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The Aging of Working Memory

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Research concerned with relations between adult age and working memory is reviewed, especially that relevant to the A. D. Baddeley (1986, 1992; Baddeley & G. Hitch, 1974) model of working memory. The evidence suggests that although increased age is associated with lower scores on measures of working memory functioning, many of the age-related influences appear to be mediated by a slower speed of processing. Furthermore, recent studies indicate that slower processing primarily influences the time required to achieve a stable encoding of the information rather than the rate at which information is lost across time or subsequent processing.

The currently accepted definition of working memory is that, in contrast to earlier notions of short-term or primary memory, working memory involves both storage and processing. One of the most influential models of working memory is that proposed by Baddeley (1986, 1992; Baddeley & Hitch, 1974). His model consists of three distinct components: a central executive responsible for coordination and monitoring of activities, particularly those performed simultaneously, and two peripheral slave systems postulated to preserve information over short intervals. The articulatory or phonological loop slave system is assumed to maintain verbal information, and the visuospatial sketchpad slave system is assumed to store spatial information.

The purpose of this article is to summarize research from my laboratory relevant to Baddeley's, and other, conceptualizations of working memory. Because most of my research has been concerned with relations between adult age and various measures of cognitive functioning, the discussion will focus on the influence of aging on working memory.

There are three major sections to this article. The first section reports the results of research investigating age-related influences on the components of Baddeley's working memory model, including the storage capacities for both verbal and spatial information and the functioning of the central executive. The second section discusses research on tasks specifically designed to assess working memory by requiring simultaneous storage and processing and on attempts to decompose the "source" or "locus" of age-related differences in working memory. Because the componential research has indicated that processing speed is an important factor in working memory, and particularly in age-related influences on working memory, the final section of the article summarizes research related to the mechanism by which speed affects working memory.

Research participants in the projects to be described were primarily convenience samples recruited from the community through newspaper advertisements, churches, and other organizations, although in some studies young adults were recruited from college classrooms. The participants ranged from 18 to older than 80 years of age, and nearly all had 12 or more years of education, with averages of between 14 and 16. Because most of the participants reported themselves to be in good to excellent health, the results to be described can be viewed as reflecting age-related effects on relatively healthy, normal, individuals.

Research Relevant to the Baddeley Model

Although not deliberately designed to investigate Baddeley's model, several studies in my laboratory are relevant to various aspects of his model. For example, a project in collaboration with Donald Kausler and Scott Saults (Salthouse, Kausler, & Saults, 1988) provided information relevant to age differences in the storage capacities of the verbal and spatial slave systems. Most tasks designed to measure verbal and spatial memory involve a confounding of type of stimuli with type of remembering. The matrix memory tasks used in the Salthouse et al. (1988) project were selected to avoid this problem by using the same stimuli in both tasks.

The stimuli in these tasks were seven target items in a 5-by-5 matrix of 25 letters that was displayed for 3 s (see Figure 1A for an illustration). In the verbal version of the task the subject was to remember the identities of the targets, and in the spatial version he or she was to remember their positions. Notice that the stimulus is exactly the same in the two tasks, but there is a difference in what must be remembered. In the verbal task the subjects were to recall the seven target letters in any order, and in the spatial task they were to recall the seven target positions regardless of the identities of the letters in those positions. Figure 1B illustrates the response displays in each task.

A total of 362 adults between 20 and 79 years of age performed eight trials in each of these tasks. Although this is a relatively small number of trials, the estimated reliabilities of the number of correct scores were adequate, with values of .77 for the verbal measure and .67 for the spatial measure.

