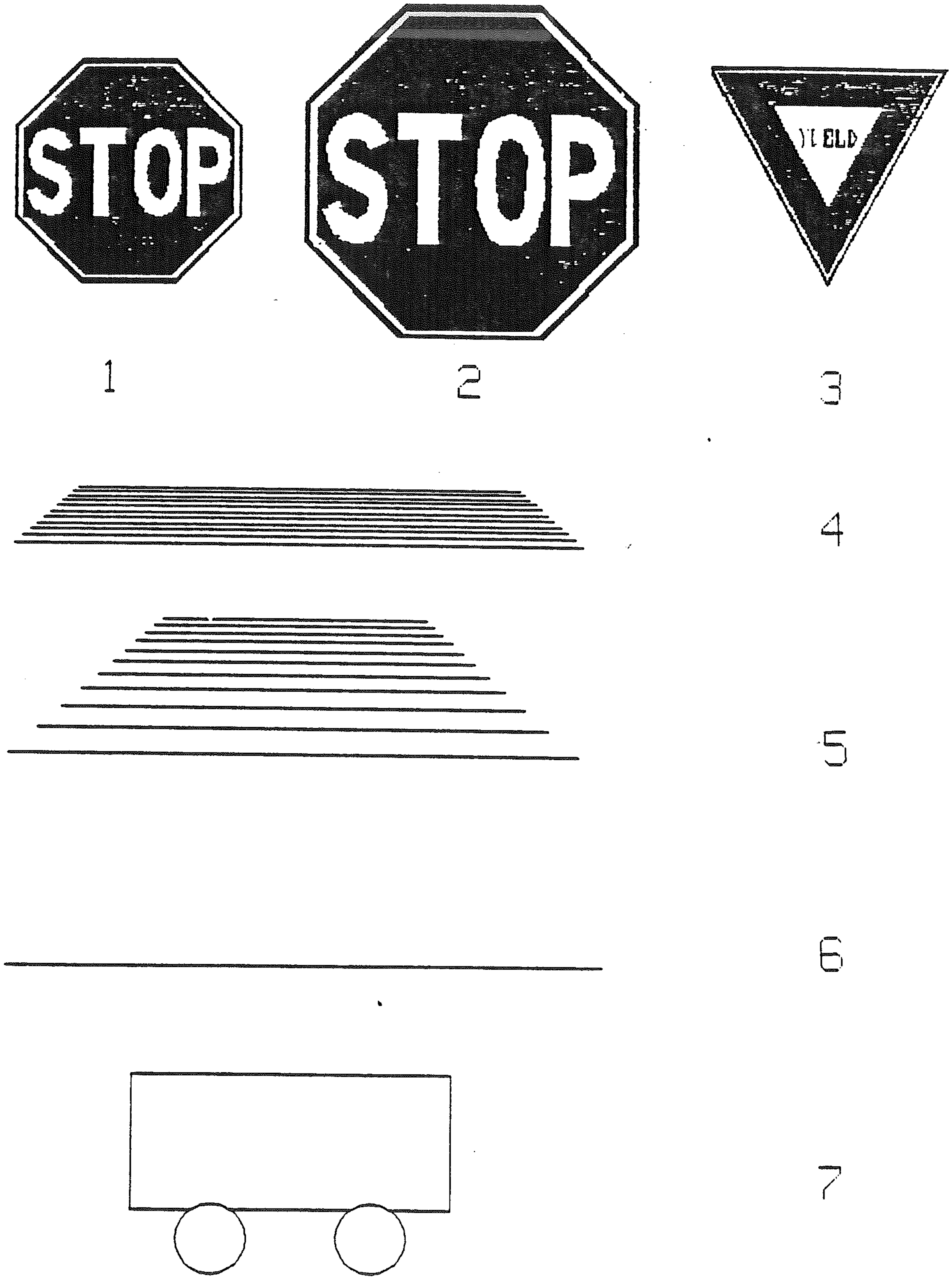

Figure 21. Driving events for Experiment 9.

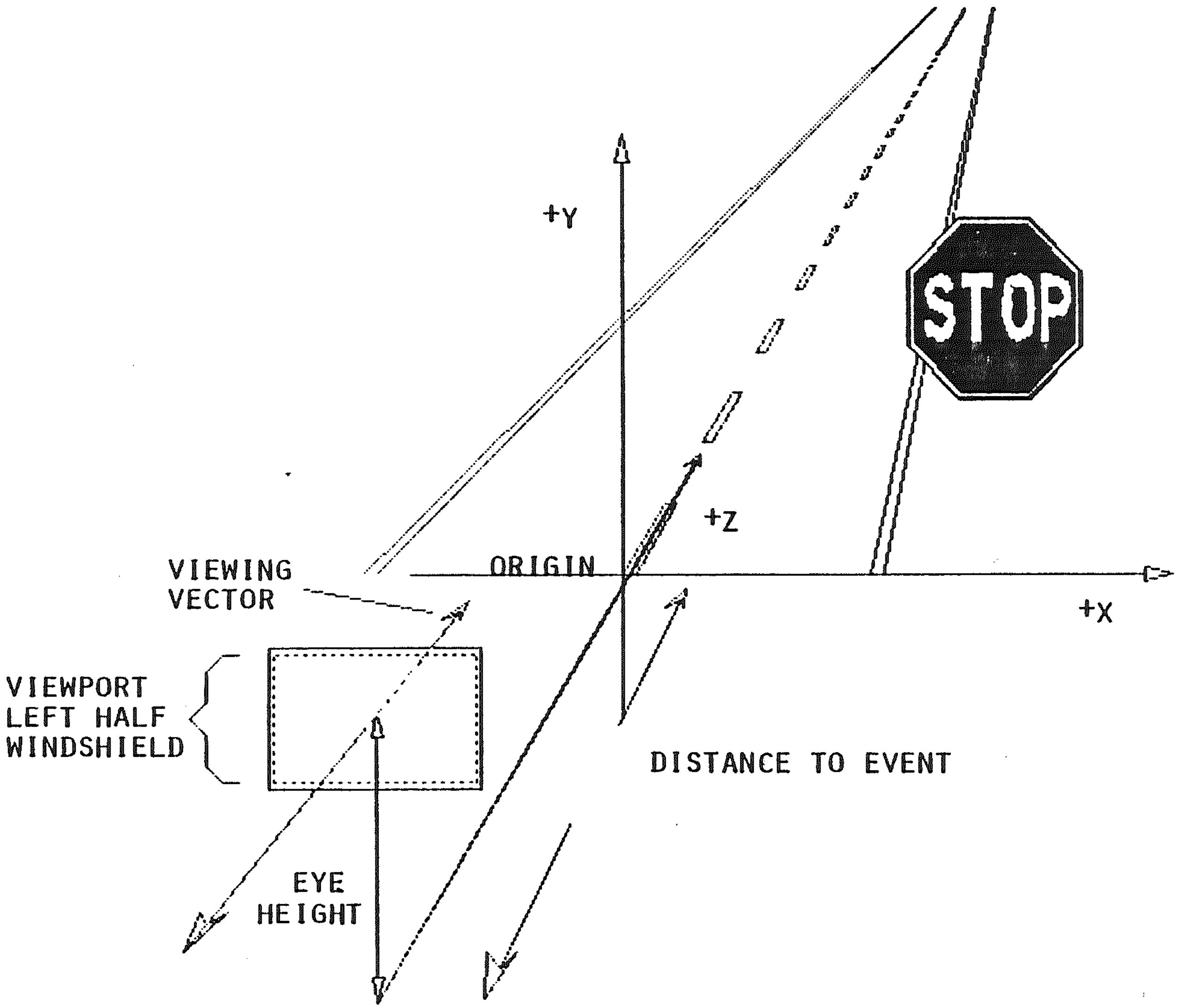

Figure 22. Geometric representation of an event, Experiment 9.

symbols were red and all of the lettering was white.

