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Skilled Performance: Effects of Adult Age and Experience on Elementary Processes

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SUMMARY

Despite a general neglect in contemporary research of the role of practice on the performance of simple components of skill, considerable evidence indicates that experience leads to substantial improvement in detection, discrimination, and speeded classification. One goal of the present research was to identify the mechanisms responsible for practice-related improvement in such elementary tasks. A second goal was to determine whether there are adult age differences in the magnitude of practice-related improvement on simple perceptual and cognitive skills or in the mechanisms used to achieve that improvement.

Eight young adults (ages 19 to 27 years) and 8 older adults (ages 62 to 73 years) performed four simple tasks for 51 experimental sessions. On several sessions the subjects received qualitatively or quantitatively different stimuli to determine the mechanisms responsible for improvement. A concurrent reaction-time task was also performed at three different periods to assess the level of residual capacity after various amounts of practice.

The results were interpreted as suggesting that improvement is due to shifts in the type of information being processed, in the identity or sequence of processing operations, and in the attention requirements of the task. A model incorporating these mechanisms is proposed and its application to the data is discussed.

Age differences persisted on nearly every performance measure throughout all levels of practice. Moreover, there was little evidence that young and old subjects were qualitatively different in the manner in which they performed the tasks. It is suggested that the major difference between young and old adults on simple perceptual and cognitive tasks is the rate of processing nearly all types of information.

Skill generally refers to the possession of expertise in some fairly complex, temporally interrelated behavior. For example, a skilled typist or pianist has a well coordinated sequence of manual keystrokes; the development of that coordination is probably the major part of skill acquisition in these domains, because the keystrokes themselves are extremely simple in isolation. However, in other areas of skill it is possible that performance of each individual component changes with increasing expertise. Perhaps substantial improvements do not occur in the quality of a simple keystroke, but other perceptual or motoric aspects of skill might improve independent of the overall coordinated integration of the components.

Consider the case of driving an automobile. Driving involves a complex coordinated sequence of perceptual and motor activities, and the skilled driver almost certainly possesses a more efficient integration and coordination of these activities than the novice driver. The expert is probably better able to turn the steering wheel while applying pressure to the brake or accelerator, to engage the clutch with his or her foot while manually shifting gears, to sound the horn while applying pressure to the brakes, and so on. One could also ask, however, if the more elementary aspects of driving also exhibit differences as a function of experience. For example, does the skilled driver have a faster reaction time to move the foot from the accelerator to the brake? Is there a quicker perception of objects seen in the rearview mirror? And is there more rapid apprehension of both speed and mileage information from a single glance at the speedometer?

In the current project several discrete tasks were combined into a complex game, and the effects of extensive practice (50 hr.) on performance of each game component were examined. The tasks were similar to many of those currently investigated in cognitive psychology, but were modified slightly to make the game context realistic. The following specific issues were studied: (a) Does experience lead to improvements in very elementary processes such as signal detection, reaction time, and visual discrimination? (b) If performance does improve, what is responsible for the improvement? (c) Are there adult age differences in the magnitude or nature of the improvements?

Improvement in Simple Tasks

A general assumption implicit in much of the literature on skilled performance is that simple tasks are immune to practice effects and are relatively pure assessments of capacity. As Ream (1922) long ago argued, however, the logic might well be reversed:

> The effect of practice is very important in considering just what the test measures. If the ability required in the test is fundamental rather than accessory, learning will play a very small part and there will be very little improvement with practice. . . . No improvement would indicate that a basic . . . capacity is being investigated. (p. 308)

Although one might suspect, on the basis of the relative neglect of practice variables in many experimental studies, that practice or experience has little or no effect on perceptual performance, the evidence to the contrary is overwhelming. As long ago as 1953, Gibson was able to locate 211 experimental studies concerned with the effects of practice on perceptual judgments, many of which clearly indicated that performance did improve with practice (Gibson, 1953, see also 1969). The more recent evidence on this topic is also generally consistent with the conclusion that practice greatly facilitates perceptual performance. For example, practice-related improvements have been reported in such tasks as visual acuity (e.g., Johnson & Leibowitz, 1979; McKee & Westheimer, 1978), pitch discrimination (e.g., Averbach, 1971; Hartman, 1954; Heller & Averbach, 1972), auditory sequence identification (e.g., Gengel & Hirsh, 1970; Neisser & Hirst, 1974; Nickerson & Freeman, 1974), visual letter identification (e.g., Carr, Lehmkuhle, Kottas, Astor-Stetson, & Arnold, 1976), visual signal detection (e.g., Colquhoun & Edwards, 1970; Taylor, 1964), auditory signal detection (e.g., Kerkhof, van der Schaaf, & Korving, 1980), speech discrimination (e.g., Samuel, 1977), dichotic listening (Ostry, Moray, & Marks, 1976; Underwood, 1974), visual backward masking susceptibility (e.g., Schiller, 1965; Ward & Ross, 1977), auditory backward masking susceptibility (e.g., Loeb & Holding, 1975), and absolute judgments (e.g., Eriksen, 1958; Fulgosi & Bartolovic, 1971; Weber, Green, & Luce, 1977).

Some indication of the potential magnitude of these practice effects is available in a comparison of the performance of experienced and naive subjects in a study by Nickerson and Freeman (1974). Naive subjects in this study were found to be relatively accurate at identifying sequences of four tones when the tones were presented at a rate of 5 per sec, but a highly practiced subject was found to be capable of performing with comparable high accuracy when the tones were presented at a rate of 500 per sec—100 times faster than the rate for the naive subjects!

A reasonable conclusion from these studies is that the psychophysical "rule of thumb that under ordinary experimental conditions the effects of practice are limited to a few minutes during [the subject's] first acquaintance with his task" (Swets & Sewall, 1963, p. 120) is grossly misleading. Neisser and Hirst (1974) seem to have stated the case more accurately by suggesting that "results obtained with naive subjects cannot safely be generalized to sophisticated ones" (p. 398).

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The literature concerned with the effects of practice on motor tasks is also quite extensive and consistent. Substantial improvements have been documented in tasks ranging in complexity from finger tapping (e.g., Provins, 1958; Ream, 1922; Wells, 1908), ball balancing (e.g., Swift, 1903), and crank turning (e.g., Provins, 1956), to telegraphy (e.g., Bryan & Harter, 1897; Fleishman & Fruchter, 1960), tracking (e.g., Archer, Kent, & Mote, 1956) and typing (e.g., Conrad & Longman, 1965; Leonard & Carpenter, 1964). Moreover, virtually all relevant experiments have demonstrated that response time is greatly reduced as a function of practice, and in many of the studies it has also been reported that the initially most difficult conditions exhibit the greatest improvements with practice. As a consequence of this differential improvement across conditions, many of the phenomena thought to be fundamental characteristics of human performance are altered at least quantitatively, and possibly qualitatively, with extensive practice. For example, marked reductions in the magnitude of the phenomenon with extensive practice have been demonstrated in stimulus-response compatibility tasks (e.g., Brebner, 1973; Fitts & Seeger, 1953; Leonard & Newman, 1965), psychological refractory period tasks (e.g., Gottsdanker & Stelmach, 1971), and Stroop interference tasks (e.g., Reisberg, Baron, & Kemler, 1980; Shor, Hatch, Hudson, Landrigan, & Shaffer, 1972; Stroop, 1935). It has also been reported that subjects shift from a serial to a parallel mode of information processing with prolonged practice (e.g., Conrad, 1962; Corcoran, 1967; Davis, Moray, & Treisman, 1961; Grill, 1971; Marcel, 1970; Mowbray & Rhoades, 1959; Neisser, 1963, 1974; Neisser, Novick, & Lazar, 1963; Shurtleff & Marsetta, 1968), but other experiments suggest that although the slope of the function relating reaction time to amount of stimulus information is much reduced with practice, it is still greater than zero—indicating that true parallel processing is not in effect (e.g., Briggs & Blaha, 1969; Burrows & Murdock, 1969; Dumas, 1972; Graboi, 1971; Kristofferson, 1972a, 1972b, 1972c, 1977; Kristofferson, Groen, & Kristofferson, 1973; Nickerson, 1966; Prinz, 1979; Ross, 1970; Seibel, 1963; Yonas & Pittenger, 1973).

The important point to be noted from these results is that extensive practice does have substantial effects on a variety of motor tasks, just as it was demonstrated to influence perceptual tasks. Motivated repetition of a task may not lead to a qualitatively different type of performing, but it surely leads to a quantitatively more efficient and effective mode of performance for many perceptual and motor tasks. The implicit assumption in many earlier studies that basic performance capacities were being measured under conditions of very limited practice is therefore almost certainly incorrect.

From the perspective of ecological validity, the investigation of practiced performance would seem to be necessary if one's results are to have much practical relevance. Most daily activities are performed with many (perhaps thousands) of hours of practice, and without adequate data it is impossible to know whether the findings obtained from studies with only a few minutes of practice are even addressing the same types of phenomena as those encountered in normal (i.e., nonlaboratory) situations.

What Improves?

One possible reason for the reluctance to accept the existence of substantial practice effects in very elementary tasks might be an inability to specify how performance could be improving in a simple task. What is it that could be learned in a signal detection task, for example, that leads to dramatic improvements in performance? To state that the individuals, or the processes used by the individuals, become more proficient or efficient is merely to describe the phenomenon; an explanation requires some specific mechanism that is altered as a function of experience and that is responsible for the increased efficiency or proficiency. Moreover, since the concern here is with practice extending over many sessions, such transient factors as general task unfamiliarity and situation anxiety are probably relatively unimportant.

There appear to be at least three broad categories into which speculations about the nature of improvement in simple tasks might be grouped. For the purpose of description these classes of explanation will be considered as though they were mutually exclusive, but it is likely that two or more mechanisms typically contribute to practice-related improvements in many tasks.

The first class of explanation maintains that improvement results because of a change in the type of information being processed. The qualitative shift in the nature of the information may be a consequence of (a) more efficient figure–ground separation of relevant from irrelevant information; (b) perceptual tuning or sensitization to specific stimulus features; (c) perceptual categorization based on the experience history or physical characteristics of the stimuli; (d) perceptual coding into higher-order units analogous to words or phrases rather than single letters; or (e) a shift from one modality of input to another, as when a typist shifts from monitoring visual to monitoring kinesthetic information. Specific alternatives within this class thus differ in the means by which a change in the type of information occurs, but they can be grouped together on the basis of a common assumption that a primary factor responsible for experience-related improvement is a qualitative shift in the type of information being processed.

A specific example of a shift in the nature of information being processed comes from an analysis of Morse code learning data reported by Shepard (1963). By examining previously reported data on Morse Code letter confusions at different stages of practice, Shepard was able to identify a trend for errors early in practice based on reflection (e.g., dash–dot–dot substituted for dot–dot–dash) and complementation (e.g., dash–dash–dot substituted for dot–dot–dash), and for errors late in practice based on the number of elements (e.g., dot–dot–dot–dash substituted for dot–dot–dash). An implication of this finding is that experience led to the development of a system of coding and classifying signals that resulted in a change in the nature of the information being used at different levels of experience.

A second class of explanation contends that experience leads to a change in either the specific processes or operations to which the information is subjected, or in the sequence of these processes or operations. For example, it might be argued that some information-processing stages could be omitted after extensive practice, or that separate operations could be performed in parallel, rather than serially, after sufficient amounts of experience. The distinguishing characteristic of this class of explanation is that experience is assumed to produce a shift in the nature of the processing, regardless of the rate of processing or type of information being processed.

An example of an interpretation based on a change in the type of processing carried out is Neisser's (e.g., 1967) explanation of his visual search results. In several studies Neisser and his colleagues found that after moderate experience subjects could search for the presence of any of 10 targets as rapidly as for a single target. The interpretation suggested by Neisser was that after practice the feature analyzers relevant for all targets could be examined in parallel, rather than serially as was necessary at early stages of practice.

A third class of explanation is comprised of those interpretations suggesting that experience with a task reduces the attention requirements of that task. Initially, the task demands might exceed the available resources of attention or consciousness, but with practice some of the processes required for the task may become "automatic" and occur without necessity of deliberate conscious control or attention. The automatic processes may be faster or less susceptible to distraction than processes under attentional control, or they may simply allow more of the attentional resources to be concentrated on the most difficult operations in the task. It is also possible that the allocation policies by which attention or conscious monitoring is directed toward specific processes become more efficient with practice, such that only the most important operations receive attention after moderate amounts of experience. In either case, it is assumed that residual resources of attention or consciousness become more plentiful as a consequence of experience with a task, and that this increase in resources somehow leads to improved task performance.