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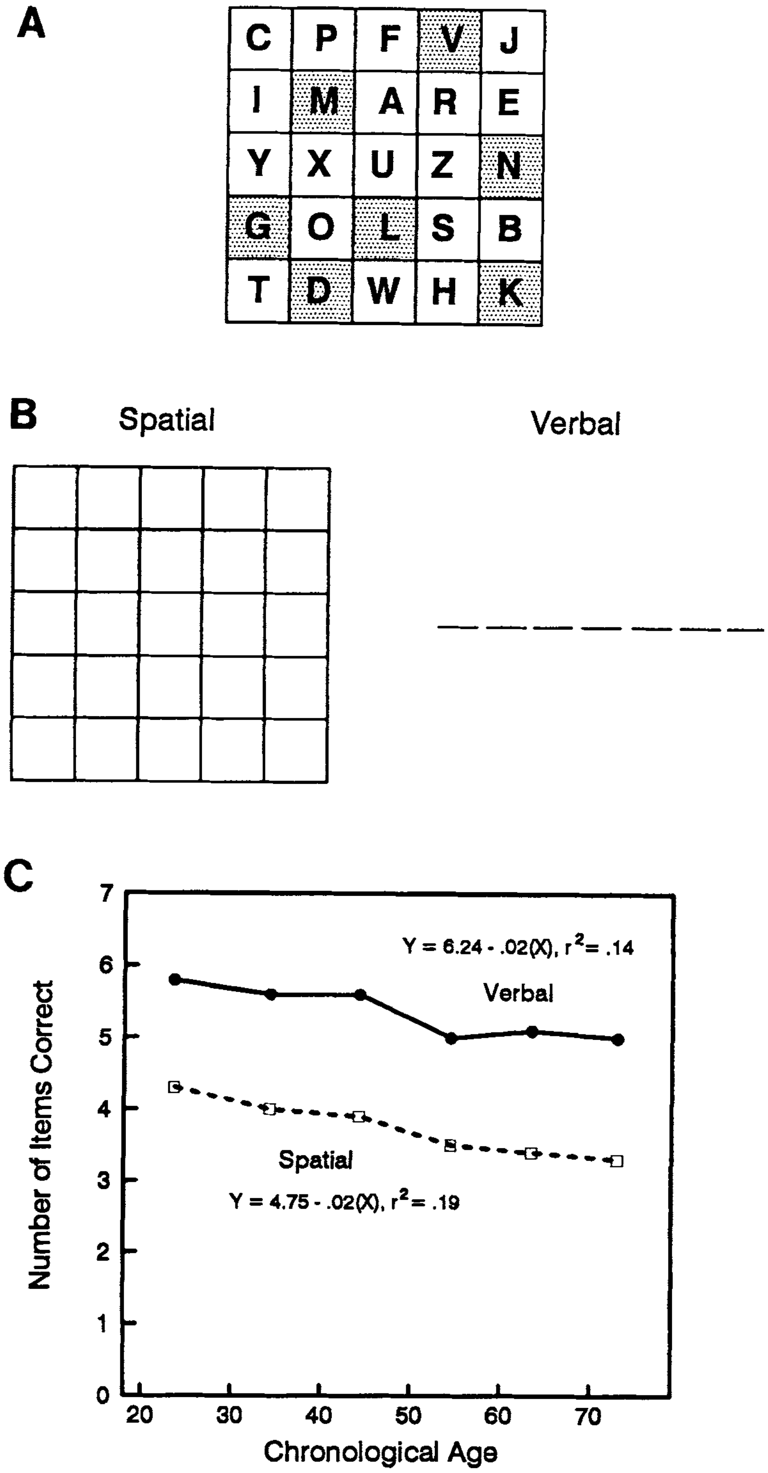

Figure 1. Illustration of stimulus displays (A), response displays (B), and age relations for 362 adults (C) in the matrix memory tasks used by Salthouse, Kausler, and Saults (1988).

Average performance at each age decade in the two tasks is portrayed in Figure 1C. It is apparent that there were substantial, *and very similar*, age-related declines in each measure. In fact, the regression equations reveal that there was a decrease of 0.20 items per decade in both the verbal memory measure and in the spatial memory measure. Roughly comparable age-related effects therefore seem to be evident in the short-term storage capacity of both verbal and spatial information.