The DI-3000 computer graphics package allowed placement of the events according to three axes: X, Y, and Z. The Y = 0 point was designated as the top surface of the road; the X = 0 point was the middle of the driving lane; and the Z = 0 point was where the event would theoretically be passed by the driver. The designated viewport was the left side of the windshield,and the viewing vector was in the Z direction aimed at a point approximately 5 feet above the origin (see Figure 22).

The symbols were created with a specific passing time and vehicle speed stated. Given these variables, an image started as a point at "infinity" and grew in discrete, recurring images until the passing point was reached. Only one symbol was generated at a time and no symbol originated until the previous one was passed. Since the wagon represented an emergency situation (i.e, a child on a wagon rushing into the street directly in front of the automobile), it did not originate at infinity. Rather, it appeared at almost full size at a time that would correspond to a distance of several hundred feet in front of the vehicle.

The events were generated so that the standard regulatory devices would appear in their actual position to the right of the road and the pavement markings would appear on the road surface. The wagon appeared in the center of and on the road surface.

Three random, 18-minute sequences of two presentations of

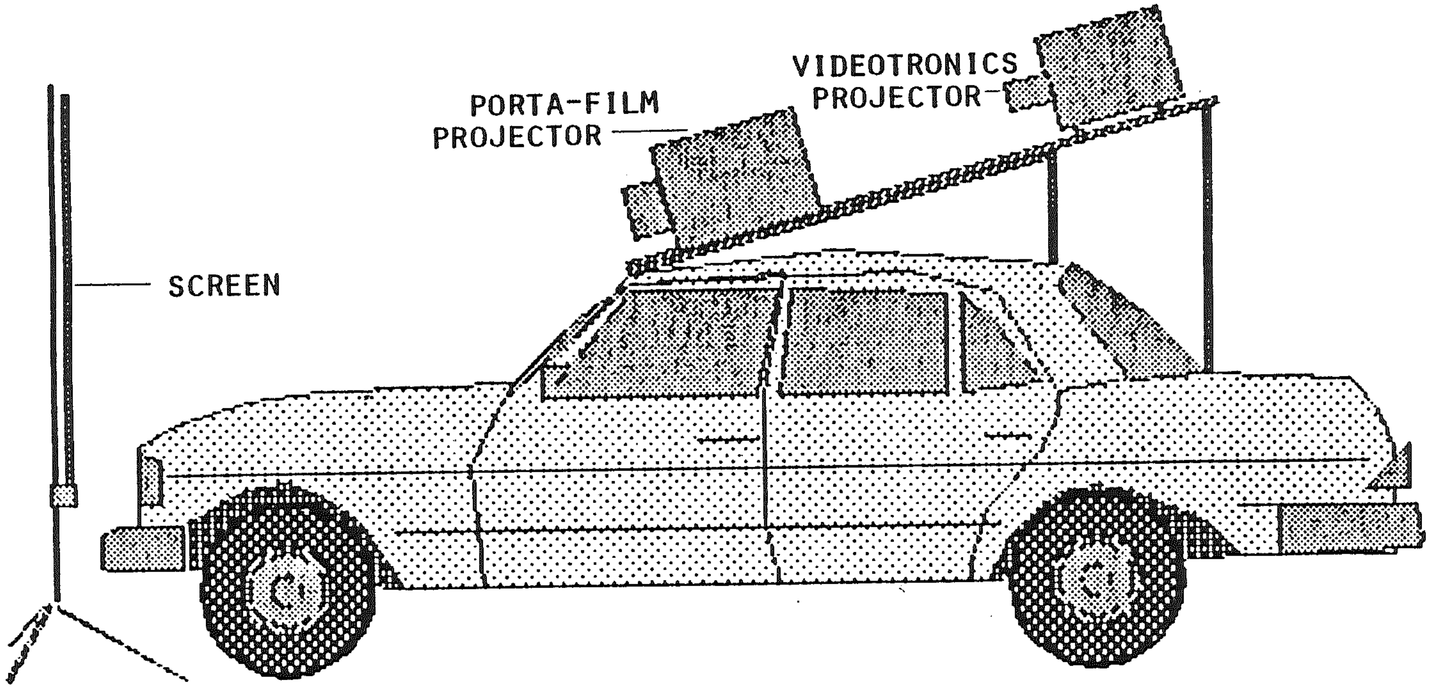

Figure 23. Experimental site equipment configuration (side view).

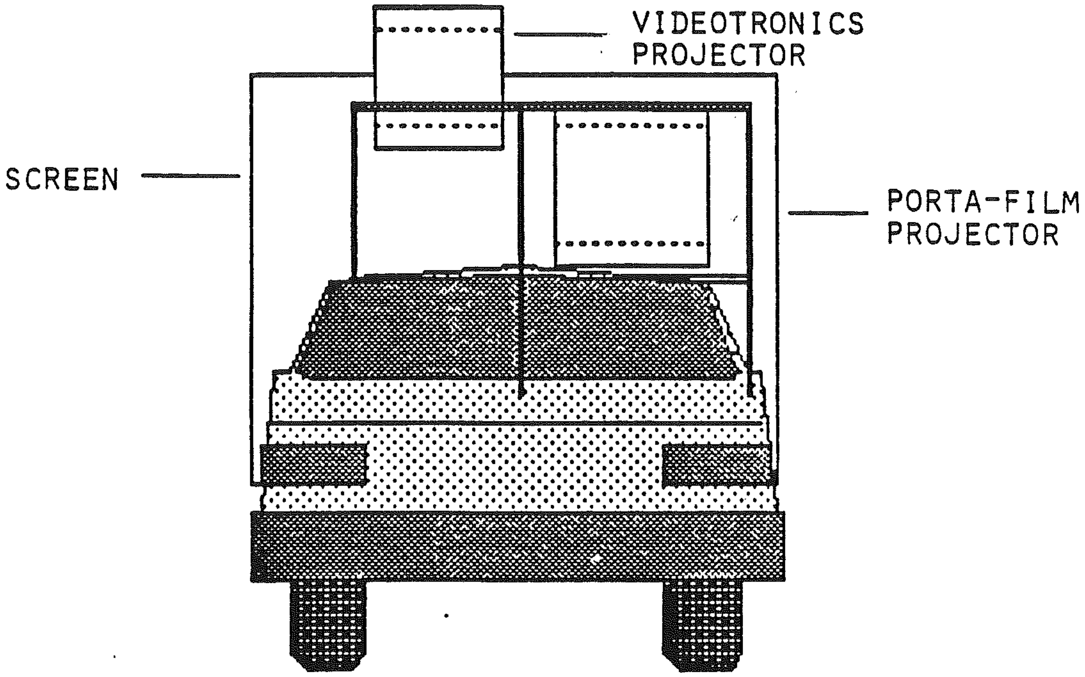

Figure 24. Experimental site equipment configuration (rear view).

each of the seven events were generated on a Tektronix 4027A color graphics terminal. A JVC Video Camera/Recorder was used to create videotapes of these sequences, which were designated Show 1, Show 2, and Show 3.

During the experiment the subjects were seated in a full-bodied 1974 Pontiac Catalina. The accelerator and brake of the car were connected to a Motorola Microsystems Exorcisor I microcomputer. A clock attached to the computer was used to record the times associated with release of the accelerator and depression of the brake. These times were printed on an ITT Model 43 digital printer for hand scoring.

