

Memory Development
throughout the Life Span:
The Role of Processing Rate

Timothy A. Salthouse

UNIVERSITY OF MISSOURI AT COLUMBIA
COLUMBIA, MISSOURI

and

Robert Kail

PURDUE UNIVERSITY
LAFAYETTE, INDIANA

I. Introduction	90
II. Illustration of Possible Effects of Processing Rate on Memory Processes	92
A. Rehearsal	92
B. Semantic Memory Activation	93
III. Developmental Data	94
A. Problems	94
B. Child Development	95
C. Adult Development	98
D. Provisional Evaluation	100
IV. Predictions from the Processing-Rate Hypothesis	102
A. Manipulations of Rate of Processing	102
B. Correlations between Processing Rate and Memory Performance	104
C. Elimination of Age Differences in Memory by Speed Matching	105
V. Criticisms and Limitations	106
A. Past Criticisms	106
B. Too Few Data	107
C. Too Comprehensive	107
VI. Possible Causes of Differences in Response Speed	107
A. Hardware	108
B. Software	108
C. Internal Representations	109
D. Size of Working Memory	110
E. Concurrent Processing Demands	110
F. Input/Output Rate	111
G. Which Mechanism?	111
VII. Conclusions	112
References	113

Abstract

It is hypothesized that the rate at which humans process information may be responsible for a variety of memory and cognitive differences observed across the human life span. The possible implications of a slower rate of processing on memory functioning are examined and developmental evidence relevant to this hypothesis is reviewed. It is concluded that although the hypothesis has at present only moderate support, rate of processing represents a potentially important dimension for conceptualizing the causes of developmental differences in cognition.

I. Introduction

One of the most dramatic of the behavioral changes observed across the human life span is a progressive increase and then a decrease of response speed. Figure 1 illustrates this trend with data from two simple reaction-time experiments (Bellis, 1933; Hodgkins, 1962). Several other researchers have reported similar U-shaped functions (e.g., Hodgkins, 1963; Miles, 1931; Pierson & Montoye, 1958; Stern, Oster, & Newport, 1980), and hundreds of additional studies have yielded comparable data over more limited age ranges.

Perhaps in part because of the large developmental and individual differences, speed measures have been employed in psychological research for

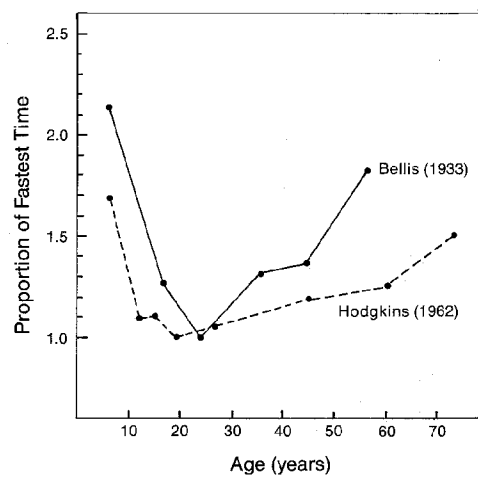


Fig. 1. Reaction time across the life span expressed as a proportion of the fastest time across all ages. The ordinate thus represents the average percentage by which a given age group exceeds the time of the fastest age group.

many years; in fact, at one time they were even considered as a potential index of intelligence. Currently, reaction time is one of the most commonly used dependent measures in cognitive psychology. In this context, Anderson (1980, p. 16) has offered interesting guidelines for interpreting the magnitude of reaction-time differences. He suggests that a difference in reaction time of 5% is "fairly important" and that a difference of 10% is "substantial." Viewed in this light, the age differences of 50% or more illustrated in Fig. 1 must be no less than "gigantic" or "enormous."

The major purpose of this article is to explore some of the implications for memory functioning of these enormous age differences in response speed. Our principal thesis is that the variations in response speed reflect fundamental differences in the rate of processing information that may also be responsible for a variety of developmental differences in memory and cognition. This viewpoint has largely been neglected in the past because many cognitive and developmental psychologists seem to dismiss the concept of processing rate as merely reflecting an unimportant and uninteresting aspect limited to tasks such as simple reaction time (but see Dempster, 1981, and Chapter 14 of Jensen, 1980, for notable exceptions).

We will argue that the "benign neglect" perspective is very narrow because similar age trends in both the early and late portions of the life span have been observed in a number of different performance variables. In addition to measures of simple and choice reaction time, age differences in processing rate have been inferred from visual backward-masking studies in which time to escape masking is the critical variable, as well as from psychometric tests like digit-symbol substitution and letter search. Even such seemingly peripheral measures as critical flicker frequency (the rate of alternation between light and dark fields that produces the transition from flicker to fusion) and finger-tapping rate (the maximum rate of repetitive finger taps) have been used as reflections of internal rate of processing information. The major point is that most of these measures have been found to yield roughly similar age trends (i.e., increasingly faster performance until about age 20 and then steadily slower performance throughout the adult years) and thus may be interpreted as suggesting that a single fundamental mechanism underlies all of these ostensibly diverse phenomena.

The remainder of this article consists of five principal sections. We begin in Section II by demonstrating how developmental differences in processing rate could have substantial impact on memory performance. Then in Section III we review the literature on developmental change in speed of mnemonic processing. Because the relevant literature is not large, we present in Section IV some additional predictions of the processing-rate hypothesis that could be evaluated in future research. Next, in Section V, we consider some criticisms and limitations of the processing rate hypothesis. Finally,

in Section VI we propose several mechanisms that might be responsible for developmental differences in processing rate.

II. Illustration of Possible Effects of Processing Rate on Memory Processes

A. REHEARSAL

In this section we explore one possible implication of the view that the developmental differences in response speed are a reflection of age differences in the speed of internal processes. The example is based on rehearsal, the primary means by which information is transferred from a transient limited-capacity short-term store to a more permanent large-capacity long-term store. Depicted in the top part of Fig. 2 is a rote-rehearsal strategy in which early items are rehearsed in alternation with the encoding of new items. If one individual can execute the components of rote rehearsal (i.e., encoding and repetition) more rapidly than a second individual, the first

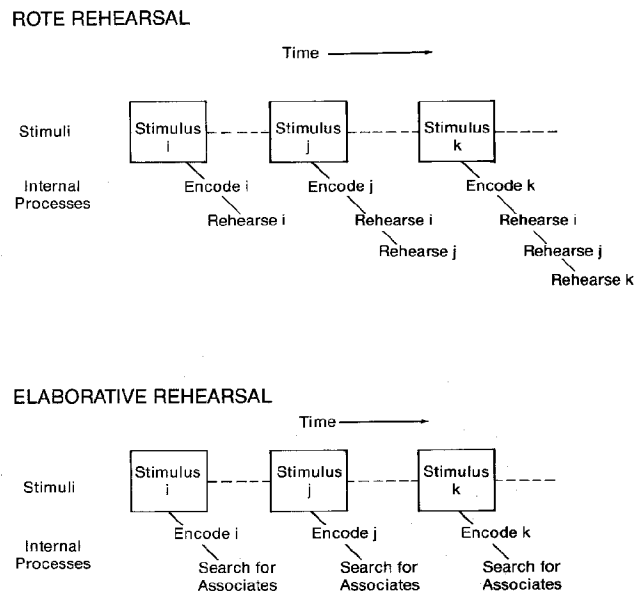


Fig. 2. Illustration of possible temporal sequencing of external and internal events with two types of rehearsal: (a) rote rehearsal; (b) elaborative rehearsal.

individual will complete more total rehearsals than the second person in a given period of time and will probably recall more as a consequence.