Research on the relationship between processing resources and practice is relatively recent; the relevant studies are mentioned in the Discussion section. Interpretations of this type are already popular enough to have warranted comment in textbooks, however, as the following selections indicate:

> The amount of attention required by a process depends on how practiced that process is. The more a process has been practiced the less attention it requires, and there is speculation that highly practiced processes require no attention at all. (Anderson, 1980, p. 30)

> How do you train someone so they will perform the proper actions, even when in panic? The solution is to overtrain anyone who performs dangerous tasks. Make all actions become automated. Practice the set of possible responses to any situation over and over again. In this way, a minimum of attention is required, and in time of danger, the appropriate sequences get performed automatically. (Norman, 1976, p. 66)

Obviously, quite complex models of skill improvement could be postulated with combinations of different mechanisms. In fact, it might even be argued that pure cases of one explanatory mechanism seldom exist, because a change in one mechanism (e.g., type of information being processed) will almost inevitably lead to a change in other mechanisms (e.g., the manner in which information is processed). An example of a sophisticated hybrid model of this type is one recently proposed by Schneider and Shiffrin (1977; Shiffrin & Schneider, 1977). They argued that consistent experience with a task leads to a change in the way the task is performed (a shift from "controlled search" to "automatic detection"), and to a reduction in the amount of processing resources required to perform the task—that is, automatic detection is presumed to occur without demands on short-term memory (attention) capacity. However, these same authors also mentioned that many models are capable of predicting a given set of results, and consequently they offer guidelines for deciding among alternative models:

> A proper evaluation of models should incorporate two tests: (a) Can the model predict a wide variety of results in differing paradigms . . . ? (b) Can the model predict results from a single series of studies on the same subjects, a series in which most of the commonly examined variables are manipulated? (Shiffrin & Schneider, 1977, p. 177)

The present study, in which the same subjects performed four different tasks for an extended period of time, was designed to satisfy the Shiffrin and Schneider guidelines in allowing an evaluation of alternative models of skill improvement.

Adult Age Differences in Improvement

Over the past two or three decades, many experimental studies have been reported in which age differences in perceptual and cognitive performance have been investigated, and most have shared two characteristics: (a) They have demonstrated that older adults perform less accurately or less rapidly than young adults on some perceptual or motor task. (b) The experimental situations have involved inexperienced subjects performing for a very limited period of time. The invariable combination of these two characteristics led Murrell (1973) to suggest the following:

> What has been overlooked is that this kind of investigation is confounded by a practice effect and the results, if they have any applicability at all, can be applied only to unpractised or inexperienced subjects. (p. 93)

Even more explicit in an earlier source, Murrell (1965) stated,

> Anyone reading the results of the laboratory experiments could be forgiven for imagining that any person who achieves the age of fifty will have become a slow, forgetful, half-blind, half-deaf, palsied character of little use in industry. In fact, many older men and women hold down jobs with complete satisfaction to their employer. This does not mean that the experimental findings are fallacious. The apparent anomaly seems to derive from the use in the laboratory of subjects who are naive in the practice of the particular faculty which is being tested. (p. 449)

Clearly, Murrell is calling for research into the effects of practice on age differences in perceptual-motor performance. The implication is that many of the age differences reported in experimental studies might be caused by such factors as task unfamiliarity, low motivation, high anxiety, or the use of suboptimal performance strategies, all of which could be eliminated with experience. Unfortunately, very little research has addressed this issue, and much of what does exist has either used only minimal (e.g., less than 1 hr.) amounts of experience (e.g., Botwinick & Shock, 1952; Botwinick & Thompson, 1967; Grant, Storandt, & Botwinick, 1978; Hoyer, Labouvie, & Baltes, 1973; Thomas, Fozard, & Waugh, 1977), or has compared experienced workers of different ages, resulting in the possible confounding of important selection factors with the age comparison (e.g., Murrell & Edwards, 1963; Murrell & Forsaith, 1960; Murrell & Humphries, 1978; Murrell, Powesland, & Forsaith, 1962).

Three studies with approximately 5–10 hrs. of practice reported equivalent effects of practice in young and old subjects with a tachistoscopic perception task (Hertzog, Williams, & Walsh, 1976), a typing task (Leonard & Newman, 1965), and a memory-scanning reaction-time task (Madden & Nebes, 1980). Poon, Fozard, Vierck, Dailey, Cerella, and Zeller (Note 1) provided subjects with the opportunity for approximately 2 hr. of practice in a choice reaction-time task and observed that old subjects improved more (i.e., reduced their reaction times by a greater amount) than did young subjects. Despite the greater improvement by the old subjects, however, the young subjects in this study still responded nearly twice as fast as the old subjects in the second (final) session. Jordan and Rabbitt (1977) also reported a trend for greater practice-related reaction time changes in older than in young adults, but the statistical analyses were somewhat confusing, and it is not clear whether the interaction of Age × Practice was significant. A similar task, but with a much more dramatic outcome, was employed by Murrell (1970). This experiment used only three subjects, two teenagers and a 57-year-old woman, but each performed for many hours, in over 12,000 trials. The result of major interest in the Murrell study was that the reaction time of the older subject, although initially greater than that of either younger subject, eventually reached the level of, and indeed became indistinguishable from, the reaction times of the younger subjects. As intriguing as this result may be, it is important not to overlook the fact that the major conclusion is based on the performance of one 57-year-old woman!

The relationship between amount of experience with a task and age differences in performance on that task is important for both practical and theoretical reasons. The practical significance derives from the need to determine whether performance in short-term testing situations is an accurate reflection of what can be expected after an individual has mastered the fundamentals of the task. Tests designed to measure an individual's maximum capabilities may be completely invalid if moderate amounts of practice result in substantial changes in performance. The theoretical importance concerns the issue of what is responsible for the observed age differences in short-term situations. If experiential factors such as lack of relevant recent practice are responsible for the initial age differences, then moderate amounts of practice might lead to the elimination of those age differences. However, if physiological or biological factors are involved, then it would be unlikely that any amount of practice would result in the disappearance of age differences in performance.

Current Study

The three issues discussed previously (i.e., Does performance improve on simple tasks? What is responsible for the improvement? Are there adult age differences in the type or magnitude of improvement?) served as the primary goals of the present study. There were two phases in the project. In the first phase, 50 young adults and 24 older adults performed the "Space Trek" game (consisting of signal detection, memory-scanning reaction time, visual discrimination, and temporal-anticipation tasks) for a single session to determine the normative levels of performance for the two age groups. In the second phase, 8 young adults and 8 older adults performed the Space Trek game for 51 experimental sessions over a period of 2–5 mo.

The effects of practice could be examined by comparing performance at various levels of experience with the tasks. The mechanisms responsible for any improvement that might occur were investigated with the use of several transfer conditions, and the periodic introduction of a concurrent reaction-time task. One transfer condition involved changing the qualitative nature of the stimuli used in the task. It was assumed that if the performance improvement was due to the development of a stimulus-specific mechanism, then the transfer to new stimuli should become progressively more difficult with increased experience. A quantitative transfer condition consisted of reducing either the spatial size or the temporal duration of the stimuli. The assumption here was that if performance improves because of an increase in available processing resources, then one should be better able to perform the task under these demanding conditions later in practice than early in practice. A similar rationale guided the inclusion of the concurrent task, with reaction time in the secondary task now serving as the measure of "spare capacity." Possible changes in the processes used in carrying out the task were investigated by examining specific dependent variables within each task (e.g., the slope of the function relating reaction time to set size in the memory-scanning task). Because adults in two different age groups served as subjects, the magnitude of improvement and the mechanisms responsible for improvement could be directly compared in the two age groups.

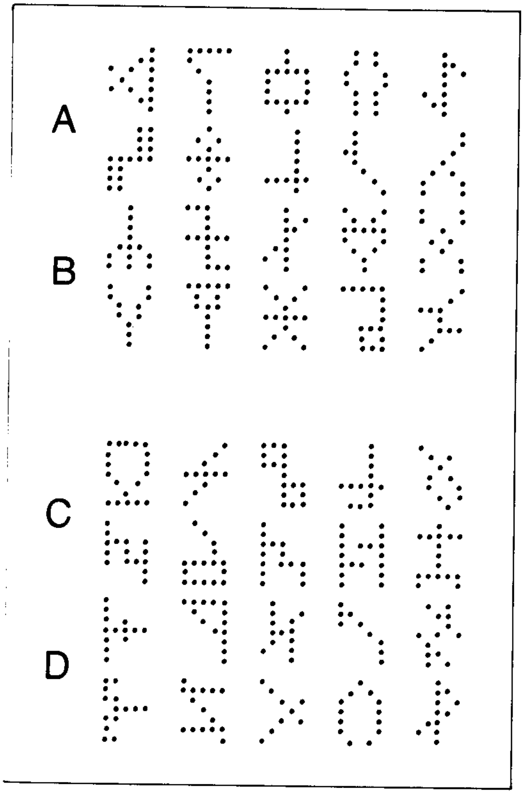

Figure 1. Stimulus items used in the memory-scanning task. (A given subject received one subset, e.g., A, as positive items and another subset, e.g., B, as negative items.)

Method

Apparatus

A PDP 11/03 laboratory computer was used to present stimuli on a Hewlett-Packard 1311A Display and record responses from two 10-key telephone keyboards. Koss PRO 4AA headphones and a Hunter Model 320S voice-activated relay were used to present auditory stimuli and register vocal responses.

Subjects

Young participants were recruited from the university community, and older participants from senior citizen groups and referral from previous participants. All subjects reported themselves to be in reasonably good health. Further characteristics, including the Wechsler Adult Intelligence Scale (WAIS) Vocabulary and Digit Symbol raw scores, are presented later, in Table 1.

Experimental Tasks

Signal detection. In this task the subject viewed a display screen with a randomly varying pattern of 60 dots for 250 msec. The target, which appeared in approximately 50% of the observation intervals, consisted of a configuration of 5 of the 60 dots subtending a visual angle of approximately .4° and moving at a rate of about 6° per sec in a consistent direction across the screen. The direction of target movement varied randomly across trials. Presence or absence of the target was indicated by the subject pressing a key on the right (for yes) or the left (for no) keyboard. Accuracy feedback was presented after each response.

Memory scanning. In this task the subject inspected a list of one to four stimulus items (varied randomly across trials), and then rapidly classified a probe item with respect to whether it was in the earlier memory list. Forty stimulus items were constructed from a 5 × 7 matrix subtending a visual angle of approximately 2.3° × 3.2°. The symbols had approximately the same average number of matrix elements and overall complexity as letters and digits, but all of the symbols were unfamiliar and did not have readily available verbal labels. The set of 40 stimulus items was divided into four 10-item subsets, as indicated in Figure 1. For a given subject, one of the subsets served as the population of possible positive items, and another served as the population of possible negative items. With the exception of the transfer conditions, only members of the positive subset ever appeared in the list of 1-4 memory items. The assignment of subsets as positive or negative was balanced across subjects within each age group.

The probe stimulus, which was randomly selected from the memory list or the negative subset, was classified by a key press on the right (for yes) or on the left (for no) keyboard. Information about the accuracy and speed (on an analog scale) of the response was displayed immediately after the response.

Visual discrimination. The visual-discrimination task consisted of two visual arrays: squares and diamonds for one half of the subjects (Figure 2a), Xs and +s for the other half of the subjects (Figure 2b), with each array having a .5 probability of containing a target element. One of the arrays had four 2.1° squares (or Xs) positioned at the corners of an imaginary 27° rectangle, with a .6° diagonal (or for the Xs, horizontal or vertical) line in one corner of one of the squares (or Xs) as the target element. The other array had four 2.1° diamonds (+s) positioned in the middles of the sides of the imaginary 27° rectangle, with a .6° vertical or horizontal (for the +s, diagonal) line in one corner of one of the diamonds (+s) as the target element.

The two arrays were presented either in immediate succession for 400 msec each, in which case full attention could be devoted to each array, or simultaneously for 400 msec, in which case attention had to be divided between the two arrays. Simultaneous and successive displays were randomly intermixed within trial blocks. Two independent responses were required in this task, one indicating the presence or absence of a target element in the square (X) arrays, and another indicating the presence or absence of a target element in the diamond (+) arrays. Responses consisted of keypresses on the left response panel for one array and keypresses on the right response panel for the other array. Separate feedback for each response was presented after both responses had been registered.

No poststimulus mask was presented, and thus there was some iconic persistence that allowed information extraction to continue after the termination of the display. The luminance of each array was the same in the successive and simultaneous displays, however, and with no delay interval between successive displays the duration of the persistence should have been equivalent in the two-display conditions.

Temporal prediction. In this task the subject was required to anticipate the intersection point of two trajectories. One trajectory was primarily horizontal from left to right with a speed that varied randomly between 22.5° and 45.0° per sec across trials. The other trajectory was vertical from bottom to top with a constant speed, either 60° or 150° per sec, but had a variable starting location along the horizontal axis. The subject had control over the time of initiating the vertical trajectory with the goal of trying to make the two trajectories intersect one another at the same point in time. When this occurred a visual explosion was displayed on the screen and a crash sound was presented through the earphones. A key on the right response panel was used to initiate the vertical trajectory.