The driving scene films and the videotapes of the computer-generated images were both projected onto a 6' X 6' movie screen placed directly in front of the car and parallel to the windshield (see Figures 23 and 24). The films were projected by means of a Videotronics projector; the videotapes via a Porta-Film Video Projection System. A blue film was taped over the movie projector to enhance the superimposed images of the computer-generated events. Although the blue filter diminished the quality of the filmed driving scenes, it made the video projected events easier to see.

Procedure. The subjects were given written instructions that included a graphic representation (see Figure 21) of the events to which they should respond (the two stop signs, the two pavement markings with multiple lines, and the wagon). The members of the negative set (the yield sign and single line) were not described, but the subjects were told that other events would occur.

Each subject saw three 18-minute showings, with a brief break between showings. Show 1 was presented first as a practice session for subjects 11 through 60. This procedure was not followed for the first 10 subjects, precluding the use of their data in subsequent analyses.

Subjects were allowed to ask questions throughout the practice showing. Questions were not allowed during the second and third showings and no feedback was given. The order of presentation of Show 2 and Show 3 was roughly counterbalanced. However, the videotape for Show 3 broke during the testing of one of the subjects. Show 1, which had been presented to the subject for practice, was then repeated in place of Show 3. This same procedure was followed for the next 10 subjects tested.

The subjects were instructed to keep their right foot on the accelerator, with pressure, at all times except when responding. They were told to respond to the presentation of one of the symbols from the positive set by taking their foot off of the accelerator and hitting the brake. The experimenter emphasized that it was important not to guess.

Results

Each event passed the subject at a designated time, after which it was no longer displayed. For each positive event to which the subject responded, the difference between the accelerator release time and the event passing time was determined manually. The larger this "lead time," the earlier the subject responded. If a subject failed to respond or responded after an event passed, it was recorded as a miss. Responses to members of the negative set were recorded as false positives.

Four of the older subjects were either unable to resolve the computer generated images or responded so erratically during the task (e.g., released the accelerator several times between events) that it was impossible to score their data. These subjects were excluded from all of the statistical analyses.

The data for each showing were reduced separately. For the lead time analyses, a subject's performance for an event was represented by the average of the two lead times for that show, if the subject responded to both presentations of that event, and by the single lead time, if the subject responded to only one of the two presentations. If the subject failed to respond to both presentations of an event, his performance for that event was treated as missing. Since subjects sometimes failed to respond to both presentations of a positive event, it was not possible to conduct an analysis of the lead time data with "event" as a within-subject variable. Therefore, analyses were conducted on the median of the lead time scores for the positive events for which there was at least one response.

In order to maximize the number of subjects included (N = 45), an analysis was performed on the median lead times for all subjects with interpretable Show 2 data. Neither the age nor the gender effect was significant in this analysis, although lead times tended to decrease with age.

An analysis was also conducted on the median lead times for the 34 subjects with data from both showings. Averaged over shows, there was a nonsignificant tendency for lead times to decrease with age. The only significant effect was "show": Lead times for Show 3 were longer than lead times for Show 2. This finding indicates that the sequence and placement of the events, which varied with show, had a significant effect upon subject performance.

The error rate was high for this task -- both false positives and misses. Averaged over all subjects with interpretable data for Show 2, the miss rate was 18% and the false positive rate was 19%.

Separate analyses were conducted on the number of misses, number of false positives, and total number of errors for Show 2. Although none of the effects in these analyses were statistically significant, the young subjects tended to make fewer errors (of both kinds) than the two older groups. There were also no significant effects in the analyses of the error data for the subjects with data for both Show 2 and Show 3, although errors (particularly misses) tended to increase with age and to be higher for Show 2 than for Show 3.

The loss of data from some of the elderly subjects, due to their inability to perform the task, makes it difficult to interpret the (nonsignificant) results from the partial sample. Given that all of the young and middle-aged subjects produced usable data and that they tended to respond with longer lead times and fewer errors than the elderly subjects who could perform the task, it is probably justifiable to conclude that aging is associated with poor performance on this task.

We doubt, however, that poor performance on this task is indicative of an inability to drive safely. Although an effort was made to create a realistic visual environment, the actual display fell short of this goal in several important respects (Fiedler, 1984): First, in order to increase the visibility of the computer generated images, it was necessary to reduce the quality of the road scenes by means of a blue filter. Second, although the event generation program was designed to place the events in their proper position in the driving environment, irregularities in the roads filmed and in the placement of the camera resulted in considerable variability in the placement of the events relative to the actual driving scene. Third, rather than growing continuously, the computer generated events grew in fairly large, discrete steps. The events had to be redrawn for each new size, and the time necessary to redraw an event depended upon various characteristics of the pattern. Completion of the entire image frequently required several raster scans. Thus, the events were neither realistic nor well defined. Finally, it was necessary for subjects to ignore driving-relevant information (such as stop signs) in the filmed scenes.

The high error rate in this experiment suggests that the combination of shortcomings in the visual environment made this a very difficult task for many subjects. It is not surprising that a few of the elderly subjects were unable to meet the task demands.

AREAS OF APPLICATION

Screening Instrument

Development of a more adequate screening instrument for driver licensing is dependent upon a better understanding of a) the nature and extent of individual and age-related differences in visual information processing capabilities and b) the relationship between these capabilities and the ability to handle the demands of driving. The present research project provides information concerning age-related differences in visual processing capabilities.

In Experiment 1, visual acuity was assessed for target speeds of 0, 30, 60, and 90 degrees per second. When acuity was expressed as the minimum visual angle resolvable, age differences increased with target speed. When acuity was expressed as the maximum spatial frequency resolvable, however, the age effect did not vary with speed. Although further work is needed before a firm conclusion can be drawn, the results of Experiment 1 suggest that Burg's (1966) finding of large age-related differences in the effect of target speed on acuity may have reflected characteristics of the stimulus set, testing procedure, and acuity scale rather than an important age-related processing disability. If subsequent research supports our findings, the addition of tests of dynamic visual acuity to the current visual screening procedures would not be warranted.

In Experiments 2 to 4, response latency and backward masking procedures were used to test the hypothesis that aging is associated with an increase in neural noise, a manifestation of which is disproportionately long processing times when stimuli of high similarity must be discriminated or identified. Stimulus similarity was manipulated by varying the magnitude of the difference on a single attribute, namely, line length.

The results of these experiments did not support the hypothesis: The effects of stimulus similarity were comparable for the three age groups. Moreover, whereas age differences were substantial when an adaptive backward-masking procedure was used, the overall age effect was not significant when response latency was the measure of processing time.

Our failure to find an effect of age on response latency contrasts with the results of most prior studies of visual information processing and aging. This discrepancy suggests that our sample of older subjects may have had especially high motivation or may have set less conservative response criteria. It should be noted in this regard that it was more difficult to recruit middle-aged and elderly men than to recruit middle-aged and elderly women, and the men expressed more concern about our ability to detect any age-related decrements in their performance. Although not statistically significant, there was a tendency for the female subjects to show the predicted effects.

Additional research is needed to determine whether the SOA to evade backward masking is a reliable and valid measure of target processing time. If so, and if it also proves to be a measure that is relatively free of response criteria and motivational effects, a backward masking task might be a valuable component of a test battery for driver-license screening. Even if the SOA necessary to evade masking proves to reflect processing capabilities quite independent of more direct measures of information processing speed, it has potential as a screening measure because of its sensitivity to age-related changes. Research would, of course, be needed to determine if the capacities it measures are related to driving ability.