Rate limitations would also affect elaborative types of rehearsal. In the bottom panel of Fig. 2 is a rehearsal strategy in which items are elaborated as they are presented; elaborations consist of locating the items in a network of related items, forming a visual image, or creating some other semantically based representation of the item. As with rote rehearsal, if one person's processing rate is faster, then that individual will be able to complete more elaborated rehearsals in a fixed period of time and would be expected to have greater recall.

In general, then, the quality or durability of a memory trace can be expected to be greater in the individual who can carry out more relevant memory operations in the same period of time. Moreover, because more complicated (and possibly more powerful) mnemonics will typically involve additional stages of processing or increasingly complex operations, more complicated strategies will require larger amounts of time to be completed successfully. Thus, if two individuals differ in rate of processing, the difference in their effective use of various strategies should increase with the complexity of these strategies.

B. SEMANTIC MEMORY ACTIVATION

A second example of the potential influence of processing rate on memory comes from the study of long-term or permanent memory. In most theories (e.g., Collins & Loftus, 1975), long-term semantic information is assumed to be represented in the form of a network of associated concepts, with closely related concepts having shorter and/or more connecting links. Any mental functioning that requires utilization of this information is postulated to occur via a spreading activation throughout the network, with the magnitude of the activation inversely proportional to the time and distance from the source of activation.

Now consider two individuals attempting to read several paragraphs of instructions and then attempting to perform the activity described by the instructions. If one individual has a slower rate of activation throughout the network than the other individual, he or she is likely to be slower in identifying the meaning of individual words, relating consecutive words to one another to understand a phrase or sentence, relating consecutive sentences to one another to understand a paragraph, and so on. Moreover, not only will this person require more time to comprehend the instructions, he or she will probably also experience "memory" problems when attempting to perform the activity because the global task perspective, corresponding to the simultaneous activation of all relevant task components, was never

acquired because early concepts were deactivated before late concepts could be activated. Only if the interval until deactivation was lengthened in proportion to the slower rate of activation, and there were no external pacing constraints, would one not expect severe memory and other cognitive deficits with a slower rate of semantic activation.

This example and the previous one concerning rehearsal demonstrate that variations in rate of processing can have a wide range of effects in memory tasks. One of the most important points is that differences in rate of performance will frequently lead to differences in quality of performance, and are not simply restricted to measures with an obvious temporal aspect. In self-paced situations the clichés "slow but sure" and "haste makes waste" may hold true, but the world is not always a self-paced environment. Whenever there is external control on the rate of stimulation, on the pace of response, or more generally on the number of activities to be completed in a given period of time, there may be reductions in performance quality because the processing rate was too slow to allow all task components to be completed satisfactorily.

III. Developmental Data

A. PROBLEMS

Although the speculations discussed in the previous section might lead one to expect that considerable evidence documents the influence of processing rate on memory performance, there is actually very little directly relevant research. Ideally, one could identify all memory processes sensitive to processing rate and then simply report the results of developmental investigations of those processes. Unfortunately, there are two problems with this type of approach. First, because memory is currently an area of active theoretical speculation, there is not consensus yet as to the exact processes involved in memory functioning, quite independent of whether they are sensitive to rate of processing. Second, even if certain likely processes could be identified, there are very few operational procedures for measuring the rate of memory processes. To take just one example, it is not obvious how one might measure speed of transfer from short- to long-term memory, if these are considered structurally distinct memory components.

As a consequence of these problems, there simply is not much developmental research available that has addressed rate-sensitive memory processes. Further, there is virtually no life-span developmental research. Instead, the existing research consists of a group of studies dealing with children and another independent group of studies dealing with adults of

varying ages. We will review each area separately, as there is minimal overlap in the kinds of research that have been done in the two areas. Both literatures consist of many one-shot studies that have never been replicated and that will not be discussed here. Response time is such a sensitive (and in some ways, complicated) dependent variable that studies dealing with response time must be replicated before much confidence can be placed in their findings.

B. CHILD DEVELOPMENT

One process that has been reasonably well investigated in both children and adults is the rate of scanning items in short-term memory using the paradigm introduced by Sternberg (1966, 1969, 1975). The procedure involves presenting subjects with a short list of items to be remembered, and then presenting a single probe item that is to be classified as rapidly as possible with respect to whether or not it was in the earlier list. By varying the number of items in the initial memory list a function can be constructed in which decision time is related to the number of items in the list. This function is reasonably linear (Sternberg, 1969, 1975), and hence the slope can be interpreted as the time required to scan one item in memory. All other processes involved in encoding the probe item, making a decision, and executing a response are presumed to be reflected in the function intercept, and thus the slope is considered to be a relatively direct measure of memory-scanning time.

The Sternberg procedure has been used with children and adolescents in several different studies, but at first glance the literature seems full of contradictions. On the one hand, Harris and Fleer (1974) reported that 8-, 16-, and 24-year-olds all scanned memory for digits at approximately 40 msec/digit; on the other hand, Herrmann and Landis (1977) derived scanning rates of 223, 84, and 42 msec/digit for 7-, 12-, and 17-year-olds, respectively. The first study suggests no developmental change in speed of scanning, but the second study suggests a fivefold increase in speed across a 10-year span. However, the studies in this area differ considerably in the amount of practice that children received prior to the trials used in deriving estimates of scanning speed. At one extreme, Naus and Ornstein (1977) used 240 practice trials; at the other, Herrmann and Landis (1977) used only 16 practice trials in each of two sessions. Not surprisingly, Naus and Ornstein estimated that 11-year-olds scanned short-term memory at a much faster rate than the 12-year-olds in the Herrmann and Landis (1977) study. The threefold difference in scanning rate seems largely attributable to the difference in amount of practice, as the studies were otherwise very similar.

In fact, when studies are distinguished in terms of the amount of practice,

the findings become much more consistent. In the studies in which there was minimal practice (i.e., Herrmann & Landis, 1977; Hess & Radtke, 1981; Keating & Bobbitt, 1978; Keating, Keniston, Manis, & Bobbitt, 1980; McCauley, Kellas, Dugas, & DeVillis, 1976) scanning speed became faster with age, from approximately 80 or 90 msec/digit for 8- and 9-year-olds to 50 or 60 msec/digit for adolescents, and to 40 or 50 msec/digit for young adults. For studies in which subjects had moderate practice (i.e., from 48 to 240 trials), age is unrelated to scanning rate (i.e., Dugas & Kellas, 1974; Harris & Fleer, 1974; Naus & Ornstein, 1977). All age groups scan at approximately 40 msec/digit, a value that differs by only a few msec from Sternberg's (1969) original estimate of the scanning rate of young adults. Further, the standard deviation of the six means associated with these three studies is less than 6 msec, an astonishingly small figure considering the fact that the points were derived from three separate studies and from persons differing in age by as much as 16 years.

These data therefore suggest that large differences in scanning rate among children are eliminated when subjects have received moderate amounts of practice. The initial developmental differences appear to reflect age differences in the ability to adjust quickly to a new task rather than a fundamental limitation in the child's speed of performing internal operations.

Another cluster of studies has focused on a paradigm devised by Posner and Mitchell (1967) to measure the speed of gaining access to information in long-term or permanent memory. Individuals are shown pairs of letters and asked to make rapid decisions about whether they were the same or different. Judging that the letters were the same in name (e.g., Aa) has been found to take about 70–100 msec longer than judging that the letters were physically the same (e.g., AA). This difference has been interpreted as reflecting the time needed to access letter names from long-term memory.

The Posner–Mitchell letter-matching task has been employed in three studies with children of varying ages (Bisanz, Danner, & Resnick, 1979; Keating & Bobbitt, 1978; Reitsma, 1978). The results of these studies are illustrated in Fig. 3, where name-access time, defined as the response time for a physical match subtracted from the response time a name match, is plotted as a function of chronological age. Access speed appears to increase considerably during childhood, and approximates adult levels during early adolescence.