The experimental tasks were embedded in the context of a game called Space Trek, with the signal detection task identified as a "radar watch," the memory scanning task as a "UFO classification," the visual discrimination task as a "weapons scan," and the temporal prediction task as a "photon torpedo." The probability of a signal in each of the first three tasks was .5, and thus, on the average, 50% of the radar watches were followed by a UFO classification, 50% of the UFO classifications were followed by a weapons scan, and finally, 50% of the weapons scans were followed by a photon torpedo. Note that although the tasks were embedded in a game context, they were discrete and independent activities with sequencing determined without reference to the subject's performance.

Alternate versions of the tasks. Both qualitative and quantitative versions of the basic tasks were created that were similar in format to the original tasks but differed in an important respect. The qualitative versions of the tasks involved different stimulus items in the signal detection (radar watch), memory scanning (UFO classification), and visual discrimination (weapons scan) tasks. The alternative stimuli in the signal-detection and memory-scanning tasks were similar in structure, but different in identity, to those used in the standard versions of the tasks. For example, subjects receiving Sub-

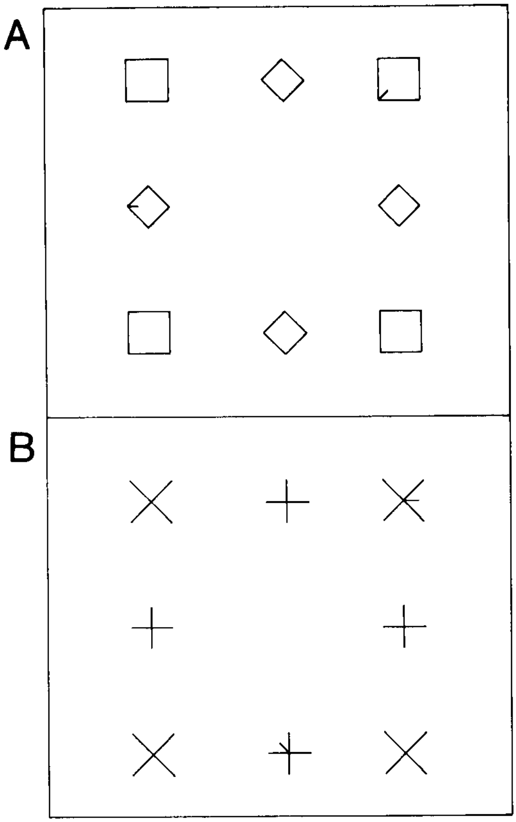

Figure 2. Stimulus arrays in simultaneous-presentation condition in the visual-discrimination task. (One half of the subjects received the arrays in A, and one half received those in B.)

sets A and B as the positive and negative sets in the memory-scanning task now received Subsets C and D in their place. The alternative stimuli in the visual-discrimination task consisted of ×s and +s in the locations previously occupied by the squares and diamonds, respectively, or vice versa, depending on the standard version of the task for that subject. The targets to be detected remained as either vertical or horizontal lines or diagonal lines in one segment of one of the items. There was no qualitatively different version of the temporal-prediction (photon torpedo) task.

Quantitatively different versions of the tasks were created by reducing the stimulus duration by one half in the signal-detection (from 250 to 125 msec) and visual-discrimination (from 400 to 200 msec) tasks, and by reducing the size of the probe stimulus (from 2.3° × 3.2° to 1.2° × 1.6°) in the memory-scanning task. No quantitative variation was introduced in the temporal-prediction task.

The memory-scanning task also involved a reversed assignment transfer version in which the stimulus items previously used as the positive set were switched to the negative set, and vice versa. For example, a subject who had received Subset A as the population of positive items and Subset B as the population of negative items in the standard version, now received Subset B for the population of positive items and Subset A for the population of negative items.

Procedure. The experiment had two distinct phases. In the short-term phase, 50 young (ages 18 to 23 years) and 24 old (ages 60 to 79 years) adults participated in a single one-block session consisting of 100 signal-detection trials, approximately 50 memory-scanning trials, approximately 25 visual-discrimination trials, and approximately 12.5 temporal-prediction trials. In the long-term phase, 8 young (ages 19 to 27 years) and 8 old (ages 62 to 73 years) adults participated in the first one-block session and in 50 additional two-block sessions that each involved a total of 200 signal-detection trials, approximately 100 memory-scanning trials, approximately 50 visual-discrimination trials, and approximately 25 temporal-prediction trials. In both phases, one half of the subjects in each age group received one standard version of the tasks and one half received a different standard version. No performance differences were evident across the two versions. A 10-min demonstration segment illustrating how each of the four tasks was to be performed was presented prior to the experimental block of trials in the first session.

Long-term subjects were presented with quantitatively different versions of the tasks on Sessions 8 and 34, with qualitatively different versions on Sessions 11 and 37, and with the reversed stimulus-response assignment version of the memory-scanning task on Sessions 14 and 40. In addition, a vocal reaction-time task was performed before and after the primary tasks on Sessions 4, 5, and 6, Sessions 24, 25, and 26, and Sessions 44, 45, and 46. On Sessions 5, 25, and 45 the vocal reaction-time task was also performed concurrent with the primary tasks.

The signals in the vocal reaction-time task were auditory tones presented at random intervals 1–10 sec apart, and the response was the word "pip" said as quickly as possible. Sixty tones constituted a trial block. One trial block was administered before and after the primary tasks, and six trial blocks were administered in the concurrent condition. The concurrent vocal reaction-time task started 2 min after the beginning of the primary tasks, and ended several minutes before the completion of the primary tasks. This procedure, and the instructions to the subjects to concentrate most on the primary task, were designed to encourage treatment of the vocal reaction-time task as the secondary, rather than primary, task in the dual-task situation.

The long-term subjects participated for 1 hr. per session, with most subjects performing one session on each of 5 days during the week. Four weeks after the completion of Session 50 the subjects participated in a final follow-up session to determine the amount of forgetting during a 1-mo. period without intervening practice.

As a check of motivational effects on performance, on Session 48 the long-term subjects were offered a monetary bonus of $.10 for every millisecond they were faster than their previous fastest time in the memory-scanning task, provided that they committed fewer than 10% errors.

Results

The principal measures of performance for the four tasks were the area under the receiver operating characteristic (ROC) curve, a measure closely related to percentage correct derived from signal-detection theory (Green & Swets, 1964) for the signal-detection task, the reaction time in milliseconds and the percentage of incorrect responses in the memory-scanning task, the percentage of correct decisions in the successive and simultaneous conditions in the visual-discrimination task, and the percentage of "hits" (intersections of the vertical and horizontal trajectories) in the temporal-prediction task.

Because there were so few trials per block in the temporal-prediction task (an average of 12.5), and so many variations in target speed (horizontal trajectory) and launch position (vertical trajectory), performance on this task was analyzed by collapsing data across Sessions 2 through 16 and across Sessions 36 through 50. This precluded detailed examination of specific practice or transfer effects and therefore is not discussed except to mention that young adults were more successful in all conditions than older adults.

Session 1 Analyses

The initial analyses focused on examining age differences in the Session 1 data for the short-term and long-term subjects and determining the representativeness of the long-term subjects with respect to the larger samples of short-term subjects. Data relevant to these issues are presented in Table 1.

Table 1 indicates that the two age groups in both the short-term and long-term samples differed significantly on all performance measures except the percentage of errors in the memory-scanning task. In all cases the older subjects performed at a lower level (either slower or with less accuracy), than the younger subjects. In contrast to the age differences, the sample differences were slight to nonexistent. The long-term young subjects had significantly higher vocabulary scores and error percentages in the memory-scanning task than did the short-term young subjects, but no other differences in either young or old samples were significant.

Because many of the analyses of the memory-scanning data involve comparisons as a function of the number of items in the memory set, Figure 3 was prepared to illustrate the relationship between memory-scanning performance and set size. Analyses of variance revealed that the effects of age $F(1, 86) = 80.98$, $MS_e = 320{,}995.7$, $p < .001$, and set size, $F(3, 258) = 44.66$, $MS_e = 13{,}071.3$, $p < .001$, but not sample ($F < 1$), were significant in the reaction-time data. The set size, $F(3, 258) = 55.29$, $MS_e = 41.5$, $p < .001$, Age × Set Size, $F(3, 258) = 4.79$, $MS_e = 41.5$, $p < .01$, and Sample × Set Size, $F(3, 258) = 8.18$, $MS_e = 41.5$, $p < .001$, effects were significant with the error percentage data. (Although the qualitative trends are unequivocal, one should not place much confidence in the quantitative relationships between age and set size because of the small number of trials per subject and the extremely high error rates.)

Taken together, the results of Table 1 and Figure 3 indicate that the long-term subjects are generally similar in initial performance to larger samples from their respective age groups, and that substantial age differences are evident in each of the experimental measures examined.

Long-Term Analyses

Signal detection. The mean areas under the ROC curve for young and old subjects across the 51 sessions are displayed in Figure 4. It is clear that signal-detection performance increased dramatically for both young and old subjects. An analysis of variance conducted on the data at three levels of practice (Sessions 2–5, 22–25, and 42–45), revealed significant age, $F(1, 14) = 20.83$, $MS_e = 95.5$, $p < .001$, practice, $F(2, 28) = 81.45$, $MS_e = 25.0$, $p < .001$, and Age × Practice, $F(2, 28) = 12.66$, $MS_e = 25.0$, $p < .001$, effects. The interaction appears to be at least partially attributable to a ceiling effect limiting performance improvement in the young subjects, as they reached a performance plateau much earlier than the older subjects. Sex differences were minimal, as on Sessions 42–45 the three males in each group ranked (from best to worst) Positions 2, 3, and 6 in the young subjects, and Positions 3, 5, and 7 in the old subjects.

An analysis of variance conducted on the nonparametric response criterion measure of percentage bias (Hodos, 1970) revealed no significant age, practice, or Age × Practice effects. The grand mean was 51.04%, indicating a tendency to make more no than yes responses.

The effects of reducing the display duration from 250 msec to 125 msec on Sessions 8 and 34 were analyzed by averaging the performances on Sessions 6, 7, 9, and 10 and on Sessions 32, 33, 35, and 36 to serve as control measures and then comparing transfer versus control performance in an analysis of variance. Performance in the transfer sessions was slightly worse than in the control sessions (.858 vs. .835), $F(1, 14) = 8.36$, $MS_e = 6.7$, $p < .05$, but this effect did not interact significantly with age or practice. Halving the display duration thus seems to produce roughly equivalent effects early (Session 8) and late (Session 34) in practice, and with young and old adults. The practice effect was also significant in this analysis (.785 vs. .905), $F(1, 14) = 23.47$, $MS_e = 100.2$, $p < .001$, indicating an improvement between Sessions 6–10 and 32–36.

The effects of changing the target configuration on Sessions 11 and 37 were analyzed by averaging performances on Sessions 9, 10, 12, and 13 and on Sessions 35, 36, 38, and 39 to serve as control measures, and then comparing transfer versus control performance in an analysis of variance. Neither

Table 1
Subject Characteristics and Session 1 Performance

Sample	Age	% females	Digit symbol	Vocabulary	Signal detection area	Memory scanning, reaction time	Memory scanning, % error	Visual discrimination, successive	Visual discrimination, simultaneous
Short-term									
Young (*n* = 50)									
M	19.5	44	67.5	60.7	.69	687	18.2	79.7	68.6
SD	1.9		8.5	9.2	.12	156	7.8	11.6	13.2
Old (*n* = 24)									
M	70.0	50	44.0	73.6	.55	1446	22.0	56.5	51.3
SD	4.8		8.6	6.7	.12	475	10.2	14.3	10.3
Long-term									
Young (*n* = 8)									
M	22.9	63	69.4	67.9	.66	658	25.0	78.3	65.8
SD	3.0		6.9	7.8	.12	211	8.1	11.4	8.5
Old (*n* = 8)									
M	68.8	63	51.0	75.5	.50	1367	22.0	53.0	51.5
SD	4.6		13.8	3.2	.12	215	16.0	14.8	11.1
t values									
Short-term, young vs. old	699.44*		11.04*	6.83*	4.70*	7.63*	0.17	6.93*	6.15*
Long-term, young vs. old	23.6*		3.37*	2.55*	2.67*	6.66*	0.47	3.83*	3.89*
Young, short-term vs. long-term	3.11*		.70	2.36*	.66	.37	2.22*	.32	.79
Old, short-term vs. long-term	.63		1.35	1.07	1.02	.64	0.00	.58	.05

* $p < .05$.

the transfer effect nor any of its interactions with age or practice were significant. Apparently, young and old subjects, both early and late in practice, can transfer their detection abilities equally well to a novel target in the same display context. Performance improved with practice (.825 vs. .910), $F(1, 14) = 26.02$, $MS_e = 44.4$, $p < .001$, between Sessions 9–13 and 35–39.