In light of the similar age trends in the verbal and spatial memory measures, it is interesting to consider the relation between them. The magnitude of the relation between two measures is typically evaluated in terms of the proportion of variance in each measure that is shared with the other measure. However, it is possible to compute the shared proportion relative to the total variance in the measures or relative to only the age-related variance. The proportion of total variance that is shared corresponds to the square of the traditional correlation coefficient, but the square of the proportion of shared age-related variance in each measure yields what has been termed a quasi-partial correlation coefficient (Salthouse, in press-b). The correlation between the verbal and spatial matrix memory measures in this project was only .36, but the quasi-partial correlation was .71. These values therefore indicate that although the two measures had only about 13% (i.e., $.36^2$) of their total variance in common, they shared 50% (i.e., $.71^2$) of their age-related variance. The considerably larger proportion of shared age-related variance than of shared total variance suggests that the age-related effects on the verbal and spatial measures are not independent. A possible implication of this lack of independence is that models such as Baddeley's may have to be modified to incorporate a common age-related influence that contributes to the age differences in the two types of span measures.

As Baddeley (e.g., 1986, 1992) has acknowledged, it has been difficult to evaluate functioning of the central executive in his model. Because a principal function of the central executive is the monitoring and coordination of concurrent activities, one possible means by which it could be investigated involves examining the ability to perform two tasks simultaneously. However, to investigate the ability to monitor and coordinate two simultaneous tasks, it is important to take into account the subject's ability to perform each task in isolation. Furthermore, because subjects can alter their emphasis across the two tasks, such that for some subjects a dual-task decrement may be manifested in performance variations on one task and for other subjects it may be manifested in performance variations on the other task, it is desirable to use a dependent variable that integrates performance across both tasks.

One project incorporating these considerations involved a comparison of young and old adults in the ability to perform concurrent letter span and digit span tasks (Salthouse, Rogan, & Prill, 1984). Each subject's span for letters and for digits was determined, and then 75% of his or her span length was presented when the tasks were performed concurrently. In addition, subjects were instructed to systematically vary their emphasis on the two tasks to allow the generation of attention-operating characteristics in which performance on each task is portrayed as a function of performance on the other task. A measure based on the area under the attention-operating characteristic curve then served as the measure of dual-task performance.

The major finding across three independent studies in the Salthouse et al. (1984) project was that older adults were less effective than young adults at concurrent task performance. That is, compared to young adults, older adults suffered a greater decrement relative to their single-task performance when two tasks had to be performed simultaneously. These results imply that there is an age-related decline in central executive functioning. This conclusion must be considered tentative, however, because other studies involving concurrent tasks have found no significant differences between young and old adults (e.g., Baddeley, Logie, Bressi, Della Sala, & Spinnler, 1986).

The results described above suggest that increased age is associated with decreased levels of effectiveness in each of the three components of the Baddeley working memory model. Although one can question whether the measures used in these studies are the best reflections of the hypothesized components, doubts are nonetheless raised with respect to whether the Baddeley model provides the best analytical framework for understanding the source of adult age differences in working memory. That is, to the extent that significant age differences exist in each of the hypothesized components, this framework may not be very useful for differentiating, and potentially localizing the source of, age-related effects in working memory.

Research on Tasks Designed to Measure Working Memory

Another line of research in my laboratory has focused on tasks designed to measure working memory by including both a storage requirement and a processing requirement. One task is based on the Daneman and Carpenter (1980) reading span task, which requires the subject to answer questions about sentences while also remembering the last word in each sentence. Another task, the computation span, requires the subject to answer arithmetic problems while simultaneously remembering the last digit in each problem. Figure 2 illustrates the sequence of successive displays in computer-administered versions of each of these tasks. (See Salthouse & Babcock, 1991, for an illustration of the sequence of events in paper-and-pencil versions of the tasks.)

Performance in these tasks is typically represented in terms of the subject's span, which is defined as the largest sequence of sentences or arithmetic problems in which the subject was correct on both processing (answering questions or arithmetic) and storage (remembering the sequence of items) on at least two of the three trials for a given sequence length. The reliability of the span measures with paper-and-pencil administrations has been estimated to be above .84 for both tasks (Salthouse & Babcock, 1991).