The tasks in Experiments 5 to 8 differed in the cognitive processes upon which a response was based, and thus provided a test of the hypothesis that aging is associated with a general reduction in processing speed that results in a constant relative increase in response latency across a variety of tasks. The stimulus set for these experiments consisted of eight geometric forms created by combining two levels of each of three stimulus attributes. Similarity was defined in terms of the number of attributes with respect to which stimuli differed. Comparisons of age-related differences in discrimination latency as a function of similarity provided converging tests of the neural noise hypothesis. Age-related differences in the processing of specific stimulus attributes (spatial frequency, orientation, and pattern goodness) were also examined.

The results of these experiments were complicated and can not be accounted for by the hypothesized age-related differences in processing speed and neural noise. Although advanced age was, in general, associated with longer response latencies, the relative age difference varied with both the attributes of the stimulus and the requirements of the task. In certain tasks, stimulus attributes that had only a small effect upon the performance of young subjects had a large effect upon the performance of elderly subjects. The elderly subjects were not, however, affected disproportionately by high stimulus similarity.

The results of these experiments, in conjunction with those of Lindholm and Parkinson (1983), indicate that perceptual matching tasks are sensitive indicators of age-related differences in information processing capabilities. Therefore, a matching task might be a valuable component of a screening instrument. In both the earlier and present experiments, however, there were strong stimulus and age x stimulus effects which can not yet be explained. It would be advantageous to understand the basis of these effects before selection of a matching task for inclusion in a study of the relationship between processing capabilities and driving record.

Geometric Design Standards

A number of highway design standards depend, in part, on estimates of a driver's "perception-reaction time." This general driver characteristic includes the times necessary to execute a number of perceptual and cognitive processes as well as a variety of movements. The exact mental operations and movements depend (in a general sense) upon the application.

The results of our experiments suggest that attributes of the target stimulus (e.g., the stimulus for which one needs to stop) may have a substantial effect upon the results obtained in studies designed to provide improved perception-reaction time specification values. There is still much to be learned, however, about the stimulus dimensions that influence processing time and about the interactions between these dimensions and the surrounding visual environment. Most of this research can be laboratory based.

Accurate estimates of optimal perception-reaction time values will require field studies that, to the fullest extent possible, duplicate realistic, and nonoptimal, driving conditions. Ideally, design standards would accommodate all licensed drivers. Since aging is associated with increases in both processing and movement times, design standards that accommodate elderly drivers will certainly accommodate normal young drivers. Thus, it would be reasonable to test only elderly drivers in the on-the-road studies that will be necessary to provide appropriate specification values. Moreover, such studies should use stimuli and environmental conditions that require relatively long processing times.

Signing and Pavement Marking Standards

The development of standards for the format and lettering style of sign messages (and pavement markings) will depend upon studies in which processing time and accuracy are determined for the actual stimulus alternatives (e.g., different letter fonts). Our results indicate that it is very important to test elderly people in such studies because some stimulus attributes that have little if any effect on the performance of young adults have a large effect on the performance of elderly adults.

Standards for sign spacing and placement should be based on consideration of at least two driver characteristics: information processing speed and short-term memory capacity. The position of a sign, relative to the place where action is required, should provide sufficient time for the driver to process the sign message and to execute any preliminary maneuvers. If the time provided is too long, however, the driver may no longer remember the message when a response is required. Moreover, since processing, response, and memory demands are all likely to vary with the format and message of the sign as well as with numerous aspects of the driving environment, optimal sign placement may be both situation and sign specific. Because aging is associated with reductions in both memory capabilities and processing speed, sign spacing and placement should be optimized with respect to the elderly driver's capacities.

Needs and Problems of the Elderly

The difficulty of a driving situation depends, in large part, on the speed with which information must be processed. Although the results of our research indicate that relative (as well as absolute) age-related differences vary with both task demands and stimulus attributes, advanced age is, in general, associated with longer processing times. Thus, transportation situations that are mildly-to-moderately difficult for young drivers or pedestrians are likely to be very difficult for some of their elderly counterparts. Characterization (and potential modification) of situations in which elderly drivers experience disproportionate difficulties will require both careful analysis of traffic accident data and research in which key elements of these situations are reproduced.

As the population ages it becomes increasingly important that transportation design and operation standards accommodate older drivers. At the same time, it is important to provide other means of transportation for elderly people who are not capable of driving safely. Accurate estimation of the future need for public transportation will require both good demographic data and knowledge of the percentage of each age group with disabilities of a severity to preclude safe driving. This knowledge, in turn, will require a better understanding of the nature and extent of age-related changes in basic information processing capacities and of the relationship between these capacities and driving ability.

CONCLUSIONS AND SUGGESTED RESEARCH

Conclusions

In this research project we examined the nature and extent of age-related differences in performance on a series of perceptual and cognitive tasks. The selection of tasks and stimuli was guided by a previously proposed account of the changes in processing capacity that accompany advancing age, namely, that aging is associated with a decrease in processing speed and an increase in neural noise. Had the results supported this account, it would have provided a basis for the design of a preliminary, experimental screening instrument for driver licensing. In addition, it would have provided a) a potential means, though not the exact values, by which specification values, based on research with young drivers, could be adjusted to accommodate elderly drivers and b) a framework for the selection and design of studies directly concerned with improving traffic control devices and geometric design standards.

This account of the nature of age-related differences in information processing capabilities was not, however, supported by our findings. Age-related differences in performance varied with task and, thus, with processing requirements. For certain tasks, moreover, age differences were much larger for some stimuli than for others.

Although our results are not consistent with the processing speed/neural noise hypotheses, they do indicate an age-related decline in central nervous system functioning: In general, the magnitude of the age effect increased with cognitive complexity. There was no evidence that age-related differences in either cautiousness or peripheral sensorimotor function could account for our results.

Given the complexity of age-related changes in information porcessing capabilities, improvement of the roadway system to accommodate the majority of elderly drivers and development of screening procedures to identify those individuals who can not be accommodated will require a major, national research effort. As a state with one of the highest percentages of elderly residents and many elderly winter visitors, Arizona should be a leader in this effort.

Additional basic research is needed to determine if there are general factors that can account for age-related differences (and differences among elderly people) on a variety of perceptual and cognitive tasks or, alternatively, if aging is associated with a number of specific processing disabilites that vary qualitatively as well as quantitatively from individual to individual. This type of research will be relatively long-term, and it is difficult to predict when it will result in knowledge that can be directly implemented. Its importance, however, should not be underestimated. Development of an efficient and valid screening instrument for driver licensing will be greatly facilitated if driving capability can be estimated by performance on a few tests of basic information processing capabilities. With respect to engineering applications, the understanding that results from such basic research will both limit and direct subsequent applied studies.

Ideally, many of the basic-research questions would be answered before initiation of an applied research program. It is important, however, to improve the current situation as quickly as possible, and to do so will require that a range of applied question be addressed without delay.

First, both laboratory and field studies are needed to provide better estimates of the driver characteristics used in the computation of geometric design standards and to evaluate specific alternative forms of signs and pavement markings. Because processing time is a function of many stimulus and task variables, the stimuli for such research should be chosen with great care, and relevant aspects of the driving task should be reproduced as accurately as possible. Moreover, the subject population for these studies should always include elderly drivers; in most instances, no important information would be lost if only elderly subjects were tested.

Second, careful analysis of traffic accident data and in depth interviews are needed to identify situations in which elderly drivers experience disproportionate difficulty. Ways in which these situations could be modified to better accommodate elderly drivers should then be examined.

Finally, work should begin on the development of an instrument to screen driver license applicants for perceptual and cognitive disabilities. In its early stages, such an instrument would serve primarily as a research tool, but as predictive relationships are discovered, it could function increasingly as a warning device, identifying individuals who should be given a road test.