The effects of introducing a concurrent vocal reaction-time task on Sessions 5, 25, and 45 were analyzed by averaging performances on Sessions 3, 4, 6, and 7, on Sessions 23, 24, 26, and 27, and on Sessions 43, 44, 46, and 47 to serve as control measures and then comparing concurrent versus control performance in an analysis of variance. Signal-detection performance was slightly impaired with a concurrent task (.862 vs. .845), $F(1, 14) = 11.37$, $MS_e = 6.5$, $p < .01$, but the interactions with practice and age were not significant. Performing a simultaneous vocal reaction-time task therefore hinders performance, but the magnitude of impairment is about the same at three levels of practice for both young and old adults.

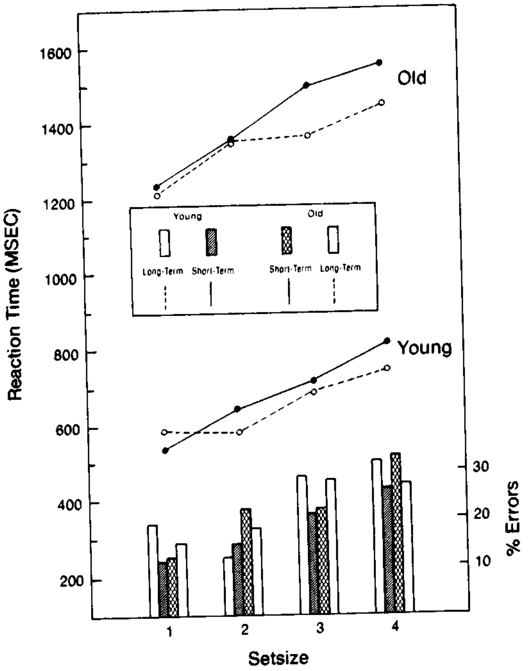

Figure 3. Reaction times and error rates as a function of memory-scanning set sizes for young and old short-term and long-term subjects, Session 1.

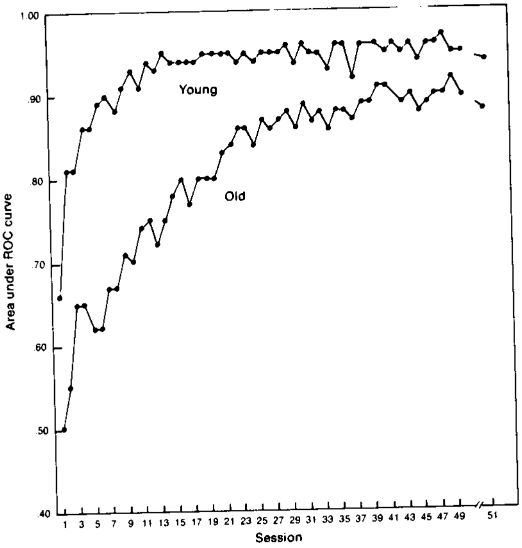

Figure 4. Mean signal-detection performance for young and old subjects as a function of practice. (ROC = receiver operating characteristic.)

The final manipulation examined with the signal-detection data was the effect of a 1-mo. delay between the 50th and 51st sessions. Control performance was determined by the average performance on Sessions 49 and 50 and this was contrasted with the delayed performance (Session 51) in an analysis of variance. The delay effect was significant (.931 vs. .913), $F(1, 14) = 6.43$, $MS_e = 4.1$, $p < .05$, but the interaction with age was not. Imposing a 4-wk. interval between successive sessions of the signal-detection task thus seems to have approximately the same slight impairment effect on both young and old adults.

Memory scanning. All data subjected to analysis in the memory-scanning task were first edited to remove trials with abnormally short (less than 100 msec) or long (greater than 1,500 msec) reaction times. The mean reaction times and percentages of correct responses for the young and old subjects across the 51 sessions are displayed in Figure 5. On Sessions 42–45 the three males in each group ranked, from fastest to slowest, Positions 1, 4, and 7 for the young subjects, and Positions 3, 5, and 8 for the old subjects.

In an attempt to examine the type of search process used in memory scanning, reaction times were computed separately for

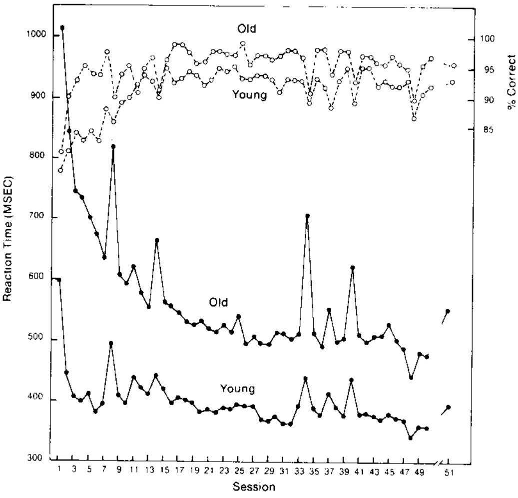

Figure 5. Mean reaction times and accuracy in the memory-scanning task for young and old subjects as a function of practice.

positive and negative trials for each set size. Figure 6 illustrates these data at three levels of practice. An analysis of variance revealed a significant interaction of Set Size × Trial Type, $F(3, 42) = 43.21$, $MS_e = 453.3$, $p < .001$, indicating a shallower slope for negative than for positive trials (31 vs. 49 msec/item). Figure 6 suggests that the slope differences are primarily due to the fast responses for positive one-item trials, however, and when the one-item trials were eliminated the Set Size × Trial Type interaction based on the remaining data from set sizes of two through four was not significant, $F(2, 28) = 1.34$, $MS_e = 511.8$, $p > .10$ (slopes = 22 and 24 msec/item). This pattern of results suggests that the search process was a serial, exhaustive search conducted after an extremely rapid comparison of the previous one-item positive set. (See Clifton, 1973, for additional discussion of the fast one-item set size phenomenon.) It is important to note, however, that in neither of these analyses were the triple interactions involving age or practice significant. Whatever the nature of the search process, therefore, it apparently did not differ as a function of practice or subject age.

Figure 7 portrays reaction time and error rate as a function of set size and practice for young and old subjects. Separate analyses were conducted on the reaction-time and error-rate variables. All main effects and interactions were significant with the reaction-time variable: age, $F(1, 14) = 46.92$, $MS_e = 41{,}894.3$, $p < .001$; set size, $F(3, 42) = 15.21$, $MS_e = 997.4$, $p < .001$; practice, $F(2, 28) = 37.62$, $MS_e = 10{,}009.0$, $p < .001$; Age × Set Size, $F(3, 42) = 11.64$, $MS_e = 997.4$ $p < .001$; Age × Practice, $F(2, 28) = 22.35$, $MSe = 10{,}009.0$, $p < .001$; Set Size × Practice, $F(6, 84) = 12.19$, $MS_e = 511.2$, $p < .001$; and Age × Set Size × Practice, $F(6, 84) = 8.24$, $MS_e = 511.2$, $p = .001$. The effects can be seen in Figure 7. Older subjects and larger set sizes produced the longest reaction times, but these effects became smaller with practice. Separate analyses at each stage of practice revealed that age, $F(1, 14) > 19.7$, and set size, $F(3, 42) > 58.7$, effects were highly significant throughout practice, but that their interaction became weaker: $F(3, 42) = 11.10$, 5.20, and 3.01 at Sessions 2–5, 22–25, and 42–45, respectively. Slopes of the set-size – reaction-time functions on Sessions 42–45 were 27 and 33 msec/item for young and old subjects, respectively, with all set sizes, and 14 and 15 msec/item, respectively, for only set sizes of 2, 3, and 4. With the error variable, significant effects were obtained for age, $F(1, 14) = 7.26$, $MS_e = 215.6$, $p < .05$; set size, $F(3, 42) = 21.95$, $MS_e = 15.1$, $p < .001$; practice, $F(2, 28) = 14.55$, $MS_e = 74.9$, $p < .001$; Age × Set Size, $F(3, 42) = 4.70$, $MS_e =$

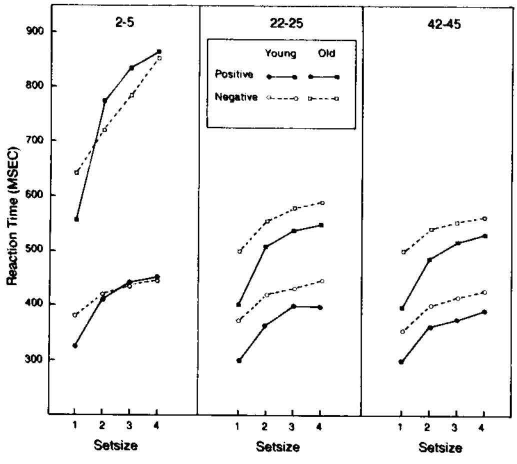

Figure 6. Mean memory-scanning reaction times for positive and negative trials as a function of set size, age, and practice.

15.1, $p < .01$; and Set Size × Practice, $F(6, 84) = 4.95$, $MS_e = 10.4$, $p < .001$. Reaction time was faster but error rate was higher for young subjects relative to older subjects, thus suggesting that a speed–accuracy trade-off was partially responsible for the age differences in reaction time. With the other effects, however, both reaction time and error rate increased, and thus a speed–accuracy trade-off contamination is unlikely.

The effects of reducing the size of the probe stimulus by one half on Sessions 8 and 34 were analyzed by using the average performances on each set of four adjacent sessions (6, 7, 9, and 10 and 32, 33, 35, and 36) as control measures, and then comparing transfer versus control performance in an analysis of variance. These data are illustrated in Figure 8. The size reduction had a significant main effect, $F(1, 14) = 50.96$, $MS_e = 24{,}796.9$, $p < .001$, and an interaction with age, $F(1, 14) = 9.17$, $MS_e = 24{,}796.9$, $p < .01$ on the reaction-time variable. Size reduction, $F(1, 14) = 18.65$, $MS_e = 64.5$, $p < .001$, and the interaction of Age × Set Size × Size Reduction, $F(3, 42) = 4.41$, $MS_e = 21.9$, $p < .01$, were significant with the error variable. The practice main effect was significant on the reaction-time variable, $F(1, 14) = 20.72$, $MS_e = 16{,}508.7$, $p < .001$, as reaction time changed from 580 to 508 msec from Sessions 6–10 to Sessions 32–36.

The main effect of size reduction indicates that the smaller probe stimulus leads to greater overall reaction time (612 vs. 475 msec), but the absence of an interaction with set size suggests that the slopes of the function relating set size to reaction time were not affected. The Age × Size Reduction interaction indicates that the older subjects had a greater increase in reaction time with the reduced stimuli than the young subjects (196 vs. 79 msec).

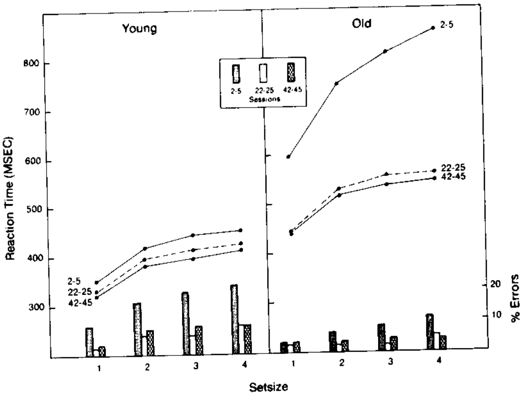

Figure 7. Mean memory-scanning reaction times and error rates as a function of set size for young and old subjects at three levels of practice.

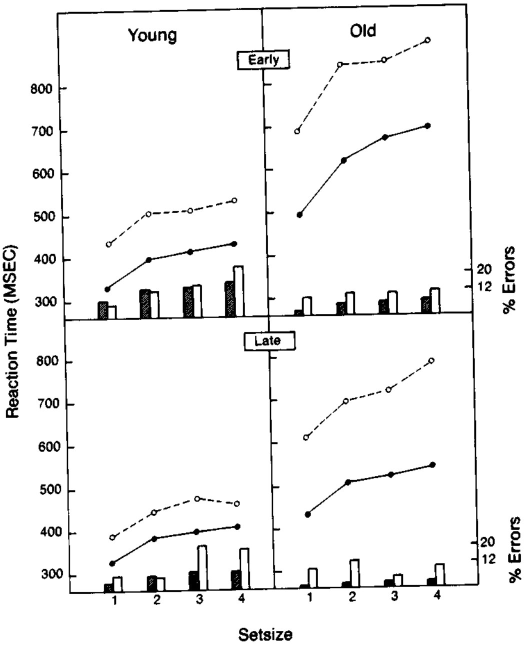

Figure 8. Mean memory-scanning reaction times and error rates in control and reduced stimulus conditions. (Solid lines and bars indicate performance in the control condition. *Early* refers to Sessions 6–10 and *late* refers to Sessions 32–36.)