This pattern of increasing speed of access from permanent memory with increasing age has also been found with a slightly different paradigm. Duncan and Kellas (1978) showed pairs of pictures to 8-year-olds, 10-year-olds, 12-year-olds, and adults, with the instructions that they were to judge whether the pictures were from the same conceptual category. Physically

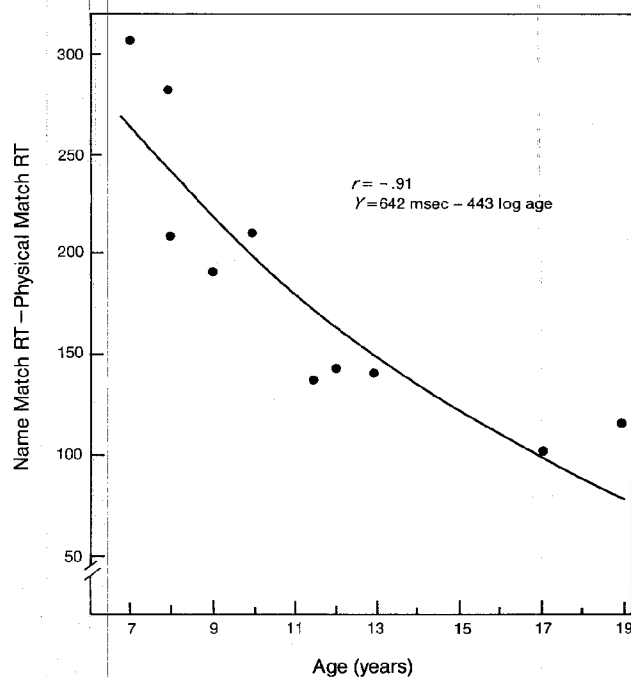


Fig. 3. Name-access time as a function of chronological age across three published studies (Bisanz, Danner, & Resnick, 1979; Keating & Bobbitt, 1978; Reitsma, 1978). The line is fitted by eye, although the equation is based on the actual data.

identical pairs (e.g., two identical spoons) were judged to belong to the same category more rapidly than physically dissimilar pairs (e.g., a fork and a spoon), but the additional time to judge physically dissimilar pairs—the estimate of memory-access speed—dropped from approximately 600 msec for 8-year-olds to 300 msec for adults. These times are roughly twice as large as those derived from comparisons of letters (presumably because of either the greater complexity of the judgments or the lesser familiarity of the items), but the 300-msec decline in access time over a 10-year age span is nearly the same as that obtained with the letter-matching task.

In neither of these latter two tasks has there been sufficient data with variable amounts of practice to allow an analysis similar to that performed with the memory-scanning results. At the present time, therefore, one cannot rule out the possibility that age differences in speed of memory access among children might also be eliminated with moderate experience.

C. ADULT DEVELOPMENT

The Sternberg memory-scanning paradigm has been used in several adult development studies with fairly consistent findings. Significantly slower memory scanning in older adults as compared to young adults has been reported in at least seven separate experiments employing slightly different procedures, age groups, and stimuli (e.g., Anders & Fozard, 1973; Anders, Fozard, & Lillyquist, 1972; Eriksen, Hamlin, & Daye, 1973; Ford, Roth, Mohs, Hopkins, & Kopell, 1979; Madden & Nebes, 1980; Salthouse & Somberg, 1982a, 1982b). Marsh (1975) failed to find a significant age difference in the memory-scanning parameter, but there were only 10 individuals in each age group; in addition, abnormally long reaction times by some individuals in the older groups with one-item list lengths served to distort the typical linear relationship between list length and decision time. With such small samples and the atypical memory-scanning functions it is difficult to draw firm conclusions. Anders and Fozard (1973) also employed a modified memory-scanning procedure that allowed comparisons of the speed of scanning secondary or long-term memory. Age differences comparable to those observed in primary or short-term memory were reported.

Unlike the case with children, it seems doubtful that moderate variations in amount of practice would substantially alter the age relationships in these studies. All of the experiments had at least 150 memory-scanning trials, with Madden and Nebes (1980) presenting a total of 2,592 trials. Salthouse and Somberg (1982b) did find a convergence of slope parameters in young and old adults after 50 sessions (5,000 trials) of practice, but with such extensive experience it is possible that all individuals had altered the manner in which the task was performed so that the slope measure is no longer an accurate reflection of memory-scanning speed.

A variety of ingenious techniques to measure retrieval time from semantic memory have been employed in studies with older adults, but the results have been confusing and inconsistent. Eysenck (1975) presented a category name and a single letter to individuals with the instructions to name rapidly an exemplar of the category that began with the target letter. For instance, an appropriate response to "Fruit—A" would be "Apple." The time to produce the response was considered a measure of retrieval time from semantic memory. An alternative measure of retrieval time from semantic memory was utilized by Thomas, Fozard, and Waugh (1977) and Poon and Fozard (1978), who measured the speed of naming pictures on the assumption that picture names had to be accessed from semantic memory. Waugh, Thomas, and Fozard (1978) employed a procedure to measure retrieval time of items just attended (primary memory) or of items out of the span of awareness (secondary memory). Poon and Fozard (1980) used still another

procedure consisting of old/new speeded recognition judgments of recently presented (primary memory) or earlier presented (secondary memory) words in a continuous recognition task.

No age differences in the relevant measures were found by Eysenck (1975) or Poon and Fozard (1978), but older adults were slower in the Poon and Fozard (1980), Thomas *et al.* (1977), and Waugh *et al.* (1978) studies. There are clearly many differences in procedure among the studies, but one factor that may be contributing to the inconsistent results in retrieval time is the use of vocal reaction time measures in all but the Poon and Fozard (1980) study. For a reason not yet clear, adult age differences have been reported to be much larger with manual responses than with vocal responses (Nebes, 1978; Salthouse & Somberg, 1982b). Moreover, earlier studies of semantic memory retrieval time in which individuals were asked to write as many words as possible beginning with specific letters found consistently slower performance in older adults (e.g., Birren, Riegel, & Morrison, 1962; Riegel, 1959; Schaie, 1958; Schaie, Rosenthal, & Perlman, 1953; Schaie & Strother, 1968). In view of the conflicting evidence, it is premature to attempt any conclusion about adult age differences in the speed of access to, or retrieval from, long-term or semantic memory.

Two studies have provided comparisons of rote rehearsal time in young and old adults. Salthouse (1980) had research participants subvocally rehearse words to themselves one, two, or three times, and then used the slope of the function relating rehearsal time to number of repetitions as the measure of time per rehearsal. Adults with a mean age of 71 were found to require 28% more time per rehearsal than adults with a mean age of 23. Very similar results with a quite different procedure were reported by Sanders, Murphy, Schmitt, and Walsh (1980). These investigators employed an overt rehearsal method in which participants were instructed to rehearse aloud so that tape recordings could be made to analyze rehearsal strategies. The important result for the present discussion was that older adults were found to have fewer rehearsals than young adults in the same period of time. The Salthouse (1980) and Sanders *et al.* (1980) results with age differences in rehearsal time are therefore quite consistent with one another and with the processing-rate interpretation of memory. Further research in which specific aspects of memory functioning were related to rate of rehearsal, both across and within age groups, would be desirable.

There are other results in the adult development literature that can be considered indirect evidence for the processing-rate hypothesis because they are consistent with that perspective, although they might also be explained by alternative interpretations. Within this category are the often-reported findings that older adults are more disadvantaged than younger adults by faster pacing in paired-associate or serial-learning tasks (see Arenberg and

Robertson-Tchabo, 1977, for a review), and that older adults typically exhibit less imaginal mediation of mnemonic organization than younger adults (see Craik, 1977, for a review). Both findings are interpretable from the processing-rate perspective because if older adults have a slower rate of processing they will require more time to learn associations between items, to form mediators, or to establish internal organization.