Recommended Extensions of the Present Research

1. We found that processing time frequently varied with the attributes of the stimulus. Moreover, in certain tasks, stimulus effects were significantly greater for elderly adults than for young adults. Given the importance of visual stimuli in the driving environment and the possibility of controlling characteristics of many of these stimuli (e.g., signs), research designed to examine the nature and extent of these stimulus effects should be supported.

2. The task battery developed for this research project consisted solely of tasks with minimal spatial and temporal uncertainty. In other words, subjects knew where and (albeit less precisely) when a stimulus would occur. The driving task, in contrast, is characterized by uncertainty in both of these realms.

Performance on tasks with high uncertainty is thought to reflect attentional capacities, and performance on an _auditory_ task that requires rapid attention switching has been shown to be predictive of driving accident history (Kahneman et al., 1973). Because driving is primarily a visual information processing task, visual attentional capacities should be even more predictive. A visual task (or series of tasks) with high temporal and spatial uncertainty should be developed for the study of age-related differences in attentional capacities.

3. In a more applied vein, extensions of the present research effort should be directly concerned with development of an instrument that could be used to screen driver license applicants for disabilities of a severity that preclude safe driving. This goal necessitates examination of the relationship between driving ability and information processing capabilities. Because people with severe disabilities are likely to be elderly, the most efficient method of assessing this relationship would be to compare the information processing capabilities of good drivers who are elderly with those of poor drivers who are elderly.

Such studies require valid, reliable measures of both driving and information processing capabilites. Although far from perfect, driving record data (numbers and types of accidents and citations) are the best available measures of driving ability. The initial choice of information processing tasks will be somewhat arbitrary, however, since we do not yet know the basic dimensions of information processing capacity. At a minimum, the selected tasks should be both reliable and sensitive to age-related differences.

We found a large effect of age with the adaptive backward-masking procedure developed for Experiment 3, even though these groups did not differ in response latency on a comparable task. It would be interesting to see if the SOAs required to evade masking are longer for elderly people with poor driving records than for elderly people with good driving records. Similarly, a comparison of the perceptual matching latencies of elderly groups that differed in accident and citation history would be informative, although selection of the stimulus set and basis for matching should await further study.

4. As more is learned about the underlying structure of perceptual and cognitive capabilities, the nature of age-related changes, and the relationship between driving ability and performance on perceptual and cognitive tasks, a test battery of increasing power should evolve. A concerted effort will be necessary, however, if this battery is also to be a practical tool for screening driver license applicants. The characteristics of a reliable and efficient screening instrument are not necessarily the same as those of a valuable research task. First, a screening instrument is more likely to employ adaptive procedures -- that is, procedures in which the task parameters on any one trial are determined by the preceding parameters and responses. Second, the value of a predictive screening instrument does not depend upon any particular theoretical perspective. Third, if designed to identify individuals of extreme disability (or ability), a screening instrument need not provide highly reliable measures of the abilities of people who do not fall near that end of the distribution. With these considerations in mind, brief, adaptive versions of tasks thought to measure basic processing capabilities should be developed and evaluated.

APPENDIX

Driver characteristics involving perception and reaction times are parameters in the equations used to determine many geometric design and traffic operations standards. In the following section, the effects of changes in the driver characteristic are examined for several important standards.

Stopping Sight Distance

Stopping sight distance is defined (AASHTO, 1984) by the following equation:

$$SSD = 1.47Vt + V^2/30(f + g) \qquad (1)$$

where

SSD = stopping sight distance (feet),
t = perception-brake-reaction time (seconds),
V = velocity of vehicle (miles per hour),
f = coefficient of friction, and
g = grade of roadway.

In order to assess the importance of misspecification of driver perception-brake-reaction time, stopping sight distances were determined for the combinations of six perception-brake-reaction times and five velocities. In these and subsequent calculations the grade was assumed to be zero and friction was assumed to decrease from .35 at 30 mph to .28 at 70 mph. The perception-brake-reaction time values were taken from Hooper and McGee (1983), who estimated, by the addition of separately estimated components, the perception-brake-reaction times of various percentiles of the population. The values used here -- 2.3, 2.9, 3.2, 3.5, 3.8, and 4.6 seconds -- were their estimates for the 50th, 75th, 85th, 90th, 95th and 99th percentiles, respectively.

As shown in Figure A1, stopping sight distance increases as a linear function of perception-brake-reaction time. The slope of the function increases with the velocity of the vehicle. Therefore, in terms of additional feet traversed before stopping, the effect of perception-brake-reaction time increases with vehicle speed, and the effect of speed is greater at longer perception-brake-reaction times.

Another approach to the importance of variation in perception-brake-reaction time was provided by Hooper and McGee (1983). They derived a sensitivitiy expression by taking the partial derivative of Equation 1 with respect to perception-brake-reaction time, dividing by the original expression, and multiplying by the perception-brake-reaction time. The resulting equation

$$(dSSD/dt)/(SSD/t) = 1.47Vt/[1.47Vt + V^2/30(f+g)] \qquad (2)$$

gives the percentage change in stopping sight distance that results from a one percent change in the driver perception-brake-reaction time.

We computed these percentages for the six perception-brake-reaction times used in Equation 1 (rather than for just the current specification value) for velocities between 30 and