The effects of changing to new stimulus items on Sessions 11 and 37 were analyzed by using the average performances on sessions 9, 10, 12, and 13 and 35, 36, 38, and 39 as control measures and then comparing transfer versus control performance in an analysis of variance. These data are illustrated in Figure 9. The stimulus-change manipulation was significant with both the reaction-time, $F(1, 14) = 13.88$, $MS_e = 6244.5$, $p < .01$, and error-rate, $F(1, 14) = 13.61$, $MS_e = 47.3$, $p < .01$, variables, as was the Stimulus Change × Set Size interaction: reaction time, $F(3, 42) = 6.38$, $MS_e = 649.6$, $p < .01$; error rate, $F(3, 42) = 12.89$, $MS_e = 11.2$, $p < .001$. The Stimulus Change ×

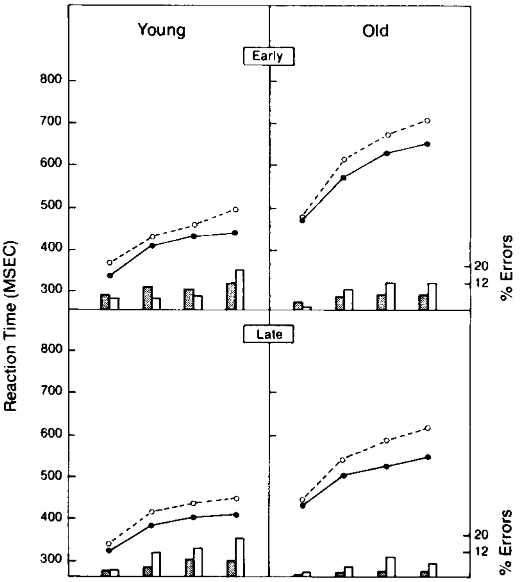

Figure 9. Mean memory-scanning reaction times and error rates in control and new stimulus conditions. (Solid lines and bars indicate performance in the control condition. *Early* refers to Sessions 9–13 and *late* refers to Sessions 35–39.)

Practice interaction was significant with the error-rate variable, $F(1, 14) = 5.39$, $MS_e = 31.4$, $p < .05$, indicating that new stimuli, relative to old stimuli, had more errors late in practice than early. All remaining significant effects involving the stimulus-change factor were evident only with the error-rate variable: Stimulus Change × Set Size × Age, $F(3, 42) = 4.58$, $MS_e = 11.2$, $p < .01$, and Stimulus Change × Practice × Age, $F(1, 14) = 5.28$, $MS_e = 31.4$, $p < .05$. Although rather complex, neither of these interactions is consistent with an interpretation that a speed-accuracy trade-off is responsible for the reaction-time pattern of results. Reaction-time performance improved between Sessions 9–14 and 35–39 (511 vs. 463 msec), $F(1, 14) = 16.69$, $MS_e = 9376.4$, $p < .01$.

The existence of an interaction with set size suggests that shifting to a new set of stimulus items affects the slope of the function relating reaction time to set size. Indeed, the slopes were 39 and 52 msec/item, respectively, for normal and new stimulus items. An analysis conducted on only the one-item set-size data also revealed a significant effect of stimulus change (390 vs. 407 msec), $F(1, 14) = 5.83$, $MS_e = 732.9$, $p < .05$. Neither the interaction with age nor with practice was significant in this analysis.

The effects of reversing the sets of positive and negative items on Sessions 14 and 40 were analyzed by averaging performance on Sessions 12, 13, 15, and 16, and on Sessions 38, 39, 41, and 42 to serve as control measures, and then comparing transfer versus control performance in an analysis of variance. These data are illustrated in Figure 10. The reversal manipulation was significant with both the reaction-time, $F(1, 14) = 23.37$, $MS_e = 20{,}826.2$, $p < .001$, and error-rate, $F(1, 14) = 55.62$, $MS_e = 28.5$, $p < .001$, variables, as was the Reversal × Set Size interaction: reaction time, $F(3, 42) = 14.88$, $MS_e = 801.5$, $p < .001$; error rate, $F(3, 42) = 4.41$, $MS_e = 30.8$, $p < .01$. Other significant effects involving the reversal manipulation on the reaction-time variable were Reversal × Age, $F(1, 14) = 6.43$, $MS_e = 20{,}826.2$, $p < .05$, and Reversal × Practice, $F(1, 14) = 5.13$, $MS_e = 4{,}942.3$, $p < .05$. No other reversal interactions were significant with the error-rate variable. In all cases the direction of the error-rate differences was the same as that for the reaction-time differences. The main effect of practice was not significant in the contrast between Sessions 12–16 and Sessions 38–42, although a reaction-time trend was apparent (519 msec on Sessions 12–16, 498 msec on Sessions 38–42).

As can be seen in Figure 10, the interactions with age and practice were due to greater reversal effects in old compared to young subjects and late compared to early practice. The set size interaction indicates that the slope of the reaction-time–set-size function was greater in reversed than in normal conditions (59 vs. 40 msec/item). The reversal manipulation was also significant in an analysis conducted only on the one-item set sizes (389 vs. 436 msec), $F(1, 14) = 10.39$, $MS_e = 3{,}528.9$, $p < .01$, however none of the interactions was significant.

The effects of introducing a concurrent vocal reaction-time task on Sessions 5, 25, and 45 were analyzed by averaging performances on Sessions 3, 4, 6, and 7, on Sessions 23, 24, 26, and 27, and on Sessions 43, 44, 46, and 47 to serve as control measures and then comparing concurrent versus control performance in an analysis of variance. The concurrent–control manipulation was significant with the reaction-time variable (491 vs. 476 msec), $F(1, 14) = 9.05$, $MS_e = 2{,}297.3$, $p < .01$, but no interactions with age, practice, or set size were significant. No concurrent-condition effects or interactions were significant with the error-rate variable.

On Session 48 a monetary incentive was offered to determine whether reaction-time performance could be improved without sacrificing accuracy. The average performance on Sessions 46 and 47 served as the control measure, and the incentive effect was analyzed in an analysis of variance. Data from Sessions 49 and 50 were not included because of the possibility that the incentive manipulation would result in a change in subsequent performance. This procedure seemed justified in light of the very small practice effects observed during this part of the experiment (cf. Figure 5). Figure 11 illustrates that reaction time improved (decreased), but error rate worsened (increased), under the incentive conditions. The incentive factor was significant with both variables: reaction time, $F(1, 14) = 60.53$, $MS_e = 1{,}020.6$, $p < .001$; error rate, $F(1, 14) = 27.27$, $MS_e = 40.3$, $p < .001$. The interactions with age, $F(1, 14) = 4.61$, $MS_e = 1020.6$, $p < .05$, and set size, $F(3, 42) = 5.38$, $MS_e = 266.6$, $p < .01$, were also significant with the reaction-time variable.

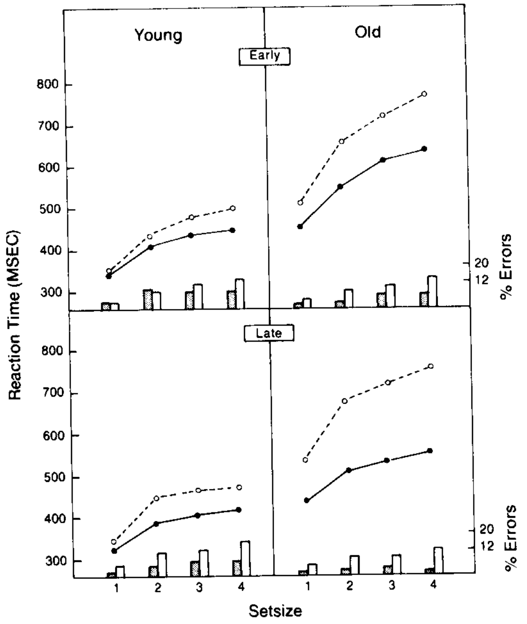

Figure 10. Mean memory-scanning reaction times and error rates in control and reversed assignment conditions. (Solid lines and bars indicate performance in the control condition. *Early* refers to Sessions 12–16 and *late* refers to Sessions 38–42.)

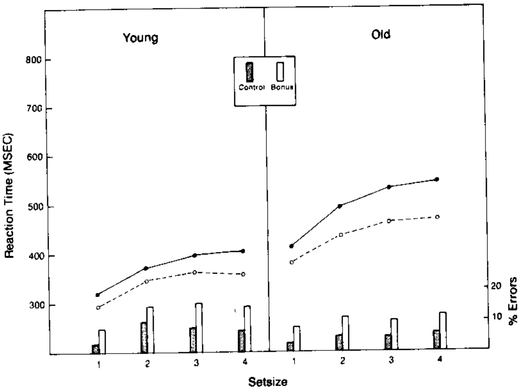

Figure 11. Mean memory-scanning reaction times and error rates in control and speed incentive conditions. (Solid lines and bars indicate performance in the control condition.)

Because of the opposite trend with the reaction-time and error-rate variables, the precise effect of providing a monetary incentive for improved performance is difficult to evaluate. Reaction time decreased (435 vs. 392 msec), but error rate increased (6% vs. 12%), and without knowing the exact form of the time–accuracy exchange function it is impossible to determine if the two trends were completely compensatory. The remaining effects suggest that older subjects were able to reduce their reaction times more than young subjects (55 vs. 31 msec), and that the set-size–reaction-time slope was shallower in the incentive condition (25 vs. 35 msec/item).

The effect of a 1-mo. delay between the 50th and 51st sessions was analyzed by contrasting average performance on Sessions 49 and 50 with the delayed performance (Session 51) in an analysis of variance. Neither the delay effect nor any interactions with the delay factor were significant with either the reaction-time or error-rate variable. In this

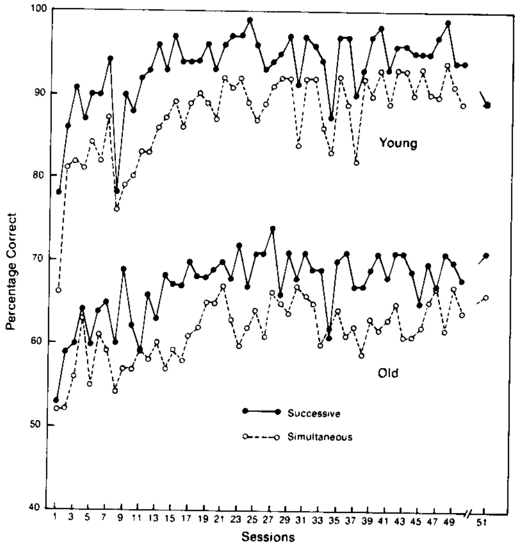

Figure 12. Mean visual-discrimination accuracy in successive and simultaneous conditions for young and old subjects as a function of practice.

particular analysis, however, the statistical outcome may be somewhat misleading because of grossly unequal variances. Seven of the young subjects and six of the old subjects increased their reaction times over the 1-mo. delay, but one older subject increased his reaction time by over 400 msec, thus contributing to extreme variance in the Session 51 data. In view of the consistency of the trend (13 of 16 subjects), and the pattern indicated in Figure 5, it is perhaps best to defer a conclusion on whether reaction time increases over a 1-mo. delay.

Visual discrimination. The percentages of correct stimulus discriminations in the successive and simultaneous conditions for the young and old subjects across the 51 sessions are displayed in Figure 12. Male subjects on Sessions 42–45 ranked, from best to worst, Positions 1, 2.5, and 7 for the young subjects, and Positions 3, 4, and 8 for the old subjects.

An analysis of variance was conducted on the data at three levels of practice (Sessions 2–5, 22–25, and 42–45) with age, practice, and attention (successive–focused vs. simultaneous–divided) as factors. All three main effects were significant—age, $F(1, 14) = 66.06$, $MS_e = 274.3$, $p < .001$; practice, $F(2, 28) = 11.60$, $MS_e = 55.2$, $p < .001$; and attention, $F(1, 14) = 135.19$, $MS_e = 6.8$, $p < .001$—but none of the interactions was significant. This pattern of results, in conjunction with the trends illustrated in Figure 12, suggests that the divided-attention deficit was approximately the same for young and old subjects, and did not change as a function of experience with the task.

A more detailed analysis examined performance in the simultaneous condition as a function of the presence or absence of a signal in each array. The four trial types differed significantly: signal, Array 1–signal, Array 2 = 66.8%; signal, Array 1–no signal, Array 2 = 74.1%; no signal, Array 1–signal, Array 2 = 70.0%; no signal, Array 1–no signal, Array 2 = 83.4%; $F(3, 42) = 9.74$, $MS_e = 25{,}466.0$, $p < .001$. However, this effect did not interact with either age or practice.