D. PROVISIONAL EVALUATION

The literature reviewed in the previous two sections provides only mixed support for the hypothesis that the rate of performing memorial operations is responsible for many of the developmental differences observed in memory performance. The finding of adult age differences in the speed of rehearsal is clearly consistent with the hypothesis, but the absence of an age difference in memory-scanning rate with children who have moderate experience on the task seems to be just as clear evidence against the hypothesis. Other evidence can be interpreted in various ways, but none of it appears overwhelmingly positive or negative at present. The major reason for the lack of definitive evidence in support or contradiction of the processing-rate hypothesis is a general absence of pertinent data. No strong conclusions can be reached without an adequate empirical data base, and that is simply not yet available with respect to the relationship between processing rate and memory performance across the life span.

There are at least three additional factors contributing to the current equivocal status of the processing-rate hypothesis. One such factor is the possibility that fundamentally different mechanisms are operating in the child and adult segments of the life span. Merely because children and older adults are both slower than young adults in a variety of speeded measures does not mean that the reasons for this slowing are the same in the two groups. Furthermore, the consequences of the slowing may also be different in the two age groups, so the relationship between rate of processing and memory performance may not be equivalent for children and older adults. As an example, by virtue of their greater experience older adults may be able to use different strategies to compensate for a slower rate of processing, whereas young children have not had the benefit of extensive experience and consequently may not be able to use such compensatory mechanisms.

A second factor that is probably contributing to the currently confusing results is, as we noted earlier, a generally inadequate understanding of the importance of speed on specific memory processes. Plausible speculations can be offered as to why certain memory processes would be detrimentally affected by slower operation speed and thus have consequences on a variety

of performance measures, but there is not yet any direct evidence supporting these speculations. Moreover, the relationship between the speed of a specific process and overall memory functioning is still poorly understood. For example, it seems reasonable to suggest that the rate of memory scanning should influence the quantity or quality of information remembered, but it is possible that this parameter is actually of little relevance to overall memory functioning in many situations. Without more detailed information about the quantitative and qualitative functioning of the processes responsible for the efficient encoding, storage, and retrieval of information it will be difficult to amass strong evidence either for or against the processing-rate hypothesis (i.e., that the speed of performing memory operations is responsible for developmental differences in memory performance).

A final reason for the current ambiguity concerning the processing-rate hypothesis is the variable, and often poor, methodology employed in many experiments. Reaction time, the dependent variable in most of the studies, is a powerful but temperamental variable, and many investigators have not used it with sufficient care. Among the often-uncontrolled factors known to influence reaction time are amount of practice, mode of response, stimulus modality, and level of accuracy. Some of these factors are undoubtedly responsible for the variability in the studies discussed earlier and for the inconsistency in the results illustrated in Fig. 1. (For relevant discussion see Kail & Bisanz, 1982a, 1982b; Pachella, 1974; Salthouse, 1981; and Wickelgren, 1977).

Two studies from the area of adult development illustrate these types of methodological problems; both have been interpreted as providing evidence against the processing-rate hypothesis. One study by Nebes and Andrews-Kulis (1976) investigated the speed at which young and old adults produced sentences relating two nouns. The authors concluded that "older subjects formed sentences just as rapidly as did the young" (p. 315), despite a difference of over 1 sec in the sentence formation time of the two age groups (i.e., 2.60 and 3.68 sec, respectively, for young and old adults). Failure to detect a difference of 40% as significant was probably attributable to the large variability, with only 28 trials presented to each research participant.

The second study, by Nebes (1976), attempted to measure the time to recode a verbal description into a pictorial form in young and older adults. The primary manipulation was the interval between the presentation of the verbal description and the presentation of geometric shapes that either did or did not correspond to the description. Recoding time was to be inferred from the interval at which the reaction time for verbal-picture pairs of stimuli was equivalent to the reaction time for picture-picture pairs of stimuli. Both young and old adults were found to have comparable reaction times

to the two types of trials with interstimulus intervals of 1 sec or more, but it is likely that the duration of the recoding process was less than 1 sec for all age groups. In other words, the grossness of the temporal manipulation precludes any statement about the relative duration of recoding in young and older adults. Only if nonzero intervals had been presented in which one or both groups of adults produced nonequivalent reaction times in the two conditions could inferences about the rate of recoding across age groups be made.

IV. Predictions from the Processing-Rate Hypothesis

In addition to the evidence discussed in the preceding sections, there are at least three further predictions from the processing-rate hypothesis of developmental memory differences. These are considered predictions because at the present time there are too little developmental data to warrant any reasonable conclusions.

A. MANIPULATIONS OF RATE OF PROCESSING

The first prediction is that the effects of age on memory should be qualitatively similar to the effects produced by direct manipulations of processing rate. Perhaps the closest we can come to manipulating rate of processing at the present time is to alter the nature of the material that is to be remembered. Some types of material may be processed at an intrinsically faster rate than other types of material, and manipulating the nature of the material might therefore be a means of simulating a change in the effective rate of processing. Mackworth (1963) was one of the first to employ this type of manipulation in an investigation of determinants of memory span. She found that across four classes of items (shapes, colors, letters, and digits), the items that could be read aloud the fastest also yielded the greatest memory spans. Later investigators (e.g., Baddeley, Thomson, & Buchanan, 1975; Standing, Bond, Smith, & Isley, 1980; Watkins & Watkins, 1973) have reported similar results with other types of material, most notably words with various numbers of syllables.

In one developmental investigation with this procedure, Salthouse (1980) analyzed free-recall serial position effects with young and old adults, and with "fast" (one-syllable) and "slow" (three-syllable) words. As expected, the pattern of differences between young and old adults paralleled that observed between one-syllable and three-syllable words.

Even more interesting than the qualitative similarity of the material and age comparisons in the Salthouse (1980) study is the quantitative relation-

ship between measures of processing rate and memory performance. As noted earlier, estimates of rehearsal rate were also obtained in the Salthouse (1980) experiment, and memory performance can be plotted against these measures as in Fig. 4. Observe that proportion of recall is related to rate of processing in such a way that the faster the rate, the higher the level of recall. These results are consistent with the suggestion that the number of items rehearsed per unit of time is responsible for the age differences in level of recall. The argument would have been more compelling had all of the data points fallen along the same rehearsal rate-recall function, but the general finding of slower rehearsal associated with poorer memory is clearly consistent with the processing-rate perspective. A similar relationship between rehearsal rate and memory performance has been demonstrated with 8-, 10-, and 12-year-old children in a recent study by Nicolson (1981).

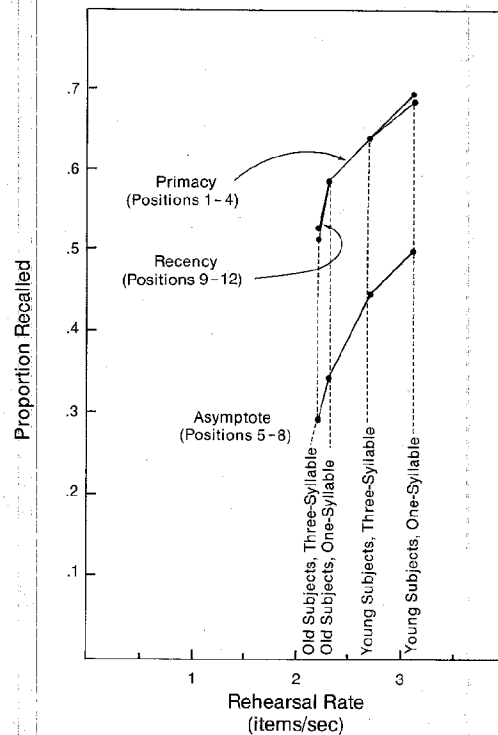


Fig. 4. Memory performance for three serial position segments as a function of rehearsal rate in the Salthouse (1980) study. Note that for each serial position segment (Primacy, Asymptote, Recency), older age and more syllables are associated with slower rehearsal and poorer recall.