Paper-and-pencil versions of these tasks have been used in five different studies, each involving 200 or more adults between the ages of 18 and 80 (i.e., Studies 1 and 2 in Salthouse & Babcock, 1991; Studies 1, 2, and 3 in Salthouse, 1991). The distribution of working memory scores in the combined sample of 1,132 adults, with between 163 and 231 individuals in each decade, is illustrated in Figure 3.

Regression analyses indicated that age was associated with 18.2% of the computation span variance and 21.6% of

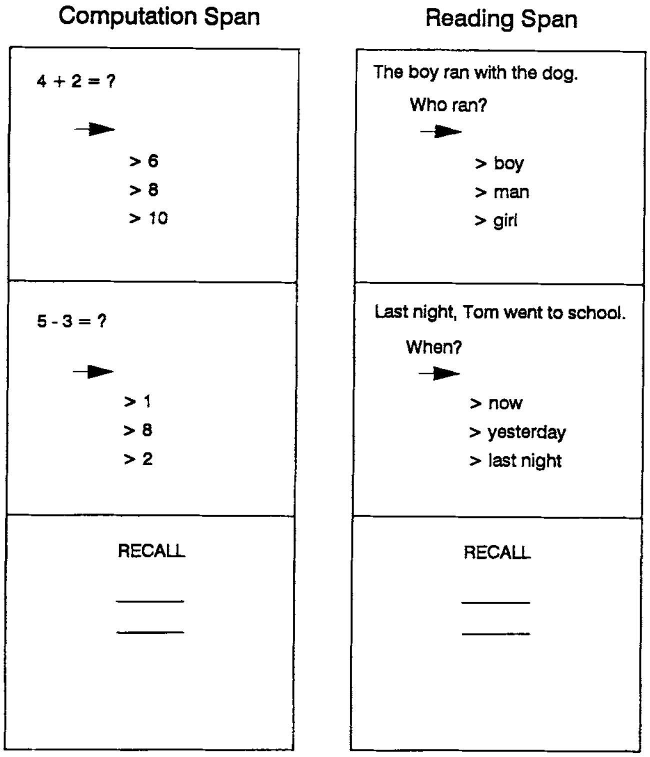

Figure 2. Examples of successive displays in the computer-administered versions of the computation span and reading span tasks.

the reading span variance, with a decrease of 0.40 span units per decade in both tasks. The correlation between the computation span and reading span measures was .61, but the quasi-partial correlation, indicating the relation among only the age-related portion of the variance, was .90. Therefore, although only 37.2% (i.e., $.61^2$) of the total variance in each measure was shared with the other measure, 81% (i.e., $.90^2$) of the age-related variance in each measure overlapped with that of the other measure. As in the case of the verbal and spatial memory measures, this pattern suggests that a common factor contributed to the age-related effects in the two working memory measures.

In some of the same studies in which these working memory measures were obtained, the subjects were also administered a variety of other cognitive tasks such as the Raven's Progressive Matrices (Raven, 1962) and miscellaneous tests of reasoning and spatial visualization (e.g., Salthouse, 1991; see also Salthouse, 1992c, 1993). In each of these studies, correlations between the working memory measures and the cognitive measures were in the moderate range, indicating that individuals with high working memory scores also tended to perform well on the cognitive tests. The results of these studies also indicated that working memory was important in the age differences in the cognitive tasks because the amount of age-related variance in the cognitive measures was greatly reduced when working memory was held constant with statistical methods.