The effects of reducing the duration of the stimulus arrays from 400 to 200 msec on Sessions 8 and 34 were analyzed by averaging performances on Sessions 6, 7, 9, and 10, and on 32, 33, 35, and 36 to serve as control measures and then comparing transfer versus control performance in an analysis of variance. The duration reduction led to a decrease in discrimination accuracy (76.8% vs. 70.0%), $F(1, 14) = 30.79$, $MS_e = 49.4$, $p < .001$, but no interactions with the duration factor were significant. Performance was better on Sessions 32–36 than on Sessions 6–10 (76.5% vs. 70.3%), $F(1, 14) = 14.09$, $MS_e = 83.9$, $p < .01$. The absence of interactions with age and practice suggests that variations of subject age or amount of experience do not affect the susceptibility to performance impairments with shortened stimulus displays. The lack of an interaction with the attention (successive–simultaneous) factor indicates that the magnitude of the divided-attention effect was essentially unchanged when the display duration was reduced by 50%.

The effects of changing the type of stimulus arrays on Sessions 11 and 37 were analyzed by averaging performances on Sessions 9, 10, 12, and 13 and on 35, 36, 38, and 39 to serve as control measures and then comparing transfer versus control performance in an analysis of variance. The stimulus-change factor was not significant, but

Table 2
Effects of Changing Stimulus Arrays on Visual-Discrimination Accuracy (Percentages Correct)

	Early (Session 11)			Late (Session 37)		
Group	Normal	New	Difference	Normal	New	Difference
Young	86.8	87.2	−.4	93.5	85.1	8.4
Old	61.7	59.1	2.6	65.0	64.3	.7
M	74.2	73.1	1.1	79.3	74.7	4.6

the interactions with practice, $F(1, 14) = 6.22$, $MS_e = 16.0$, $p < .05$, and Age × Practice, $F(1, 14) = 14.25$, $MS_e = 16.0$, $p < .01$, were significant. These effects can be seen in Table 2. Note that the detrimental effect of changing the stimulus display is more pronounced late in practice, and that young subjects exhibit this trend to a greater extent than older subjects. The practice main effect was significant (73.9% vs. 76.9%), $F(1, 14) = 6.67$, $MS_e = 51.1$, $p < .05$, indicating improvement between Sessions 9–13 and Sessions 35–39.

The effects of introducing a concurrent vocal reaction-time task on Sessions 5, 25, and 45 were analyzed by averaging performances on Sessions 3, 4, 6, and 7, on Sessions 23, 24, 26, and 27, and on Sessions 43, 44, 46, and 47 to serve as control measures and then comparing concurrent versus control performance in an analysis of variance. Neither the main effect of the concurrent task nor any interactions with age, practice, or attention (successive–simultaneous) were significant.

No significant delay effect was evident in the contrast of Session 51 performance with the average performance on Sessions 49 and 50, nor were any interactions involving the delay factor significant.

Concurrent task. Performance on the concurrent task was represented as the vocal reaction time, in msec, to the auditory stimulus. Trials with latencies less than 100 msec or greater than 1,000 msec were edited from the analysis. The remaining trials were analyzed in an analysis of variance at three levels of practice with control measures consisting of the average of two blocks of trials each on Sessions 4, 5, and 6, Sessions 24, 25, and 26, and Sessions 44, 45, and 46. The concurrent measures consisted of the averages of six trial blocks each on Sessions 5, 25, and 45. The means of these data are illustrated in Figure 13. The age effect was not significant ($F < 1.0$) in the analysis, but the concurrent factor, $F(1, 14) = 676.04$, $MS_e = 568.1$, $p < .001$, and its interactions with age $F(1, 14) = 58.23$, $MS_e = 568.1$, $p < .001$, practice $F(2, 28) = 24.34$, $MS_e = 292.8$, $p < .001$, and Age × Practice, $F(2, 28) = 5.00$, $MS_e = 292.8$, $p < .05$ were significant. Reaction time was slower (483 vs. 356 msec) when the primary task was performed concurrently. This difference was greater for older subjects than young subjects (164 vs. 89 msec), increased practice tended to reduce the difference (160 to 117 to 102 msec for Sessions 5, 25, and 45, respectively), and the magnitude of the reduction was greater for older subjects than for young subjects (from 212 to 152 to 128 msec for older subjects, from 108 to 84 to 77 msec for young subjects).

The absence of a significant main effect of age in a reaction-time task is quite unexpected, particularly in light of the substantial differences observed in other mea-

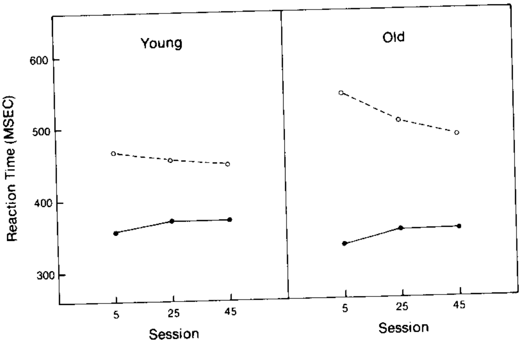

Figure 13. Mean vocal reaction times in control (solid lines) and concurrent (dotted lines) conditions for young and old subjects at three levels of practice.

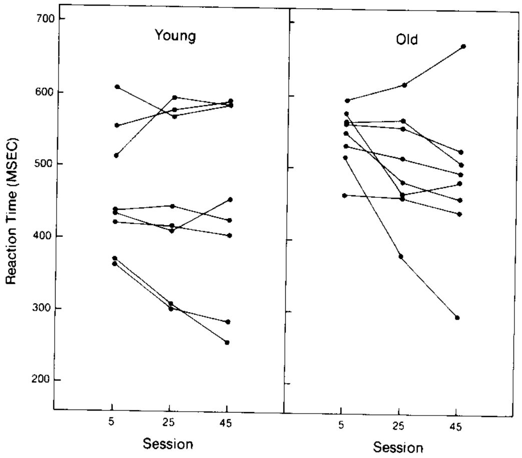

Figure 14. Concurrent vocal reaction times for individual subjects at three levels of practice.

sures with these same subjects. Inspection of the data from individual subjects revealed sizable individual differences among the young subjects. Figure 14 illustrates these differences with the mean reaction times in the concurrent condition for individual subjects at three levels of practice. Notice that two young subjects were quite fast and tended to reduce their reaction times with increased practice, that three subjects were quite slow and exhibited at least one slower reaction time with additional practice, and that three subjects were intermediate in speed and direction of change with practice. The concurrent – control measures were also quite different, as the fastest two young subjects had average values of 133, 87, and 69 msec on Sessions 5, 25, and 45, respectively, whereas the slowest three subjects averaged 95, 87, and 85 msec, respectively.

Discussion

For clarity of presentation the Results section was organized in terms of the specific tasks. In the present section, the organization is in terms of the three major issues of concern in the project.

Improvement in Simple Tasks

A strong conclusion from the present results is that performance does improve with moderate experience on simple tasks such as signal detection, reaction time, and visual discrimination. The range of performance improvement was artificially limited by the measurement scale in the signal-detection and visual-discrimination tasks, but the changes with practice are indisputable in all three tasks. It is also noteworthy that the performance improvement was relatively stable over a 1-mo. retention interval.

The conclusion that performance improves on simple tasks is really not very surprising in light of the literature reviewed earlier, but it has not yet been widely accepted by researchers. For example, according to Ream's (1922) criterion of capacity, none of these tasks would be appropriate to serve as a measure of an individual's fundamental ability, because each has been demonstrated to exhibit sizable practice-related improvements. Nevertheless, tasks similar to these, either in laboratory or paper-and-pencil forms, are frequently used to assess an individual's ability or capacity. Such assessments may still be useful for relative judgments, but they do not appear to be meaningful in any absolute sense, and should no longer be interpreted as reflections of the fundamental limits of human performance.

From the skill perspective, the demonstration that improvement occurs in elementary tasks is important, because it indicates that the development of skill does not merely involve the integration or coordination of fixed and static perceptual or motor abilities. The discovery that even such very simple activities as detecting the presence or absence of a signal or making a rapid binary classification decision improve with increased experience suggests that skill acquisition cannot be considered solely in terms of the timing or coordination of the components. The relative contributions of improvements in the components versus improvement in the integration or coordination of the components cannot be assessed at this time, but the importance of changes in the elementary processes involved in the acquisition of a complex skill should no longer be in doubt.

Nature of Improvement

In the introduction, three broad classes of explanation for practice-related improvement in simple tasks were outlined. Here we consider the relevance of the present results to each class of explanation, and also summarize some of the other evidence for each position.

The first category of possible mechanisms attributed improvement to a change in the type of information being processed. Introspective analysis suggests that something like this occurs in the signal-detection task because subjects report that they had to learn what to look for in the display. If these reports are to be believed, one could infer that improvement occurs in part because of a more precise figure–ground distinction. Early in practice the subjects apparently had difficulty distinguishing signal elements from background noise elements, and only after they were able to perceive the figure in the form of a consistently moving group of dots were they able to improve their performance.

The principal manipulation designed to investigate a possible shift in the type of information being processed was the qualitative transfer condition in which unfamiliar stimuli were presented at two points in practice. The reasoning was that if performance improvement was due to stimulus-specific mechanisms, then the introduction of new stimuli should lead to a decrement in performance. For example, if subjects developed a specialized system for coding the stimuli, one would not expect this system to be beneficial if new, unfamiliar stimuli were employed.

The amount of transfer to qualitatively different stimuli varied across tasks. Transfer was near perfect in the signal-detection task, it resulted in slight progressive impairment in the memory-scanning task, and it led to a small impairment early but a larger impairment late in the visual-discrimination task.

The absence of a performance change in the signal-detection task may be due to the peculiar nature of the stimulus change in this task. The spatial configuration of the five dots comprising the signal was altered, but the target was still defined in terms of a consistently moving group of dots against a randomly varying background. If specialized target detectors were developed for this task, the relevant dimension was probably motion rather than the static spatial configuration, and thus perfect transfer might have been expected. Indeed, the subjective experience of a target in the signal-detection task is of something moving, but the pattern of the moving object is never clearly defined. In retrospect, therefore, it might have been better to have varied the rate of motion rather than the spatial arrangement of dots during the qualitative transfer sessions.

The significant Stimulus Change × Set Size interaction with reaction time in the memory-scanning task indicates that the new stimuli in memory scanning had a greater effect with larger set sizes than with small set sizes. Since a shift in the type of information processed would be expected to produce the same result for stimuli preceded by one memory-set item as for those preceded by two, three, or four memory-set items, this finding suggests that some noncoding mechanism was probably involved when new stimuli were presented in the memory-scanning task. (But see the following for an alternative interpretation). A slight stimulus-change effect was also evident with one-item set sizes, however, and coding systems developed for the normal stimuli might be responsible. The interaction with practice was evident only with the error-rate variable, but the direction was as predicted, with a greater effect late in practice than early.

Introducing new stimuli in the visual-discrimination task produced a larger reduction in accuracy on Session 37 than on Session 11. This finding is qualified somewhat, however, because only the young subjects exhibited such a trend (see Table 2). The greater impairment later in practice is nevertheless important in that it suggests, contrary to intuition, that more experience with a task leads to reduced flexibility and generalizability. Moreover, since the formal structure of the task remained the same, and only the nature of the stimulus arrays was changed (i.e., from Figure 2a to Figure 2b, or vice versa), it can be inferred that a stimulus-specific process developed through experience was disrupted by the stimulus change. The nature of that process cannot be definitely specified at this time, but it may be hypothesized that a figure–ground discrimination is involved. The targets could be conceived as figures embedded in a complex background, and learning to extract figures from ground could play a major role in the improvement achieved with experience on this task.

A number of other researchers have used transfer procedures in visual-search or memory-scanning tasks similar to the present ones, although in no case was the transfer manipulation examined at more than one level of practice. Ross (1970) and Graboi (1971) shifted the case (from uppercase to lowercase) of the characters in the search set after a period of practice, and both reported some impairment relative to the trained items. Neither study included a control condition in which completely new items served as set members, and thus the magnitude of the transfer cannot be evaluated. The apparent implication, however, is that the practice-related improvement is at least partially attributable to mechanisms sensitive to the physical form of the stimulus.

In striking contrast to the Ross and Graboi studies, Kristofferson (1977) and Prinz (1979) reported that transfer was nearly perfect to new sets of target items when those items had not previously served as negative or distractor items, and Rabbitt, Cumming, and Vyas (1979) found perfect transfer when only the negative set was changed. One characteristic that may be responsible for this discrepancy is the use of the same negative or distractor set in training and transfer in the Kristofferson and Prinz experiments and the same positive set in the Rabbitt et al. experiment. Because the sets were relatively small (i.e., either 4 or 8 items), it is possible that transfer was mediated on the basis of either positive- or negative-set membership. This interpretation is supported in the finding that when new items were simultaneously introduced in both positive and negative sets in the present experiment and in the Madden and Nebes (1980) experiment, a substantial decrement in performance occurred.

Another source of evidence for a change in the type of information being processed comes from an experiment reported by Shiffrin and Schneider (1977, Experiment 3). In this study, groups of items were consistently paired together, although sometimes as the positive set and sometimes as the negative set. Performance with two or four items within the same group eventually became indistinguishable, suggesting that a single categorical representation was being used late in practice. Salthouse (1977) reached a similar conclusion with different material (nonsense dot patterns), although much less practice was required to establish the generic or categorical representation in this case.