Manipulation of the type of material is a very crude means of affecting processing rate, and it probably will not be useful for many memory tasks. For example, an unpublished experiment by Salthouse and Prill (1980) failed to find differences in mnemonic organization with one-syllable and three-syllable words, and Chase (1977) and Clifton and Tash (1973) failed to find differences in memory-scanning rate across these two types of material. Although this particular method of manipulating processing rate appears to have severe limitations, there might eventually be better methods of manipulation that will allow fuller exploitation of this technique for investigating the processing-rate hypothesis. It is clear that this perspective would predict comparable effects with a manipulation that influences speed of internal operations as with a comparison of individuals of different ages (and presumably different rates of processing).

Another technique that also appears to have limited potential is the control of processing time by reducing the duration of stimulus presentation. The problem here is that it is difficult to reduce duration of presentation without running the risks either that the stimuli will not be perceived or that the task will be altered from one emphasizing memory to one emphasizing perception or attention. It is also not obvious that the duration of internal processing operations will be affected merely by manipulating the length of the interval a stimulus is physically present in the environment. Nonetheless, at least one study has used this technique with apparent success. Simon (1979) compared the effectiveness in young, middle-aged, and old adults of no cues, phonemic cues, semantic cues, and context cues presented at the time of recall. The younger adults had higher recall with semantic and context cues than with phonemic cues, and the older adults achieved their highest recall with phonemic cues. However, the older adult pattern of cue utilization (i.e., best recall with phonemic cues) was produced in the young adults by reducing the presentation time from 8 sec/item to 4 sec/item. In this particular situation, then, the duration of stimulus presentation may have effectively served to control the time available for carrying out internal processing operations.

B. CORRELATIONS BETWEEN PROCESSING RATE AND MEMORY PERFORMANCE

A second prediction from the processing-rate hypothesis is that there should be substantial correlations between measures of processing rate and memory performance in individuals of all ages. At a gross level, of course, there are similarities between the two variables in that speed and memory performance both generally improve until the late teens or early twenties,

and then slowly decline throughout adulthood. If the rate hypothesis is correct, however, one might also predict similar relationships across individuals within a single age group.

Research relevant to this issue dates back to the late 1800s when perceptual-motor variables such as reaction time were being considered as potential measures of intelligence. An early study by Wissler (1901) involved the administration of a battery of sensory, reaction-time, and memory tests to about 100 college students. The reaction time-memory correlations were quite low (i.e., .06-.17), but only a few reaction-time trials were presented and thus the reaction-time measures were probably not very reliable. Later investigators have reported correlations between measures of memory performance and reaction time of .03-.59, with the majority of the correlations in the .20-.30 range (e.g., Jackson & McClelland, 1979; Kelley, 1964; Lansman, 1981; Lemmon, 1927; Lunneborg, 1977; McFarland, 1930).

Although not particularly large, these values are nevertheless interesting because the populations were relatively homogeneous (most individuals were college students), and the correlations might therefore have been attenuated from the restricted range of variation. Another reason for cautious optimism is that most of the studies employed a very gross measure of processing rate—typically either simple or choice reaction time. No better measures of processing rate are yet available, but when such measures are discovered it is unlikely that sensory and motor factors, which are an intrinsic part of crude reaction-time measures, will be included. Instead, they will probably reflect the duration of important mental or cognitive processes (e.g., the cycle time of the nervous system) and be relatively independent of peripheral factors related to sensory or motor ability.

C. ELIMINATION OF AGE DIFFERENCES IN MEMORY BY SPEED MATCHING

A third prediction from the processing-rate hypothesis, as yet unexplored, is that it should be possible to eliminate age differences in memory by matching individuals of different ages on measures of processing rate. If most of the age differences in memory are attributable to differences in processing rate, then equating individuals on the latter variable should eliminate performance differences in memory. Some attempts at this type of matching could be made using reaction time as the measure of processing rate; however, as noted above, reaction time is probably not the optimal measure of processing rate and consequently most research investigating this prediction will probably be deferred until better processing-rate measures become available.

V. Criticisms and Limitations

We have stressed the strengths of the processing-rate hypothesis for developmental differences in cognition, but we are aware of many weaknesses. Indeed, despite the relative recency of these ideas, criticisms of them have already been published. We shall briefly consider criticisms offered by Hartley, Harker, and Walsh (1980), and then proceed to a discussion of what we feel are major limitations of the processing-rate hypothesis at the current time.

A. PAST CRITICISMS

Hartley *et al.* (1980) provided three reasons for the argument that "the speed-of-processing explanation is an unproductive research hypothesis for memory investigations" (p. 243). Their reasons, offered in the context of research on aging, were:

First, . . . the speed-of-processing explanation predicts large age differences in primary memory, predictions that are not supported by much memory research. Second, the proponents of speed-of-processing explanations have not articulated the secondary memory mechanisms that would be affected adversely by slower processing. Third, the stages of memory that show the greatest slowing also show the least memory impairment, and the stages that show the greatest memory impairment show the least slowing. (p. 243)

The latter two objections were addressed, and presumably resolved, in the preceding sections of this article. In the second section we explored the implications of a slower rate of rehearsal and semantic activation in the functioning of primary and secondary memory, and in the section on developmental data we noted the confusion associated with the results on speed of semantic memory access (which is presumably the stage the authors had in mind as showing the least slowing with age).

The first objection seems to be based on a misunderstanding. We do not know why a slower rate of icon scanning or transfer to short-term memory would necessarily lead to differences in short-term memory performance, unless the exposure duration was limited to prevent complete transfer of information in all age groups. Under these conditions (i.e., tachistoscopic presentations with poststimulus visual mask), there are large and consistent developmental differences in report accuracy (cf. Hoving, Spencer, Robb, & Schulte, 1977; Walsh & Prasse, 1980). Without such limited exposures, however, our version of the processing-rate hypothesis does not lead to any predictions about primary memory capacity, if that is defined in the customary fashion as the number of items that reside in the span of consciousness without active rehearsal. Structural capacity and rate of

information transfer are distinguishable characteristics of short-term memory that need not be related.

B. TOO FEW DATA

If the Hartley *et al.* (1980) comments are interpreted as concerns about the lack of relevant data and the vagueness of past speculations, they are quite valid and legitimate. The obvious solution to both problems, however, is more empirical data and greater precision in theoretical statements. We have attempted throughout this article to indicate the type of evidence that would be relevant to this hypothesis. However, until a number of reports addressing such issues become available, the processing-rate hypothesis must clearly be considered merely a possibility, and by no means definitely established or categorically rejected.

C. TOO COMPREHENSIVE

Another objection that could be legitimately raised against the current version of the processing-rate hypothesis is that it attempts to be too comprehensive in accounting for nearly all developmental changes in cognition. This is a fault to which we readily admit. In our discussions we have implicitly adhered to the proverb (which is probably old and claimed by many cultures): "One must open the mouth as wide as possible to find out how much one can bite and chew." Even if confirmed in certain respects, we realize it is highly unlikely that all developmental differences in memory and cognition can ultimately be attributed to a single mechanism such as a slower rate of processing. Nevertheless, the true limitations of the hypothesis will not be known until a wide range of potential applications is explored.