On the basis of this information it can be inferred that the measures from these working memory tasks are reliable, age sensitive, and valid in the sense that they are correlated with measures of cognitive performance. The next goal in this line of research was to attempt to determine the relative importance of different hypothesized components of working memory (Salthouse & Babcock, 1991). The conceptualization guiding these investigations was not the Baddeley model of working memory, but instead was based on an intuitive or rational analysis (Salthouse,

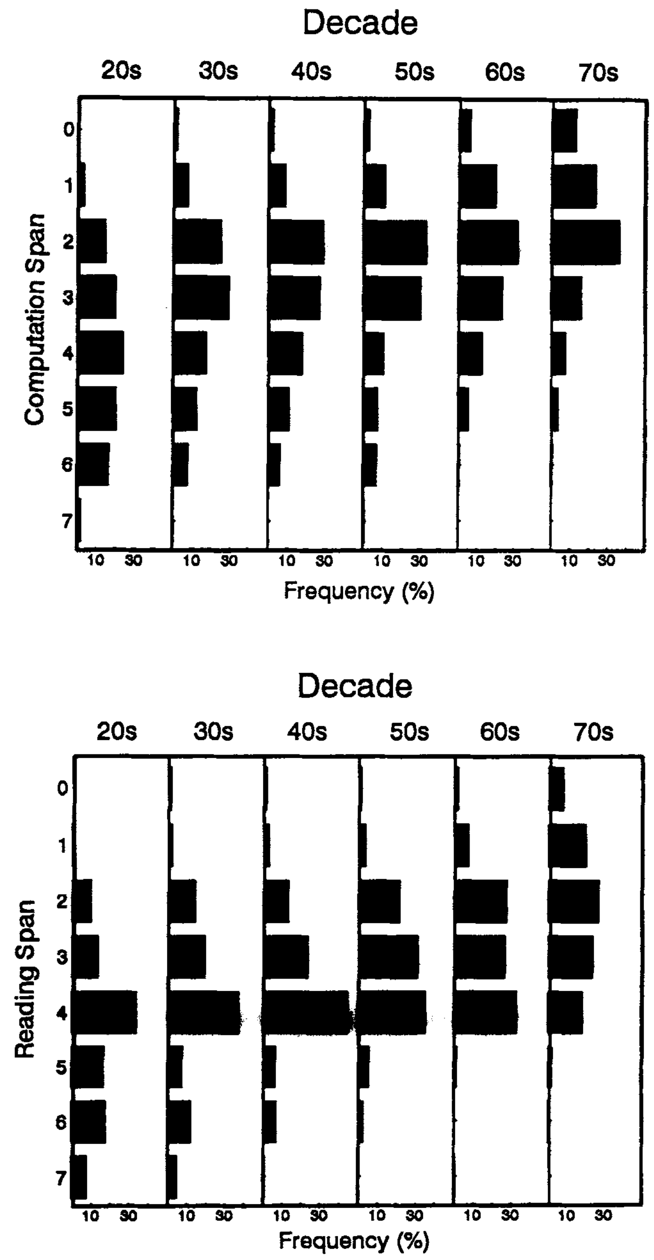

Figure 3. Distribution by decade of computation span and reading span scores from paper-and-pencil versions of the tasks, n = 1,132.

1990) that involved the following three components: (a) storage capacity, reflecting the ability to preserve relevant information; (b) processing efficiency, representing the ability to perform required processing operations rapidly; and (c) coordination effectiveness, corresponding to the ability to monitor and coordinate simultaneous activities (such as maintaining stored products while also executing appropriate processing).

Two measures of each of these hypothesized components were derived from versions of the reading span and computation span working memory tasks. For the storage component the measures were simple word span and digit span in which little or no concurrent processing was presumably required. Quickness of answering questions about sentences and of performing arithmetic of the type required in the working memory tasks were used as the measures of processing efficiency. Coordination effectiveness was assessed by the speed and accuracy of answering the sentence comprehension questions or of solving arithmetic problems when they were performed concurrently, with the materials for one task presented auditorily and those for the other task presented visually.

The age correlations in each measure were all negative, with a range from −.34 to −.66, but the correlations between measures postulated to represent the same component were all positive, with a range from .57 to .77. To increase generalizability, composite scores were created for working memory and for the three hypothesized components by converting all of the measures to *z* scores and then averaging the relevant *z* scores across the two task versions.

Two types of analyses were conducted on the composite scores. In one analysis, working memory was predicted from the hypothesized components when each was considered alone and also when they were in combination. The goal of these procedures was to determine how much of the total variance in working memory could be accounted for by the component measures.