Under the interpretation that a single categorical representation may have been established after practice, the reduction in the *slope of the set-size–reaction-time function* might be attributed to a shift in the mixture of processing modes from examination of separate item representations to examination of a single categorical representation. Introducing new stimuli might eliminate the effectiveness of the categorical representation and cause processing to revert to specific examination of each item representation, thus accounting for the significant Stimulus Change × Set Size interaction.

The evidence in support of practice-related improvement arising from a change in the type of information being processed may be summarized as follows. First, it is consistent with introspective reports from the signal-detection and visual-discrimination tasks. Second, introducing new stimuli disrupted performance in the memory-scanning and visual-discrimination tasks, and the amount of disruption was greater late in practice than early. Third, the slope of the set-size–reaction-time function reduced with practice as would be expected if subjects were shifting to the use of a single categorical representation from multiple-item representations.

A second class of explanation for practice-related improvement maintains that a change in the identity or sequence of some processing operations may be contributing to increased performance. There is no suggestion of a fundamental change in the manner in which the task is performed at different levels of practice in the signal-detection task, as the only available index of such a shift, the response criterion used in making signal decisions, did not exhibit practice-related differences. The visual-discrimination task also provides no indication of a shift in the way the task is performed with different amounts of experience. At all stages of practice, accuracy is poorer when the two arrays are presented simultaneously rather than successively, and accuracy is poorer when both simultaneous arrays contain targets than when one or neither of the arrays contains a target.

The situation with the memory-scanning task is more complicated. The slope of the set-size–reaction-time function decreased with practice, but it was always greater than zero, and the relationship between fuctions for positive and negative trials remained constant across sessions. A serial, exhaustive search process therefore seems to have been employed at all stages of practice.

On the other hand, introducing new stimuli led to an increase in the slope of the set-size–reaction-time function, and this may be a reflection of a change in the processes involved in connecting stimuli to responses. Not only did new stimuli have to be encoded, but they also had to be connected to the appropriate responses. If practice leads to a change in the manner in which stimuli are associated with responses, then reversing the customary stimulus–response assignment should result in substantial performance impairment. However, since the same stimuli are involved, any performance change could not be attributed to disruption of stimulus encoding per se. The results of the stimulus-reversal manipulation revealed that changing the assignment of stimuli to responses impaired performance, and that the amount of impairment was greater late in practice than early in practice. Furthermore, reversal interacted with set size, causing greater effects with larger set sizes. A possible implication of these findings is that practice led to a short-circuiting of some of the processes involved in selecting the appropriate response for a given stimulus, and when the customary association of stimuli and responses was reversed the original complete sequence of processes had to be used. Some negative transfer is apparently also involved, since reversing familiar stimuli seems to have had a larger disrupting effect than introducing completely new stimuli (cf. Figures 9 and 10).

Results similar to these when the stimulus–response assignment is reversed have also been reported by Shiffrin and Schneider (1977, Experiments 1 and 2) and Logan (1979, Experiment 1). In each case, transfer to familiar stimuli resulted in a performance impairment when the new assignment of stimuli to responses was different from the old assignment. Moreover, the amount of disruption increased with set size, suggesting that the stimulus-response linkage process was modified with practice.

Some investigators (e.g., Neisser, 1967) have interpreted the practice-related reduction in the slope of the set-size–reaction-time function as a reflection of a shift from serial to parallel processing. This is only one interpretation of the slope change, however, and other interpretations might invoke a shift from multiple to unitary representations (explained previously) or an increase in the resources available for item comparison (see the following). For these reasons the slope reductions with practice cannot necessarily be considered definitive evidence for a shift in the mode of processing within the task, although they are certainly consistent with that interpretation.

If spatially parallel processing is developed with practice, one would expect the difference between the successive and simultaneous conditions in the visual-discrimination task to be reduced or eliminated. This did not occur; performance with successive arrays was consistently better than that with simultaneous arrays. Neisser's (1967) distinction between spatially parallel and operationally parallel processes may be important here, as he suggested that only the latter are developed with experience.

To summarize, the major positive evidence in support of practice-related improvement being attributable to a change in the identity or sequence of processing operations comes from the reversal manipulation in the memory-scanning task. Progressively greater disruption of performance later in practice caused by reassigning responses to stimuli signifies that the connection process was altered with practice. Shallower slopes of the set-size–reaction-time function are also consistent with a possible shift from serial to parallel processing.

The third major class of explanation for practice-related improvement postulated a reduction in the processing resources required for the task with greater amounts of experience. One means by which this interpretation was investigated in the current project involved the quantitative transfer conditions in which the duration or size of the stimulus was reduced by 50%. If available processing resources increase with practice, then the same activity should be performed in less time or with less effort later in practice than early in practice. In other words, one would expect a briefer target duration in the signal-detection and visual-discrimination tasks to cause more difficulty early in practice (Session 8) than later in practice (Session 34). A similar argument applies to the size reduction in the memory-scanning task. The extra resources required to compensate for the smaller size are presumably more available late in practice than early.

The results of the stimulus reduction manipulation were surprising in that although performance was impaired in each task, the amount of impairment did not vary with level of practice. The Reduction × Practice interaction was not significant in any task, thus suggesting that 26 sessions of practice did not change the subjects' ability to cope with the more demanding reduced stimulus.

A second manipulation used to examine the processing-resources interpretation involved the presentation of a concurrent vocal reaction-time task at three points in practice. The instructions and procedures encouraged subjects to treat the vocal reaction-time task as secondary, and to attempt to maintain their maximum level of performance on the primary (Space Trek) tasks. They were not completely successful; slight performance reductions were evident in the signal-detection and memory-scanning tasks. However, these effects were apparently the same at all levels of practice, as none of the interactions was significant.

The results of the concurrent vocal reaction-time task were consistent with the reduced processing requirements interpretation. Reaction time was greater when the primary task was performed concurrently, and the amount of increase became smaller with more experience. One interesting aspect of these results is that although the concurrent-task effect (i.e., concurrent reaction time minus control reaction time at a given level of practice) became smaller with practice (from 160 to 102 msec), it was still substantial after over 40 sessions of practice. Furthermore, every subject exhibited this phenomenon, as the concurrent-task effects on Session 45 ranged from 63 to 195 msec across subjects. In view of the negatively accelerating function relating practice to amount of reaction-time increase (between Sessions 5 and 25 the effect reduced 43 msec, but between Sessions 25 and 45 it only reduced 15 msec), one might speculate that many hundreds of sessions would be necessary to eliminate the effect completely.

Another source of data relevant to the resource change interpretation is available in the set-size comparisons in the memory-scanning task. If it is assumed that each additional item in the memory set requires attentional capacity or resources, and that the amount of these resources increases with practice, one would expect the slope of the set-size–reaction-time functions to become flatter with increased practice. In the limiting case of capacity equal to or greater than demands, the slope should equal zero. As indicated in Figures 6 and 7, the slopes of the set-size–reaction-time function do decrease with experience, but they are still about 30 msec/item (15 msec/item for set sizes of 2 to 4) on Sessions 42–45.

A final set of data relevant to the processing-resources interpretation of practice-related improvement is available in the successive–simultaneous comparisons from the visual-discrimination task. If there are truly more attentional resources available late in practice, one might expect performance accuracy in the stimultaneous-array condition to become more similar to that in the successive array conditions as more attentional capacity becomes available. This did not occur, as evidenced by the lack of an interaction between attention condition and practice.

Several other researchers have investigated changes in available resources with experience on a task, but with greatly varying methods. Shiffrin and Schneider (1977, Experiment 1) reduced stimulus durations from 200 to 120 msec after 1,500 trials of practice and reported sizable performance impairments, similar to those found here. The stimulus reduction only occurred once, and thus possible changes in susceptibility with practice on the original conditions could not be examined, although subjects did generally improve with further massed practice sessions under these reduced conditions.

Schneider and Shiffrin (1977; Shiffrin & Schneider, 1977) also reported several experiments, and discussed many others, in which the slopes of the set-size–reaction-time (or detection-accuracy) functions became very shallow with practice. As noted earlier, this finding has many interpretations, but Shiffrin and Schneider argued that it signifies the operation of automatic, resource-independent processes.

These authors also manipulated the number of elements per display (frame size in their terminology), and found that with practice, performance became largely independent of the number of display elements. Shiffrin (1975) earlier summarized the results of a number of experiments in which discrimination performance was the same in successive and simultaneous presentations. These findings are quite different from the present visual-discrimination results, in which performance with 32 possible target locations (simultaneous condition) remained consistently below that with 16 possible target locations (successive condition). Stimuli in the current study contained more elements (i.e., had larger frame sizes), and were physically larger than those used in the earlier studies, but it is not clear whether, or why, these variables might be responsible for the different results.

Logan (1978, 1979) used a concurrent-task procedure in which subjects performed both a memory task and a reaction-time task. The influence of the memory task on reaction-time performance was significantly smaller with practice in two relevant experiments (1978, Experiment 1; 1979, Experiment 1), and slopes of the set-size–reaction-time functions in control and concurrent conditions became more similar. There was no significant change in the slope measure with a concurrent task in the present experiment, perhaps because the subjects had already received four sessions of practice before the first concurrent session, but Logan's other finding is consistent with the current result that the magnitude of the concurrent-task effect diminishes with practice.

The evidence with respect to the reduced attention-demands interpretation of practice-related improvement is somewhat mixed. The reduced interference in the concurrent task is clearly consistent with this view, and is not easily explainable by other interpretations. On the other hand, the shallower slope of the set-size–reaction-time function is explainable by other mechanisms, and practice did not lead to smaller effects of reduced stimulus size or duration, or to elimination of the successive–simultaneous difference in the visual-discrimination task.

Taken together, the current findings along with the other results previously reviewed indicate that an answer to the question of what is responsible for improvement with practice in simple skills must take into account at least three sources of change. There is evidence of changes in the type of stimulus information being used, the identity or sequence of processing operations, and in the amount of processing resources required. In the following paragraphs we briefly describe a composite model of skill improvement that incorporates each of these mechanisms, and discuss how it can account for the current results.

The model is illustrated in Figure 15. Initially (top panel) it is assumed that processing between physical stimulus and overt response occurs in a sequence of conceptually independent processing stages, each responsible for a different type of processing (Salthouse, 1981; Sternberg, 1969, 1975). All stages are presumed to require attention (Logan, 1978) and occupy time, although the durations of the various stages may overlap (Eriksen & Schultz, 1979; McClelland, 1979). It is also assumed that the encoded stimulus early in practice contains a relatively large number of stimulus components—many that are relevant but also many that are irrelevant.

It is assumed that after moderate practice with the same assignment of stimuli to responses (bottom panel), the irrelevant stimulus components are ignored and perhaps more useful components added, that the encoded representation becomes directly con-

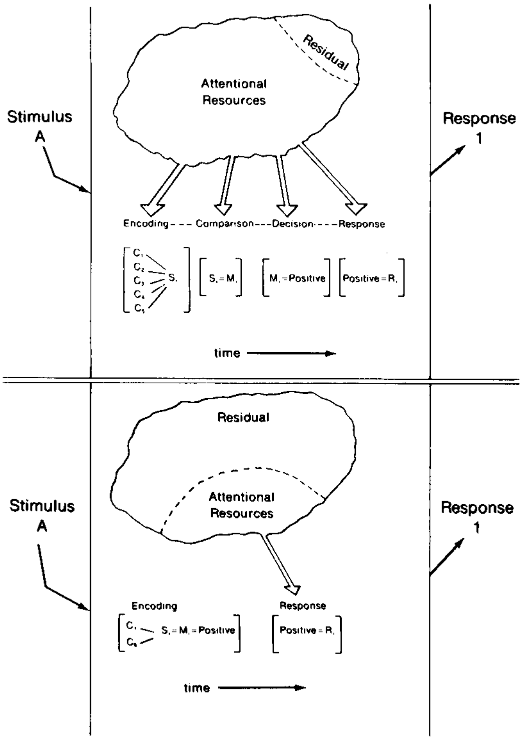

Figure 15. Model for improvement of simple skills. (Top panel indicates performance sequence for naive subjects, and bottom panel indicates sequence for practiced subjects. C_1, C_2, etc., are components or features of the presented stimulus, S_i is the encoded stimulus, M_i is the memory representation of the stimulus, *positive* is the decision category, and R_i is the internal representation of the response.)

nected to a decision category (thus bypassing some processing operations used early in practice), and that the entire task is less demanding of attentional resources.