We have attempted to respond to several of the objections that have been, or could be, raised concerning the effects of rate of processing on memory performance, but it is clear that further progress requires more detailed specification of the nature and causes of the differences in speed of processing. We begin this next step of theoretical development in the following section.

VI. Possible Causes of Differences in Response Speed

In the following paragraphs we will use a computer metaphor to describe six factors that could be responsible for individual (including developmental) differences in speed of performance. The factors to be discussed

are: (1) "hardware" or structural differences between two hypothetical computer systems, (2) "software" differences, (3) differences in the internal representation of software, (4) differences in the number of tasks awaiting execution, (5) differences in the size of core or "working" memory, and (6) differences in the rate of input to, or output from, the central processor.

A. HARDWARE

To explain how hardware differences could lead to varying rates of performance we will consider two computer systems of different degrees of sophistication. System A is an older machine that has a slower cycle time per operation than system B, which is a modern, state-of-the-art machine. Let us also assume that the software of the two systems is identical, so the two computers will perform exactly the same operations when engaged in a given task but system A will be slower for each operation than system B. As an example, suppose that the minimum cycle time per operation is 15 msec in system A and only 10 msec in system B. (These times are arbitrary and, if anything, are more representative of human than of computer processing durations). If responding to a visual stimulus can be decomposed into the process of encoding (i.e., establishing an internal representation of) the visually presented stimulus, which requires 10 cycles, and the process of initiating and executing a response, which requires 8 cycles, the reaction time would require $18 \text{ cycles} \times 15 \text{ msec/cycle} = 270 \text{ msec}$ with system A, but only $18 \text{ cycles} \times 10 \text{ msec/cycle} = 180 \text{ msec}$ with system B. Further examples with progressively more complex tasks, including the basic memory task of recognizing a previously presented stimulus, are illustrated in Table I. Note that if the two systems always perform the task in the same manner—with the same sequence of processes—the time differences will be proportionally constant but increase in absolute amount with increases in task complexity.

We will not attempt to be specific about the exact mechanism that might be responsible for differences in cycle time, but it is assumed that a variety of anatomical or physiological conditions could be proposed to account for such a difference (e.g., degree of neural myelination or adequacy of cerebral blood flow).

B. SOFTWARE

A second possibility for producing differences in performance speed is the use of qualitatively different programs or sequences of processes in the two systems. Here we will assume that two hypothetical computer systems are physically identical (i.e., have the same "hardware") but system A employs procedures that are generally less efficient than those of system B. If

TABLE I
Varying Rates of Performance by Degrees of Sophistication^a

Task	Component operations				Total number of cycles	Total time	
	Encode (10 cycles)	Compare (4 cycles)	Decide (12 cycles)	Respond (8 cycles)		10 msec/cycle	15 msec/cycle
Simple reaction time	10	—	—	8	18	180	270
Choice reaction time	10	—	12	8	30	300	450
Recognition reaction time	10	4	12	8	34	340	510

^aReaction times are arbitrarily given in milliseconds.

the programs utilized by system A require more operations than those of system B, the total task time will be longer for system A. Under these conditions, one would expect no speed differences between the two systems only with tasks so simple that they do not allow for variation in performance strategy, or when other aspects of the situation justify the assumption that the same software is employed in both systems.

As an example, assume that system A attempts to recognize an item as previously presented by conducting an exhaustive search through all relevant stored information. That is, the search process would not stop when the target item had been located, but would continue throughout all remaining items in the list even though the relevant information for a decision might already be available. If the relevant store contains much information this would obviously be a very time-consuming process and could lead to lengthy response times. System B, in contrast, might employ a generally more efficient strategy of conducting a self-terminating search, in which the search process is ended as soon as the item is located in memory. By not continuing to search after a target has been located the response time in system B should be faster than that in system A.

C. INTERNAL REPRESENTATIONS

A third potential source of differences in processing speed involves the manner in which the software is represented in memory. Software (programs) for computers are frequently prepared in a high-level language like BASIC or FORTRAN, which, although relatively easy for the programmer

to produce and comprehend, are not in the optimal form for execution by the computer. Another step, either statement-by-statement interpretation in BASIC or entire-program compilation in FORTRAN, is necessary to convert the program to a format useful to the computer. If exactly the same procedures are represented in an optimal code for the computer in system B but in a high-level language in system A, then the time to execute the procedures will be faster in system B. This time difference may be reduced or eliminated if the procedures are used frequently (i.e., if the high-level code is compiled to a machine code), although substantial time differences would be expected in early attempts to execute the program.

Phenomena of interest to cognitive psychologists that might correspond to this distinction include: (1) retrieving the name of one's fifth-grade teacher when one is in fifth grade compared to retrieving the name 10 years later—the code in the former case is more likely to be in an optimal form because of recent frequent usage, and (2) verbal understanding of how to perform a physical activity such as swimming or riding a bicycle compared to actual proficiency in that activity—the former is less likely to be in an optimal code for actual execution than the latter.

D. SIZE OF WORKING MEMORY

A fourth possible source of performance speed differences might be capacity of working memory. If system A has only a limited space for handling computations or keeping track of the state of events as compared to system B, it will have to rely on more exchange of information to and from long-term memory (i.e., the mass storage device) than will system B. Because each of the swapping operations requires time, the total duration of most tasks will be longer in system A than in system B. However, if the capacity of working memory is the major mechanism responsible for rate differences, then there should be little or no speed differences with very simple tasks that can be completed with limited working memory, but progressively greater speed differences with more complicated tasks that require frequent swapping of information to and from long-term memory.

E. CONCURRENT PROCESSING DEMANDS

The fifth determinant of performance speed invokes what might be termed concurrent processing demands to explain the time differences in dependent measures from two computer systems. In this case we assume that the computers have the same hardware (i.e., minimum cycle times) and software (i.e., control procedures), but they differ in the number of jobs either awaiting execution or currently being executed. If system A has a

backlog of several jobs that must be performed before the new task can be executed, or if it is also handling other tasks concurrently such that the new task must be performed in a time-sharing manner, then the delay between the presentation and completion of the task will be much longer than in system B, which could be completely dedicated to the task at hand. Psychological variables that might be considered analogous to backlogging or time-sharing are distraction, inattention, or even motivational fluctuations that lead to less than 100% effort devoted to the main task.

F. INPUT/OUTPUT RATE

The sixth and final determinant of response speed to be considered here relies on differences in input and/or output rate between the two hypothetical systems to account for speed variations. If the rate of communicating information into or out of system A is slower than the comparable processes in system B, the response time for most tasks in system A will be slower than that for system B. For many cognitive psychologists such differences in sensory-perceptual or motor factors are relatively uninteresting because they do not accurately reflect true limits of the central processing system. However, there are techniques available for assessing whether this type of limitation is responsible for performance differences. For example, the input and output rate should be constant across tasks with progressively increasing demands on central processing capacity but invariant input and output requirements; thus one would expect a constant absolute difference between the speeds of the two systems. As noted above, several of the alternatives discussed earlier would predict different patterns (e.g., increasing absolute but proportionally constant differences, or no differences with simple tasks but progressively increasing differences with successively more complex tasks), and thus the validity of this type of mechanism could be easily assessed.

G. WHICH MECHANISM?

Although these alternative possibilities for the production of rate differences in performance have been presented as though they were mutually exclusive, it is more likely that they operate in a combined manner. For example, a slower operation time may preclude the effective utilization of certain strategies and thus result in a difference in the manner in which a task is performed. Also, because of the slower operation time less information could be processed in the same period of time, and thus the slower system would be faced with conditions of overload that do not exist for the faster system.