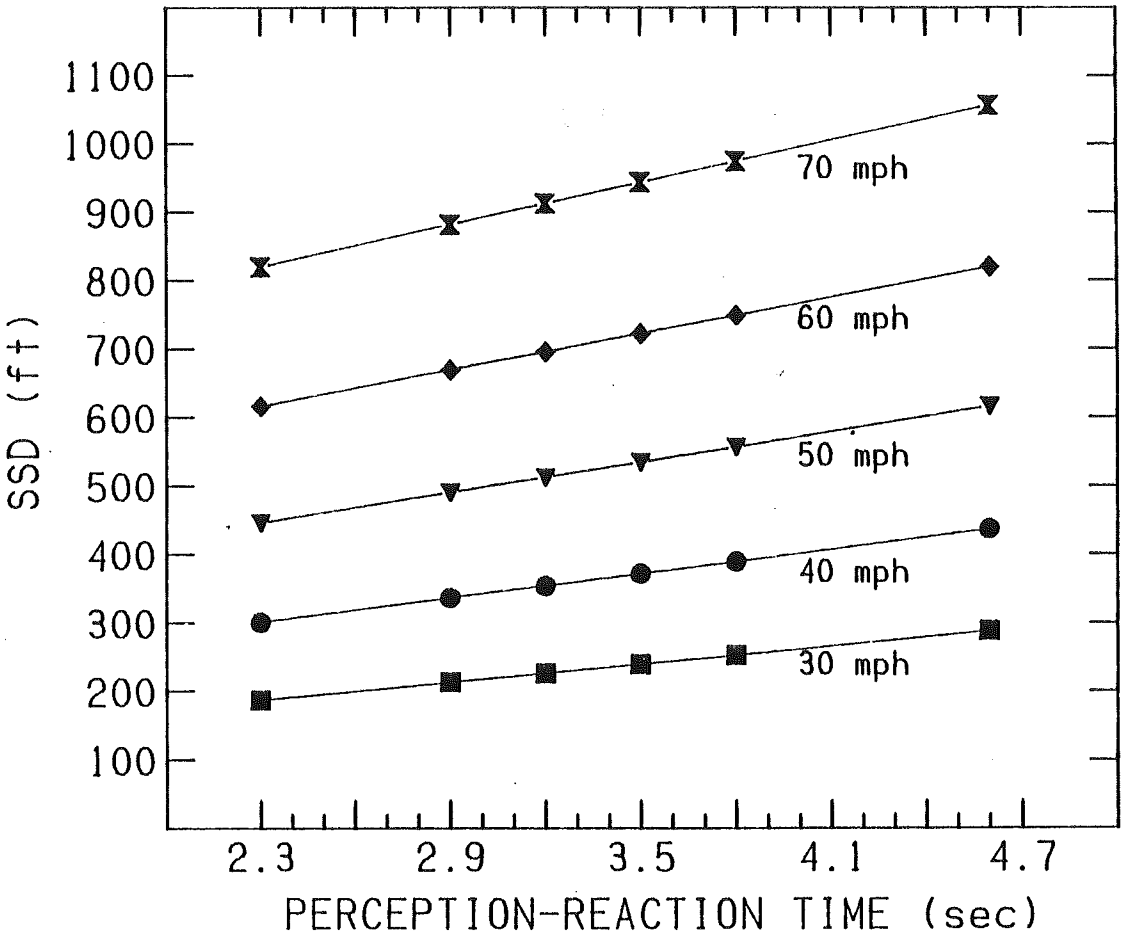

Figure A1. Stopping sight distance as a function of perception-brake-reaction time for five velocities.

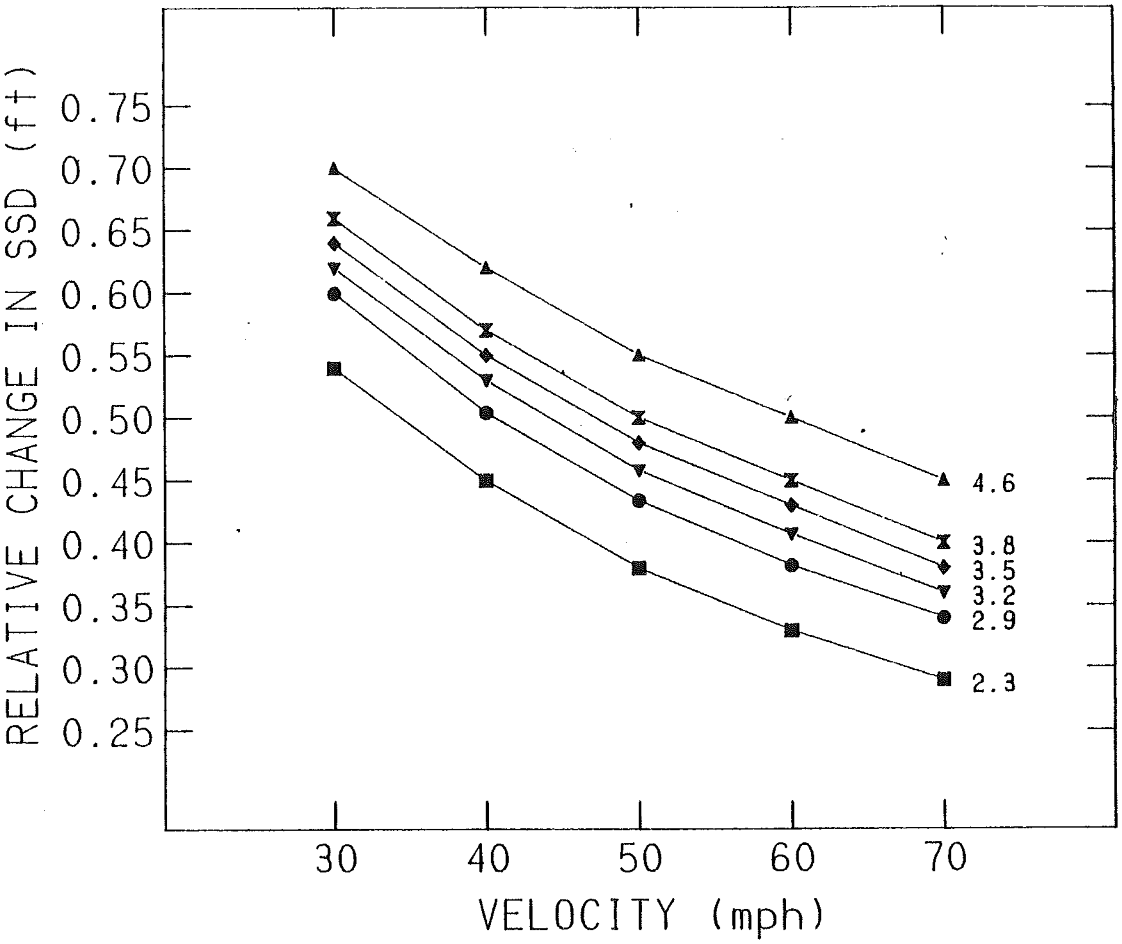

Figure A2. Percentage change in stopping sight distance that results from a one percent change in driver perception-brake-reaction time, plotted as a function of vehicle velocity for six perception-brake-reaction time values.

70 mph. As shown in Figure A2, the sensitivity of stopping sight distance to a change in perception-brake-reaction time was an inverse function of vehicle velocity. This is because the proportion of stopping sight distance accounted for by brake reaction distance (the first distance in Equation 1) decreases with velocity. Since brake reaction distance, and thus the proportion of stopping sight distance, increases with perception-brake-reaction time, the percentage change in stopping sight distance for a one percent change in perception-brake-reaction time increases with the parameter value.

Lateral Clearance on Horizontal Curves

Sight distance can be reduced by obstructions (e.g., terrain, buildings) on the inside of horizontal curves. To maintain stopping sight distance, obstacles must be far enough back from the road for the driver to be able to see (across the inside of the curve) that part of the road corresponding to the stopping sight distance. The minimum lateral clearance, or middle ordinate of the curve, is calculated from the following equation:

$$m = R[1 - \cos(SD/200)] \qquad (3)$$

where

m = middle ordinate,

R = radius of the curve measured to the center line of the inside lane (feet),

S = stopping sight distance (feet), and

D = degree of curvature (degrees).

In order to assess the effect of perception-brake-reaction time on the the length of the middle ordinate, the stopping sight distance S in Equation 3 was replaced by the expression for stopping sight distance in Equation 1. The following equation was attained:

$$m = (5730/D)\ \{1 - \cos[(1.47Vt + V^2/30(f \pm g))D/200]\} \quad (4)$$

This equation was solved for each of the six perception-brake-reaction times and the five velocities considered previously. For these calculations, design speed was assumed to equal vehicle velocity and the curves were assumed to be designed at the maximum degree of curvature: Thus, the values of D were 24.75, 13.25, 8.25, 5.25, and 3.50 for speeds of 30, 40, 50, 60, and 70 mph, respectively. As shown in Figure A3, the minimum lateral clearance increases substantially with increases in perception-reaction time.