In the case of the present signal-detection and visual-discrimination tasks it is presumed that most of the improvement is attributable to a change in the nature of the encoded information. In the early sessions subjects have difficulty identifying the relevant stimulus components (consistent motion and extra line, respectively) in the presence of similar but irrelevant background elements (random motion and square/diamond or X/+ arrays, respectively), but in later sessions the encoding occurs quite readily. However, at least some aspect of stimulus encoding appears to be resource independent, since reducing the duration of the stimulus had approximately the same effect early, when resources were scarce, as late, when processing resources were plentiful. It seems likely that this is a consequence of the reduced durations falling in the data-limited rather than resource-limited segments of the performance-resource functions (Norman & Bobrow, 1975). We suspect that there are probably also changes in the sequence of processing operations, and possibly in the attention demands of encoding, but we have no evidence for this in these tasks at the present time.

Improvement in the memory-scanning task is assumed to result from changes in all three major mechanisms. Stimulus encoding becomes more efficient by using only the minimal number of components relevant for stimulus identification, and perhaps by shifting from establishing a representation of the specific stimulus to activating the appropriate decision category. Because the product of the encoding process is assumed to become more directly connected to the appropriate response, there is also a change in the sequence and identity of processing stages. We suggest that the change is more like a bypassing of certain operations, (e.g., detailed comparison and decision) rather than parallel processing, but we know of no evidence yet available to distinguish between these alternatives. The attentional resources needed for the task decrease as various operations are eliminated and the encoding process becomes more automatic, although it is likely that some components, such as the process of initiating a response, continue to require attention throughout at least moderate levels of experience.

The current experimental findings are explained as follows. First, the reduced slope of the set-size–reaction-time function with practice is assumed to result from the development of expanded encoding (from item representation to categorical or decision activation), and from the bypassing of the comparison and decision stages. Very fast positive responses with one-item set sizes are produced because of a temporary activation of the encoding sequence for the just presented item. The fact that the slopes are greater than zero could be accounted for either by a mixture of processing modes with and without the comparison stage, or by a mixture of trials with and without the activated encoding sequence.

Following the argument presented earlier, the constant performance impairment early and late in practice with a reduction of probe stimulus size suggests that some aspect of the encoding process may be resource independent and data limited. Introduction of new stimuli forces one to engage in the slow serial comparison process, although there is probably some benefit of prior experience in the selectivity of encoding and in the connection of decision category to response. Reversing the assignment of stimuli to responses adds the negative interference of previously acquired "automatic" encodings and thus results in poorer performance than completely new stimuli. As long as some of the familiar stimuli are retained in their original response assignments, we would expect the automatic encoding to be used and to produce better transfer than that obtained with all new stimuli (cf. Kristofferson, 1977; Prinz, 1979; Rabbitt et al., 1979).

This model is offered only as a tentative means of identifying the major mechanisms that seem to be involved in the improvements found in very simple tasks. In many respects the present model is a composite of views expressed by other theorists (e.g., LaBerge, 1973, 1975; Logan, 1979; Prinz, 1977, 1979; Rabbitt et al., 1979; Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). The current formulation differs from any one of the earlier perspectives, however, in explicitly acknowledging the existence of several conceptually independent mechanisms, each contributing to practice-related improvement on a variety of simple tasks. Major issues concerning the relative contribution and time course of each mechanism in specific tasks need to be resolved. There are also detailed questions concerning the postulated mechanisms that cannot yet be answered. For example, exactly what is the nature of the final (asymptotic) encoding in each task? Is that encoding unaffected by the context in which the stimulus appears? What operations are ignored or bypassed after practice? How does an operation become independent of attention? Exactly what are the differences between automatic and attentive processing? Despite its speculative character and incompleteness, we suggest that the model illustrated in Figure 15 is a reasonable reflection of what is currently known about the nature of improvement in simple skills. In that respect, therefore, it represents a contemporary answer to the question of what improves in simple perceptual and cognitive tasks.

Adult Age Differences in Improvement

Before considering the issue of age differences in the rate or type of improvement, it is important to establish that the current samples of long-term subjects are adequately representative of their respective populations. The data in Table 1 and Figure 3 clearly demonstrate that this is the case; nearly all sample differences are much smaller than the corresponding age differences. It should be noted, however, that the experimental populations in both age groups are considerably above average for the psychometric measures. For example, converting the raw scores on the Digit Symbol and Vocabulary tests to WAIS scaled scores reveals that the young subjects' mean scores ranged from 13 to 16, whereas the older subjects' mean scores ranged from 16 to 17. These scaled scores have a mean of 10.0 and a standard deviation of 3.0 in the general population, and thus the present subjects are clearly in the upper range of the population with respect to psychometric measures of intelligence.

The remainder of this section can be organized in terms of three basic conclusions: (a) that improvement in performance is evident in both age groups and is perhaps even greater in older subjects than in young subjects; (b) that sizable age differences still remain despite considerable improvements; and (c) that there is little evidence that the way subjects perform or improve in the tasks differs between young and old subjects.

Figures 4, 5, and 12 indicate that substantial increases in performance occurred in each task. Moreover, Age × Practice interactions were significant in the signal-detection and memory-scanning tasks, indicating greater absolute improvement in the older subjects. The interaction may be artifactual in the signal-detection task because a measurement ceiling was limiting further improvement in the young subjects, but the trend in the memory-scanning reaction-time data seems unequivocal. At least with this measure, the first few sessions (involving several hundred trials) portray an unrealistic picture of the magnitude of the age differences evident at later stages of practice.

It is interesting to note that the improvements were equally retained by both age groups over a period of 1 mo. The inactive interval caused a slight performance degradation with the signal-detection task and possibly an increase in memory-scanning reaction time, but no age interactions were significant with any dependent measures.

Taken together, these two findings indicate that the acquisition and retention of simple perceptual and cognitive skills over long periods is not impaired with increased age. Older subjects appear to improve at least as much as young subjects, and they retain what they have learned over a 1-mo. interval just as well.

The present results are less encouraging with respect to the possibility that extensive practice might lead to the elimination of age differences in performance. Despite impressive improvements in the older subjects, age differences remain in nearly all measures of performance.

One might question whether the two groups of subjects maintained their levels of motivation across all sessions. There were some individual differences in the amount of enthusiasm exhibited late in practice, but these did not seem correlated with adult age. Moreover, all subjects continued to emit sounds of joy or frustration when engaged in the temporal prediction (photon torpedo) task, suggesting that high levels of interest persisted at least in this task.

An experimental check on the possibility that the older subjects were less motivated to perform at their optimum level in the memory-scanning task was carried out on Session 48 with the offer of monetary incentives to reduce reaction time. Older subjects were able to reduce their reaction times more than young subjects (55 vs. 31 msec) while increasing their error rate by about the same amount (5% vs. 6%). This result, in conjunction with the pattern of higher memory-scanning accuracy throughout the experiment (see Figure 5), suggests that the older subjects were operating with a greater relative emphasis on accuracy than were the young subjects. The magnitude of the age differences in reaction time are therefore probably slightly exaggerated, but it is very unlikely that the accuracy difference could be responsible for more than about 25 msec of the total 135-msec reaction-time differences between young and old subjects.

The evidence concerning possible age differences in the mechanisms used to perform or improve in the tasks is somewhat difficult to evaluate because of differences in the absolute levels of performance. There were no significant age interactions in the signal-detection task, and thus there is no indication of different approaches to this task. Only an interaction of Age × Stimulus Change × Practice was significant in the visual-discrimination task. This might reflect the inability of the older subjects to develop the special stimulus encoding that apparently contributed to the superior performance of the young subjects, or it might be that the older subjects were so close to a floor level in their performance that the stimulus-change effect could not be detected.

Several age interactions were significant in the memory-scanning task, Age × Set Size, Age × Size Reduction, and Age × Reversal), but these may simply reflect a tendency for all effects to be more pronounced in the older subjects. The two age groups appeared quite similar with respect to the serial, exhaustive nature of the search process, and the qualitative susceptibility to various manipulations.

The Age × Set Size × Practice interaction was also significant, indicating that the slopes of the set-size–reaction-time functions became more similar with practice. Indeed, on Sessions 42–45 the slopes for set sizes of 2 to 4 were nearly identical for the two groups.

Depending upon one's interpretation of the set-size effect, this result could indicate that older subjects (a) develop categorical representations, (b) switch from serial to parallel processing, or (c) increase the amount of residual resources to a greater absolute extent than young subjects. Whatever the mechanism, the current data suggest that the two age groups become almost equally efficient at its use late in practice, despite pronounced differences in most other performance measures.

A sizable age difference was evident in the change with practice of the concurrent vocal reaction-time increase, but this finding is also rather complicated. At face value, Figure 13 appears to suggest that older subjects reduce their secondary-task reaction times more, and by implication have a greater increase in the amount of their residual processing resources from the primary task, than do young subjects. However, the slow reaction times of the young subjects relative to the old subjects, and the striking individual differences evident in Figure 14, suggest that one or more artifacts may be operating in this task. The voice-activated relay may be triggered at slightly different times after the initiation of vocalization in some of the young subjects, or the attitude toward the task may be different across subjects in the young group. In any case, these characteristics should make one cautious about attaching too much importance to the quantitative age differences, or lack thereof, observed in Figure 13. Practice with a primary task may lead to a greater increase in residual processing capacity in older subjects than in young subjects, but the present results should not yet be considered strong evidence for this hypothesis.

We suggest that our results, and most results on age differences in perceptual–cognitive performance, can be explained by assuming that older adults go through essentially the same processing operations as young adults, but merely at a slower rate. Relative to young subjects, older subjects in the current study improved as much and also retained that improvement over a 1-mo. interval; there was also little evidence of qualitative differences between the two groups in the way the performance improvement was achieved. The same model of performance improvement therefore seems to apply to both young and old adults.

As far as could be determined, the performance of young and old adults was qualitatively very similar, and only differed in the absolute levels that were achieved. This indicates that the cause of the age differences is probably nonstrategic, in that there is no evidence of different approaches to the task, and that it is unlikely to be experientially based, because the differences persist over long periods of experience. (The lack of experience could, however, have led to irreversible changes such that no amount of later experience would compensate for the deficits. This version of the experiential interpretation cannot be ruled out by the present results). A fundamental physiological change in the nervous system therefore seems to be responsible for these performance differences.

It appears that the immediate behavioral consequence of the age-related physiological change is a slower rate of processing nearly all types of information. It is not yet clear how such a modification in overall processing rate might have occurred, but it is possible that such a change could be relatively independent of the specific mechanisms used to perform or improve in a task. For example, consider a contrast between an old, obsolete, slow computer, and a modern, state-of-the-art, fast computer. The two machines might operate on the same types of information and even use the same programs requiring approximately the same proportion of central processing capacity, and yet the output would be produced much more quickly on the faster computer than on the slower one. Such a rate-change mechanism in the human organism could therefore lead to dramatic changes in the efficiency of most, and perhaps all, types of information processing.

There are two important exceptions to the pattern of age differences in all performance measures in the present study. One is the absence of age differences in the vocal reaction-time task (see Figure 13). As mentioned earlier, the unusual distribution of reaction times in the young sample makes this result suspect. However, there are other reports of little or no age difference with vocal, as opposed to manual, reaction times (e.g., Nebes, 1978; Eysenck, 1975), and therefore the use of a vocal response may lead to real exceptions to the generalized slowing interpretation. A firm conclusion on this issue must await further research.

The second exception to the pattern of older subjects performing slower or less accurately than young subjects is evident in the slope of the set-size–reaction-time functions on Sessions 42–45, particularly for set sizes of two through four. This might be interpreted as signifying that the comparison process, by which the probe stimulus is evaluated against the memory-set items, is no longer time dependent in either age group. To elaborate, consider the analogy discussed earlier in which a slow, old computer was contrasted with a fast, modern computer. All types of information processed by the slow computer should require more time than the equivalent processing by the fast computer. However, if a new peripheral device (e.g., a hardware stimulus classifier) were introduced into both systems, the processing times for that particular operation would no longer be expected to differ between the two systems. In a sense, therefore, the operations now handled by the new procedures would have become independent of the computer's processing rate. Some mechanism such as this may be responsible for the absence of adult age differences in specific cognitive processes that might otherwise be expected to reflect the general slowing-with-age trend.

It would be desirable to have direct evidence for the processing rate interpretation of age differences rather than accepting it by virtue of elimination of reasonable alternatives. We are not presently aware of any alternative explanations of age differences in perceptual–cognitive performance, but the current results indicate several facts that must be incorporated into any such interpretation that might be proposed. First, young and old subjects appear equally adept at acquiring and retaining simple new skills over moderate periods of time. Second, there are not any noticeable differences between young and old subjects in the way they perform or improve in simple tasks. And third, substantial performance differences remain in most measures of perceptual accuracy or response speed throughout at least 50 sessions of experience.

Reference Note

1. Poon, L. W., Fozard, J. L., Vierck, B. A., Dailey, B. F., Cerella, J., & Zeller, P. *The effects of practice and information feedback on age-related differences in performance speed, variability, and error rates in a two-choice decision task.* Paper presented at the meeting of the American Psychological Association, Washington, D.C., September 1976.

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