The problem of identifying which mechanism is primarily responsible for producing performance speed differences is obviously very complex and beyond the scope of this article. (See Birren, Woods, & Williams, 1980; Botwinick, 1965; Chi, 1977; Welford, 1977; and Wickens, 1974, for further discussions of the causes of age-related slowness.) It should be emphasized, however, that each of these mechanisms leads to a different version of the processing-rate hypothesis. The strongest version, implicit in the preceding sections of this article, is based on a hardware or cycle-time mechanism. Somewhat different predictions would be generated from the other mechanisms discussed above, but only if it is eventually discovered that input and/or output processes are primarily responsible for age differences in performance speed would the speed data not have relevance for other mental tasks. It is therefore desirable to begin explorations of the feasibility of the alternative mechanisms for producing speed differences outlined earlier. Only after the most likely mechanism is identified can more precise predictions be generated concerning the relationship between processing rate and memory performance.

VII. Conclusions

If considered as a working hypothesis for exploring developmental differences in memory, the processing-rate interpretation has two very desirable characteristics. First, by utilizing measures of speed of processing as the primary classification variable, it may allow individuals to be characterized in absolute (i.e., rate in actual time) as opposed to relative (i.e., norm-referenced) terms. This would prove particularly valuable in making comparisons across cultures and generations if the rate variable is ultimately discovered to be related to memory and cognitive functioning. Second, measurement of a major variable in real time rather than in arbitrary units such as memory span or memory accuracy may provide closer linkages with psychophysiological investigations of developmental phenomena. One property that characterizes most psychophysiological measures is time, and thus this might be used as a meaningful cross-methodology metric.

The existing evidence in favor of the processing-rate hypothesis is by no means compelling, but to our knowledge there is also not yet any strong counterevidence. Moreover, our analysis of potential causes for observed age differences in response speed indicates that it is likely that the mechanisms responsible for these differences could also contribute to a variety of memory and cognitive changes.

In sum, we suggest that there are a number of good reasons for considering the hypothesis that age differences in rate of processing may account

for many of the observed developmental differences in memory functioning. Perhaps in the not-too-distant future researchers attempting to account for individual differences in memory will have not two, but three general classes of explanation available: structure, strategy, and speed!

Acknowledgments

We would like to acknowledge the valuable suggestions of anonymous reviewers of an earlier version of this manuscript.

References

- Anders, T. R., & Fozard, J. L. Effects of age upon retrieval from primary and secondary memory. *Developmental Psychology*, 1973, 9, 411-416.
- Anders, T. R., Fozard, J. L., & Lillyquist, T. D. Effects of age upon retrieval from short-term memory. *Developmental Psychology*, 1972, 6, 214-217.
- Anderson, J. R. *Cognitive psychology and its implications*. San Francisco, Calif.: Freeman, 1980.
- Arenberg, D. A., & Robertson-Tchabo, E. A. Learning and aging. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging*. New York: Van Nostrand, 1977.
- Baddeley, A. D., Thomson, N., & Buchanan, M. Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, 1975, 14, 575-589.
- Bellis, C. J. Reaction time and chronological age. *Proceedings of the Society for Experimental Biology and Medicine*, 1933, 30, 801-803.
- Birren, J. E., Riegel, K. F., & Morrison, D. F. Age differences in response speed as a function of controlled variations of stimulus conditions: Evidence of a general speed factor. *Gerontologia*, 1962, 6, 1-18.
- Birren, J. E., Woods, A. M., & Williams, M. V. Behavioral slowing with age: Causes, organization and consequences. In L. W. Poon (Ed.), *Aging in the 1980's: Psychological issues*. Washington, D.C.: American Psychological Association, 1980.
- Bisanz, J., Danner, F., & Resnick, L. B. Changes with age in measures of processing efficiency. *Child Development*, 1979, 50, 132-141.
- Botwinick, J. Theories of antecedent conditions of speed of response. In A. T. Welford & J. E. Birren (Eds.), *Behavior, aging and the nervous system*. Springfield, Ill.: Thomas, 1965.
- Chase, W. G. Does memory scanning involve implicit speech? In S. Dornic (Ed.), *Attention and performance VI*. Hillsdale, N.J.: Erlbaum, 1977.
- Chi, M. T. H. Age differences in the speed of processing: A critique. *Developmental Psychology*, 1977, 13, 543-544.
- Clifton, C., & Tash, J. Effect of syllabic word length on memory-search rate. *Journal of Experimental Psychology*, 1973, 99, 231-235.
- Collins, A. M., & Loftus, E. F. A spreading-activation theory of semantic processing. *Psychological Review*, 1975, 82, 407-428.
- Craik, F. I. M. Age differences in human memory. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging*. New York: Van Nostrand, 1977.

- Dempster, F. N. Memory span: Sources of individual and developmental differences. *Psychological Bulletin*, 1981, **89**, 63-100.
- Dugas, J., & Kellas, G. Encoding and retrieval processes in normal children and retarded adolescents. *Journal of Experimental Child Psychology*, 1974, **17**, 177-185.
- Duncan, E. M., & Kellas, G. Developmental changes in the internal structure of semantic categories. *Journal of Experimental Child Psychology*, 1978, **26**, 328-340.
- Eriksen, C. W., Hamlin, R. M., & Daye, C. Aging adults and rate of memory scan. *Bulletin of the Psychonomic Society*, 1973, **1**, 259-260.
- Eysenck, M. W. Retrieval from semantic memory as a function of age. *Journal of Gerontology*, 1975, **30**, 174-180.
- Ford, J. M., Roth, W. T., Mohs, R. C., Hopkins, W. F., & Kopell, B. S. Event-related potentials recorded from young and old adults during a memory retrieval task. *Electroencephalography and Clinical Neurophysiology*, 1979, **47**, 450-459.
- Harris, G. J., & Fleer, R. E. High speed memory scanning in mental retardates: Evidence for a central processing deficit. *Journal of Experimental Child Psychology*, 1974, **17**, 452-459.
- Hartley, J. T., Harker, J. O., & Walsh, D. A. Contemporary issues and new directions in adult development of learning and memory. In L. W. Poon (Ed.), *Aging in the 1980's: Psychological issues*. Washington, D.C.: American Psychological Association, 1980.
- Herrmann, D. J., & Landis, T. Y. Differences in the search rate of children and adults in short-term memory. *Journal of Experimental Child Psychology*, 1977, **23**, 151-161.
- Hess, T. M., & Radtke, R. C. Processing and memory factors in children's reading comprehension skill. *Child Development*, 1981, **52**, 479-488.
- Hodgkins, J. Influence of age on speed of reaction and movement in females. *Journal of Gerontology*, 1962, **17**, 385-389.
- Hodgkins, J. Reaction time and speed of movement in males and females of various ages. *Research Quarterly*, 1963, **34**, 335-343.
- Hoving, K. L., Spencer, T., Robb, K. Y., & Schulte, D. Developmental changes in visual information processing. In P. A. Ornstein (Ed.), *Memory development in children*. Hillsdale, N.J.: Erlbaum, 1977.
- Jackson, M. D., & McClelland, J. L. Processing determinants of reading speed. *Journal of Experimental Psychology: General*, 1979, **108**, 151-181.
- Jensen, A. R. *Bias in mental testing*. New York: The Free Press, 1980.
- Kail, R., & Bisanz, J. Cognitive development: An information-processing perspective. In R. Vasta (Ed.), *Strategies and techniques of child study*. New York: Academic Press, 1982. (a)
- Kail, R., & Bisanz, J. Cognitive strategies. In C. R. Puff (Ed.), *Handbook of research methods in human memory and cognition*. New York: Academic Press, 1982. (b)
- Keating, D. P., & Bobbitt, B. L. Individual and developmental differences in cognitive-processing components of mental ability. *Child Development*, 1978, **49**, 155-167.
- Keating, D. P., Keniston, A. H., Mais, F. R., & Bobbitt, B. L. Development of the search-processing parameter. *Child Development*, 1980, **51**, 34-44.
- Kelley, M. P. Memory abilities: A factor analysis. *Psychometric Society Monographs*, 1964, No. 11.
- Lansman, M. Ability factors and the speed of information processing. In M. P. Friedman, J. P. Das, & N. O'Connor (Eds.), *Intelligence and learning*. New York: Plenum, 1981.
- Lemmon, V. W. The relation of reaction time to measures of intelligence, memory, and learning. *Archives of Psychology*, 1927, **15**, 5-38.
- Lunneborg, C. E. Choice reaction time: What role in ability measurement? *Applied Psychological Measurement*, 1977, **1**, 309-330.