Results of this analysis, in terms of the proportions of variance in the composite working memory measure accounted for by the components, are illustrated in Figure 4A. It can be seen that all of the components in combination account for about 60% of the working memory variance. However, it is noteworthy that more than 50% of the variance in the composite working memory score can be accounted for by only the processing efficiency component. This pattern suggests that although all of the components are involved in working memory, processing efficiency may be a particularly important component because it is associated with the largest percentage of variance.

The goal of the second analysis was to determine the relative contribution of each hypothesized component to the age differences in working memory. Hierarchical multiple regression analyses were used to assess the amount of age-related variance in the composite working memory measure both before and after control of the component measures. These procedures provide an estimate of the importance of a component in contributing to the age differences in working memory by the extent to which the age-related variance in working memory is reduced when that component is controlled. Figure 4B summarizes the results of these analyses.

Examination of the results in Figure 4B reveals that the greatest attenuation of the age-related variance in working memory occurred after control of the processing efficiency component, either alone or in combination with other components. It therefore seems reasonable to infer that the efficiency or speed of relevant processing is a major factor contributing to age-related, as well to other, individual differences in working memory.

Research on the Role of Speed in Working Memory

Another line of research in my laboratory concerned with working memory has focused on the role of processing speed on the age differences in working memory. These studies were motivated in large part by the discovery in the Salthouse and Babcock (1991) study that processing efficiency appeared to be a major factor contributing to the age differences in working memory. One purpose of these studies was to examine the influence of even simpler measures of processing speed on the relations between age and working memory.

In the studies in which the working memory tasks were administered with paper-and-pencil procedures, the tasks used to assess processing speed also involved paper-and-pencil procedures. Two tasks included in several projects required same/different judgments about the physical identity of pairs of letter strings (letter comparison task) or pairs of line patterns (pattern comparison task). Performance in each task was represented by the number of items completed within a fixed period of time.

In studies involving computer-administered working memory tasks, processing speed was also assessed with computer-administered tasks. The two tasks used most frequently were based on the Wechsler Adult Intelligence Scale—Revised Digit Symbol Substitution Test (Salthouse, 1992b). The digit symbol task required same/different judgments based on the associational equivalence of a digit–symbol pair, and the digit digit task required same/different judgments based on the physical identity of a digit–digit pair. In both cases, the measure of performance was the median choice reaction time across 90 trials.

Figure 5 portrays the proportion of age-related variance in the composite measure of working memory when age was the only predictor, and the increments in variance associated with age when age was entered in the regression equation after the variance in the composite measure of speed had been controlled. It is apparent that the results were similar in every study in that the age-related variance in the measure of working memory was greatly attenuated after control of the measure of speed. The fact that this same pattern has been obtained across different samples and different methods of assessing the working memory and speed constructs strongly suggests that processing speed plays an important role in the adult age differences in working memory.