To estimate the magnitude of the change in m due to a 1% change in t, a sensitivity analysis was conducted. The first derivative of the function, as applied in the stopping sight distance sensitivity analysis, could not be used because Equation 4 is a trigonometric function. Instead, small changes in t on either side of each of the six levels were substituted into Equation 4. The corresponding changes in m, expressed as percentages, are plotted in Figure A4. The percentage change in the middle ordinate for a 1% change in perception-brake-reaction time was inversely related to velocity and positively

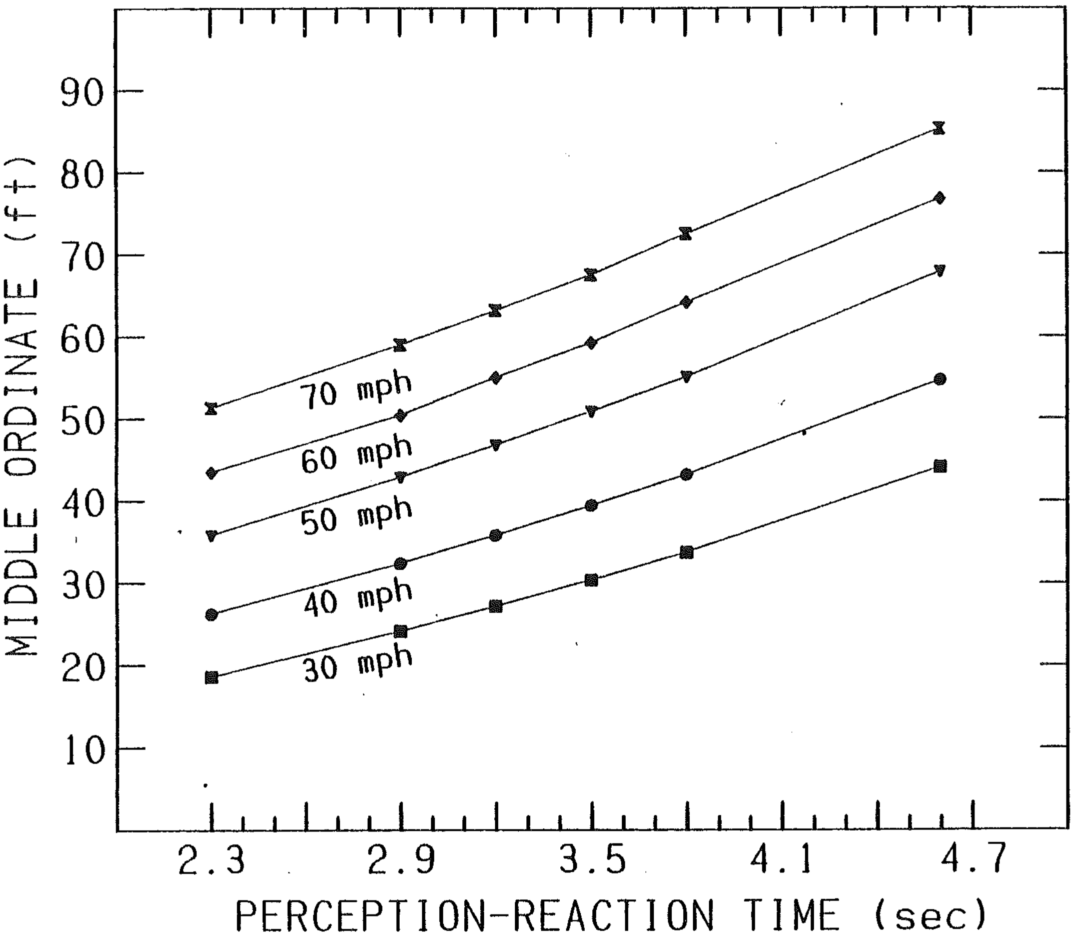

Figure A3. Middle ordinate as a function of perception-brake-reaction time for five velocities.

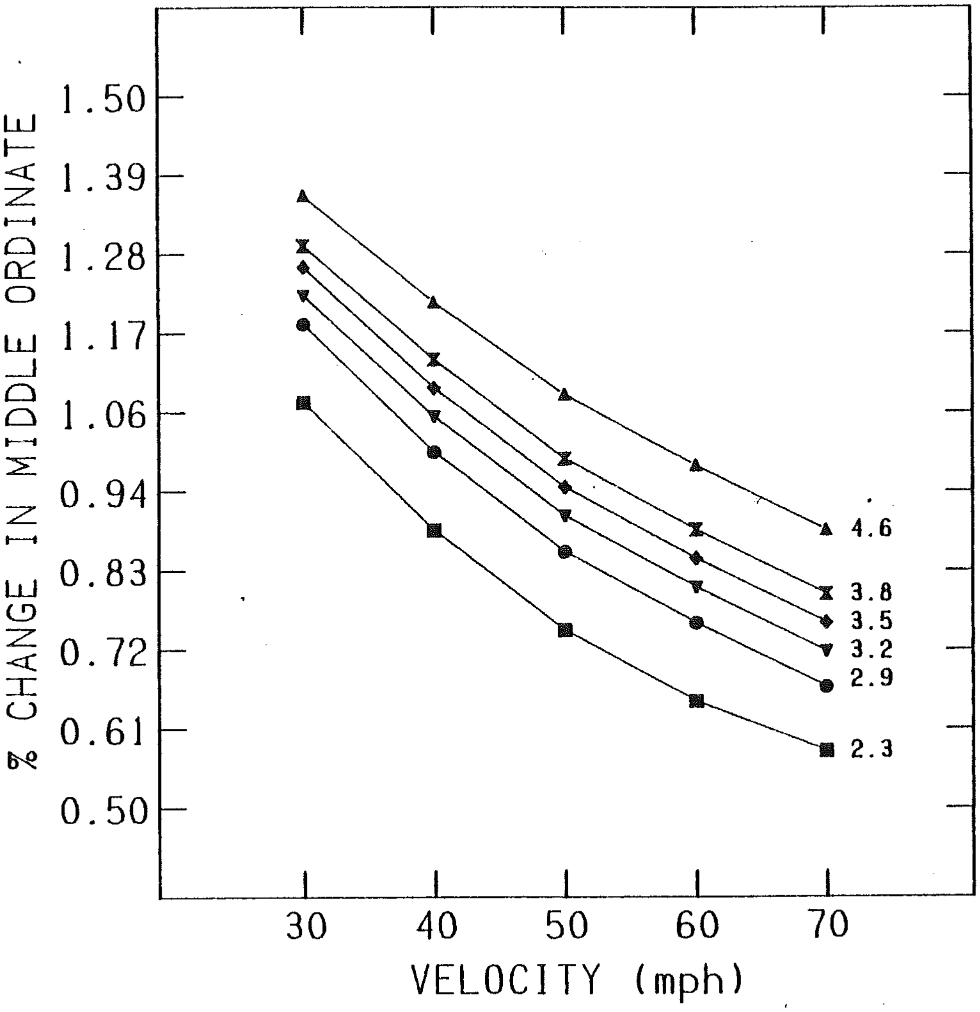

Figure A4. Percentage change in the middle ordinate that results from a one percent change in driver perception--brake-reaction time, plotted as a function of vehicle velocity for six perception-brake-reaction time values.

related to the parameter value (perception-brake-reaction time).

Passing Sight Distance for Two-Lane Highways

For design purposes, passing sight distance should be determined on the basis of the length needed to safely complete normal passing maneuvers. The driver shuld be able to see a sufficient distance ahead, clear of traffic, to complete the passing maneuver successfully.

The minimum passing sight distance for two-lane highways is defined as the sum of the following four distances:

1) Distance traversed during driver processing time and during the initial acceleration to the point of encroachment on the left lane.
2) Distance traversed while the passing vehicle occupies the left lane.
3) Distance between the passing vehicle at the end of its maneuver and the opposing vehicle.
4) Distance traversed by an opposing vehicle while the passing vehicle occupies the left lane.

The first distance represents about 15% of the total passing sight distance and is thought to be the only one of the four distances that is sensitive to the driver's capabilities. The first distance is computed from the following equation:

$$d = 1.47t_1(v - m + at_1/2) \qquad (5)$$

where:

t_1 = time of initial maneuver (seconds),

a = average acceleration (mph/sec),

v = average speed of passing vehicle (mph), and

m = difference in speeds of passed and passing vehicles (mph).

AASHTO (1984) recommends a range of 3.7 to 4.3 seconds for t_1.