- Mackworth, J. The relation between the visual image and post-perceptual immediate memory. *Journal of Verbal Learning and Verbal Behavior*, 1963, 2, 75-85.
- Madden, D. J., & Nebes, R. D. Aging and the development of automaticity in visual search. *Developmental Psychology*, 1980, 16, 377-384.
- Marsh, G. R. Age differences in evoked potential correlates of a memory scanning process. *Experimental Aging Research*, 1975, 1, 3-16.
- McCauley, C., Kellas, G., Dugas, J., & DeVillis, R. F. Effects of rehearsal training on memory search. *Journal of Educational Psychology*, 1976, 68, 474-481.
- McFarland, R. A. An experimental study of the relationship between speed and mental ability. *Journal of General Psychology*, 1930, 3, 67-97.
- Miles, W. R. Measures of certain human abilities throughout the life span. *Proceedings of the National Academy of Science*, 1931, 17, 627-633.
- Naus, M. J., & Ornstein, P. A. Developmental differences in the memory search of categorized lists. *Developmental Psychology*, 1977, 13, 60-68.
- Nebes, R. D. Verbal-pictorial recoding in the elderly. *Journal of Gerontology*, 1976, 31, 421-427.
- Nebes, R. D. Vocal versus manual response as a determinant of age difference in simple reaction time. *Journal of Gerontology*, 1978, 33, 884-889.
- Nebes, R. D., & Andrews-Kulis, M. E. The effect of age on the speed of sentence formation and incidental learning. *Experimental Aging Research*, 1976, 2, 315-322.
- Nicolson, R. The relationship between memory span and processing speed. In M. P. Friedman, J. P. Das, & N. O'Connor (Eds.), *Intelligence and learning*. New York: Plenum, 1981.
- Pachella, R. G. The interpretation of reaction time in information-processing research. In B. H. Kantowitz (Ed.), *Human information processing: Tutorials in performance and cognition*. Hillsdale, N.J.: Erlbaum, 1974.
- Pierson, W. R., & Montoye, H. J. Movement time, reaction time, and age. *Journal of Gerontology*, 1958, 13, 418-421.
- Poon, L. W., & Fozard, J. L. Speed of retrieval from long-term memory in relation to age, familiarity, and datedness of information. *Journal of Gerontology*, 1978, 33, 711-717.
- Poon, L. W., & Fozard, J. L. Age and word frequency effects in continuous recognition memory. *Journal of Gerontology*, 1980, 35, 77-86.
- Posner, M. I., & Mitchell, R. F. Chronometric analysis of classification. *Psychological Review*, 1967, 74, 392-409.
- Reitsma, P. Changes in letter processing in beginning readers. *Journal of Experimental Child Psychology*, 1978, 25, 315-325.
- Riegel, K. F. A study of verbal achievements of older persons. *Journal of Gerontology*, 1959, 14, 453-456.
- Salthouse, T. A. Age and memory: Strategies for localizing the loss. In L. W. Poon, J. L. Fozard, L. S. Cermak, D. Arenberg, & L. W. Thompson (Eds.), *New directions in memory and aging*. Hillsdale, N.J.: Erlbaum, 1980.
- Salthouse, T. A. Converging evidence for processing stages: A comparative-influence stage analysis technique. *Acta Psychologica*, 1981, 47, 39-61.
- Salthouse, T. A., & Prill, K. *Age and processing rate as determinants of mnemonic organization*. Unpublished manuscript, Department of Psychology, University of Missouri, Columbia, 1980.
- Salthouse, T. A., & Somberg, B. L. Isolating the age deficit in speeded performance. *Journal of Gerontology*, 1982, 37, 59-63. (a)
- Salthouse, T. A., & Somberg, B. L. Skilled performance: The effects of adult age and experience on elementary processes. *Journal of Experimental Psychology: General*, 1982, 111, 176-207. (b)

- Sanders, R. E., Murphy, M. D., Schmitt, F. A., & Walsh, K. K. Age differences in free rehearsal strategies. *Journal of Gerontology*, 1980, **35**, 550-558.
- Schaie, K. W. Rigidity-flexibility and intelligence: A cross-sectional study of the adult life span from 20 to 70. *Psychological Monographs*, 1958, **72** (462, Whole No. 9).
- Schaie, K. W., Rosenthal, F., & Perlman, R. M. Differential mental deterioration of factorially "pure" functions in later maturity. *Journal of Gerontology*, 1953, **8**, 191-196.
- Schaie, K. W., & Strother, C. R. A cross-sequential study of age changes in cognitive behavior. *Psychological Bulletin*, 1968, **70**, 671-680.
- Simon, E. Depth and elaboration of processing in relation to age. *Journal of Experimental Psychology: Human Learning and Memory*, 1979, **5**, 115-124.
- Standing, L., Bond, B., Smith, P., & Isley, C. Is the immediate memory span determined by subvocalization rate? *British Journal of Psychology*, 1980, **71**, 525-539.
- Stern, J. A., Oster, P. J., & Newport, K. Reaction time measures, hemispheric specialization, and age. In L. W. Poon (Ed.), *Aging in the 1980's: Psychological issues*. Washington, D.C.: American Psychological Association, 1980.
- Sternberg, S. High speed scanning in memory. *Science*, 1966, **153**, 652-654.
- Sternberg, S. Memory scanning: Mental processes revealed by reaction time experiments. *American Scientist*, 1969, **57**, 421-457.
- Sternberg, S. Memory scanning: New findings and current controversies. *Quarterly Journal of Experimental Psychology*, 1975, **27**, 1-32.
- Thomas, J. C., Fozard, J. L., & Waugh, N. C. Age-related differences in naming latency. *American Journal of Psychology*, 1977, **90**, 499-509.
- Walsh, D. A., & Prasse, M. J. Iconic memory and attentional processes in the aged. In L. W. Poon, J. L. Fozard, L. S. Cermak, D. Arenberg, & L. W. Thompson (Eds.), *New directions in memory and aging*. Hillsdale, N.J.: Erlbaum, 1980.
- Watkins, M. J., & Watkins, O. C. The postcategorical status of the modality effect in serial recall. *Journal of Experimental Psychology*, 1973, **99**, 226-230.
- Waugh, N. C., Thomas, J. C., & Fozard, J. L. Retrieval time from different memory stores. *Journal of Gerontology*, 1978, **33**, 718-724.
- Welford, A. T. Motor performance. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging*. New York: Academic Press, 1977.
- Wickelgren, W. A. Speed-accuracy tradeoff and information processing dynamics. *Acta Psychologica*, 1977, **41**, 67-85.
- Wickens, C. D. Temporal limits of human information processing: A developmental study. *Psychological Bulletin*, 1974, **81**, 739-755.
- Wissler, C. The correlation of mental and physical tests. *Psychological Review Monograph Supplements*, 1901, **3** (6, Whole No. 16).