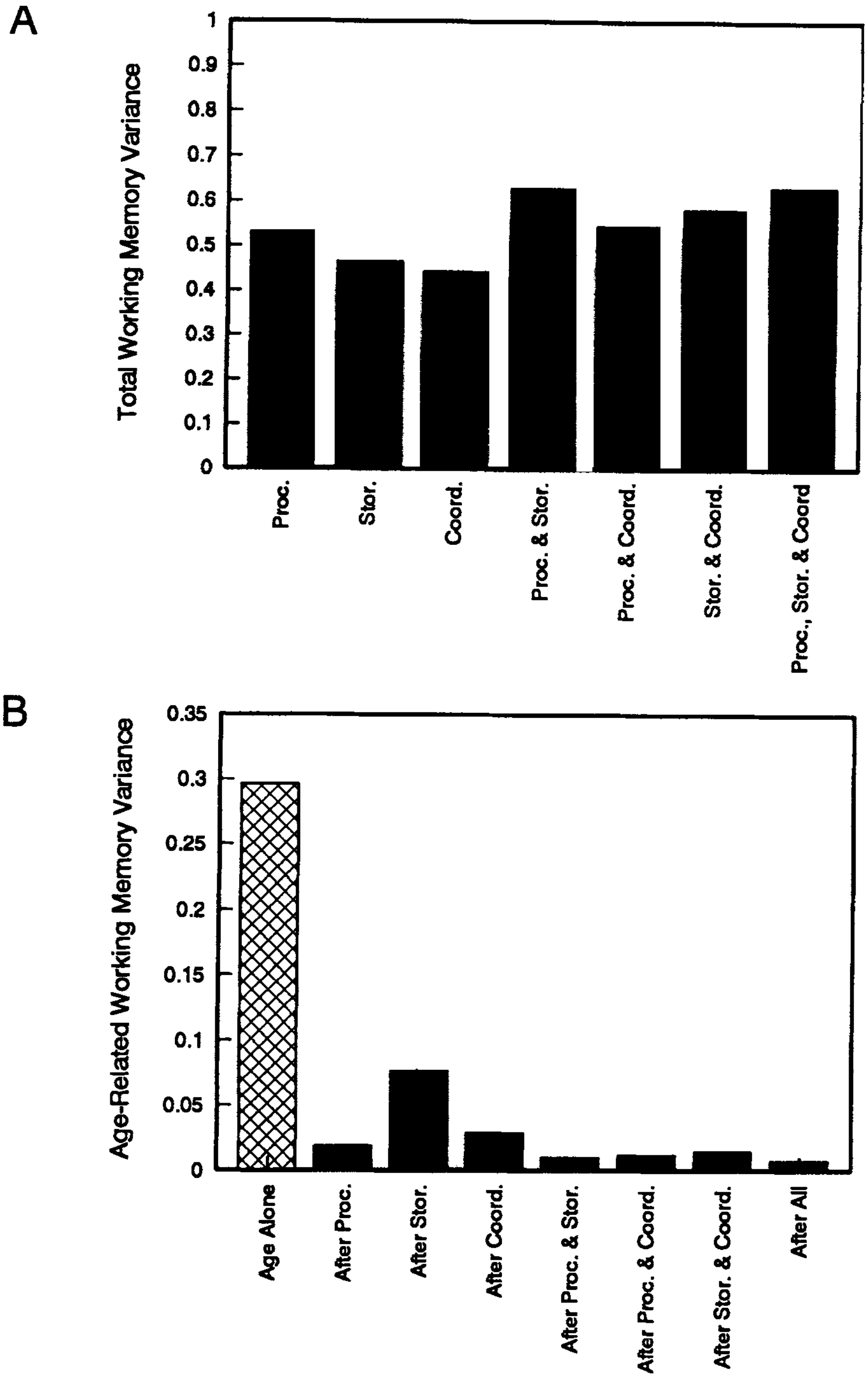

Figure 4. Proportions of variance derived from hierarchical regression analyses of the data ($n = 227$) from Study 1 in Salthouse and Babcock (1991). (A) Proportions of the total variance in the composite working memory index, and (B) proportions of the age-related variance in the composite working memory index. Proc. = processing efficiency; Stor. = storage capacity; Coord. = coordination effectiveness.

Research has also been conducted to investigate the means by which slower processing speed contributes to age differences in working memory. Two possible mechanisms for the influence of speed on working memory were discussed by Salthouse and Babcock (1991). These were that increased age might be associated with a more rapid loss of information or with a slower encoding or activation of information. In either case, the amount of simultaneously