Equation 5 was differentiated with respect to t_1, and the percentage change in $\underline{d}$ due to a 1% change in $\underline{t_1}$ was calculated for different design speeds. It was concluded from this analysis that $\underline{d}$ was relatively insensitive to variations in t_1: The percentage change varied from .153 at 30 mph to .162 at 70 mph.

This analysis was based on the AASHTO assumption that acceleration takes place in the first distance and that the second distance (that traveled by the passing vehicle while it occupies the left lane) is independent of human factors. A sensitivity analysis based on different assumptions could show that passing sight distance is more sensitive to variations in driver processing times.

Sight Distance at Stop Controlled Intersections

Vehicles stopped at a stop sign on a minor road of an intersection must have sufficient sight distance to successfully perform one of three maneuvers:

1) Travel across the intersecting roadway after clearing traffic on both left and right sides.

2) Turn left into the intersecting roadway after clearing the traffic on the left side and merging with the traffic on the right side.

3) Turn right into the intersecting roadway by entering the traffic stream with vehicles from the left.

AASHTO (1984) recommends the following equation for computing necessary sight distance:

$$d = 1.47V(J + t_a) \tag{6}$$

where:

d = sight distance along the intersecting roadway from the intersection (feet),

V = design speed on the major highway (mph),

J = sum of the perception time and the time required to actuate the clutch or actuate an automatic shift (seconds), and

t_a = time required to accelerate and traverse the distance to clear the intersecting highway pavement (seconds).

The term $\underline{J}$ represents the time from the driver's first look for possible oncoming traffic to the instant the car begins to move. A value of 2.0 seconds is assumed.

In order to quantify the changes in the sight distance $\underline{d}$

with respect to changes in the the driver characteristic $\underline{J}$, a sensitivity analysis was performed. The equation

$$(dd/dJ)/(d/J) = J/(J + t_a) \qquad (7)$$

was evaluated for the t_a figures recommended by AASHTO and a 2.0 second value for $\underline{J}$. A 1% change in $\underline{J}$ was found to result in changes from .19% (for t_a = 8.5 seconds) to .30% (for t_a = 4.5 seconds).

REFERENCES

American Association of State Highway Officials (1965). *A policy on geometric design of rural highways*, Washington, D.C.: AASHO.

American Association of State Highway and Transportation Officials (1984). *A policy on geometric design of highways and streets*, Washington, D.C.: AASHTO.

Anderson, H. L. (1979). A final word on safety. Washington, D.C.: Federal Highway Administration.

Birren, J. E. (1974). Psychophysiology and speed of response. *American Psychologist*, *29*, 808-815.

Botwinick, J., Brinley, J. F., & Robbin, J. (1958). The interaction effects of perceptual difficulty and exposure time on age differences in speed and accuracy of response. *Gerontologia*, *2*, 1-10.

Breitmeyer, B. G. (1975). Simple reaction time as a measure of the temporal response properties of transient and sustained channels. *Vision Research*, *15*, 1411-1412.

Brown, B. (1972). Dynamic visual acuity, eye movements and peripheral acuity for moving targets. *Vision Research*, *12*, 305-321.

Burg, A. (1965). Apparatus for measurement of dynamic visual acuity. *Perceptual and Motor Skills*, *20*, 231-234.

Burg, A. (1966). Visual acuity as measured by dynamic and static tests: A comparative evaluation. *Journal of Applied Psychology*, *50*, 460-466.

Burg, A. (1971). Vision and driving: A report on research. _Human Factors_, _13_, 79-97.

Cleveland, D. E., Kostyniuk, L. P., Waissi, G. R., Olson, P. L., & Fancher, P. S. (1985). Stopping sight distance parameters. Paper presented at the 64th annual meeting of the Transportation Research Board.

Fergenson, P. E. (1971). The relationship between information processing and driving accidents and violation records. _Human Factors_, _13_, 173-176.

Fiedler, H. M. (1984). Effects of age on visual information processing abilities in a simulated driving environment. Unpublished Master's Thesis, Arizona State University.

Fox, J. (1975). The use of structural diagnostics in recognition. _Journal of Experimental Psychology: Human Perception and Performance_, _104_, 57-67.

Garner, W. R. (1978). Selective attention to attributes and to stimuli. _Journal of Experimental Psychology: General_, _107_, 287-308.

Garner, W. R., & Clement, D. E. (1963). Goodness of pattern and pattern uncertainty. _Journal of Verbal Learning & Verbal Behavior_, _2_, 446-452.

Garner, W. R., & Sutliff, D. (1974). The effect of goodness on encoding time in visual pattern discrimination. _Perception & Psychophysics_, _16_, 426-430.

Henderson, R. L., & Burg, A. (1973). Visual tests for driver licensing. _Highway Research Board_, Special Report 134, 1-9.

Hooper, K. G. & McGee, H. W. (1983). Driver perception-reaction time: Are revisions to current specification values in order? Transportation Resesearch Record, 904, 21-30.

Kahneman, D., Ben-Ishai, R., & Lotan, M. (1973). Relation of a test of attention to road accidents. Journal of Applied Psychology, 58, 113-115.

Lindholm, J. M., & Parkinson, S. R. (1983). An interpretation of age-related differences in letter-matching performance. Perception & Psychophysics, 33, 283-294.

Mihal, W. L. & Barrett, G. V. (1976). Individual differences in perceptual information processing and their relation to automobile accident involvement. Journal of Applied Psychology, 61, 229-233.

Monahan, J. S., & Lockhead, G. R. (1977). Identifiction of integral stimuli. Journal of Experimental Psychology: General, 106, 94-110.

National Safety Council (1976). Accident facts. Chicago: National Safety Council.

Nickerson, R. S. (1972). Binary-classification reaction time: A review of some studies of human information processing capabilities. Psychonomic Monograph Supplements, 4, (17, whole No. 65).

Pachella, R. G. The interpretation of reaction time in information-processing research. In B. H. Kantowitz (Ed.), Human information processing: Tutorials in performance and cognition. Potomac, MD: Erlbaum, 1974.

Scott, A. (1979). Developing standards for stopping sight distances and crest vertical curvature. Tribune de L'artc, 2, 112-120.

Sekular, R. & Owsley, C. J. (1982). The spatial vision of older humans. In R. Sekuler, D. Kline, & K. Dismukes (Eds.), Aging and Human Visual Function. New York: Alan R. Liss.

Shinar, D. (1977). Driver visual limitations, diagnosis and treatment. Indiana University Final Report No. DOT-HS-1275, Bloomington, Indiana: Indiana University.

Shinar, D. (1978). Psychology on the road: The human factor in traffic safety. New York: Wiley & Sons.

Treat, J. R., Tumbas, N. S., McDonald, S. T., Shinar, D., Hume, R. D., Mayer, R. E., Stansifer, R. L., & Castellan, N. J. (1977). Tri-level study of the causes of traffic accidents. Report No. DOT-HS-034-3-535-77 (TAC), Bloomington, Indiana: Indiana University.

Vassilev, A., & Mitov, D. (1976). Perception time and spatial frequency. Vision Research, 16, 89-92.

Vickers, D., Nettelbeck, T., & Willson, R. J. (1972). Perceptual indices of performance: The measurement of "inspection time" and "noise" in the visual system. Perception, 1, 263-295.

Walsh, D. A. (1982). The development of visual information processes in adulthood and old age. In R. Sekuler, D. Kline, & K. Dismukes (Eds.), Aging and Human Visual Function. New York: Alan R. Liss.

Welford, A. T. (1977). Motor performance. In J. E. Birren & K. W. Schaie (Eds.), Handbook of the psychology of aging. New York: Van Nostrand Reinhold.