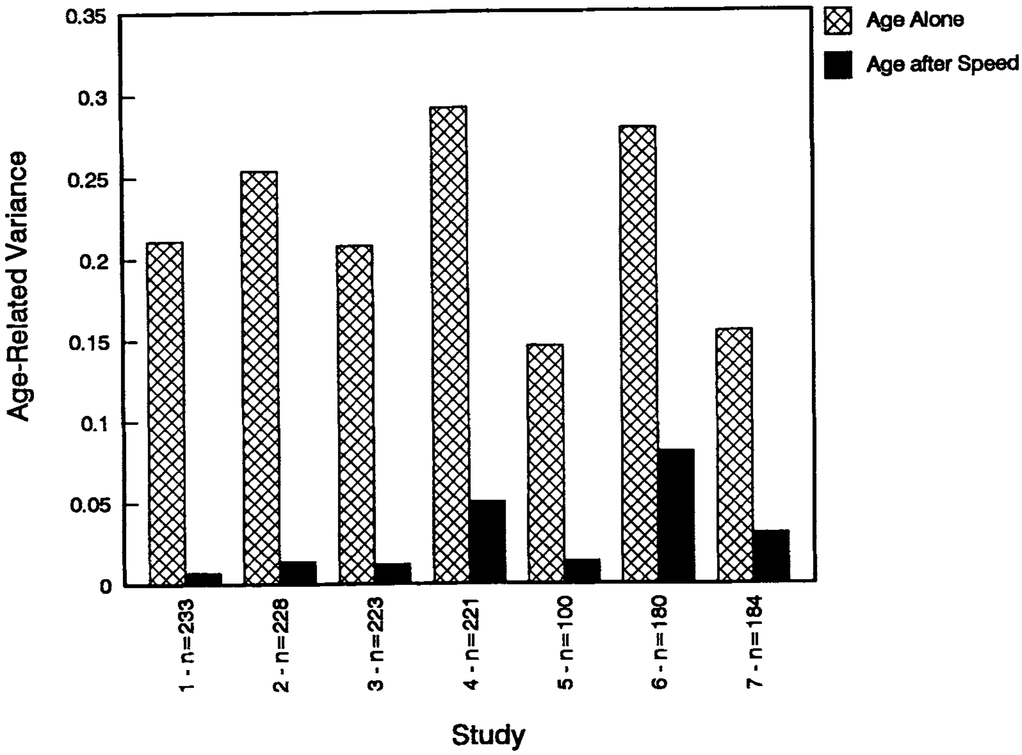

Figure 5. Proportions of age-related variance in composite measures of working memory before and after control of a composite measure of processing speed. The first four sets of bars represent results from studies with paper-and-pencil procedures, and the last three sets of bars represent results from studies with computer-administered procedures. The studies were as follows: 1, Study 2 from Salthouse and Babcock (1991); 2–4, Studies 1, 2, and 3 from Salthouse (1991); 5–6, Studies 1 and 2 from Salthouse (1992a); and 7, combined data from Salthouse and Kersten (1993) and Study 2 of Salthouse and Coon (in press).

active information, which can be considered equivalent to working memory capacity, would be smaller among older adults than among young adults. However, the mechanism would be quite different if the age differences originate because information is lost at a faster rate, or because it takes longer to activate the relevant information.

A study by Salthouse (1992a) was designed to attempt to investigate these two possibilities. Of principal interest in this study was a keeping track task in which the subject attempted to monitor the current values of a set of variables that had to be transformed by designated addition or subtraction operations. At some point during a trial the subject is asked to report the current value of one of the variables. Because the status of variables has to be continuously updated while also maintaining the values of other variables, this task can be considered to involve working memory.

An estimate of the speed of performing arithmetic operations of the type used in the keeping track task was obtained from a duration threshold procedure. That is, the presentation duration of displays containing arithmetic operations (e.g., +2, −4) was varied according to psychophysical procedures to determine the minimum time needed to perform elementary arithmetic successfully. Although not directly reflecting the time required to encode or activate information, it was assumed that this measure was at least moderately correlated with activation speed because it represented the speed of task-relevant operations. To keep the other processing demands in the task similar for all subjects, the presentation duration in the keeping track working memory task was set at twice the subject's duration threshold. A measure of the rate of loss of information was then derived from the function relating decision accuracy to the number of subtraction or addition operations between the initial presentation of the variable and its subsequent test.

The major result from the Salthouse (1992a) study was that there was a significant positive relation between age and the duration threshold measure (i.e., $r = .45$) but no significant relation between age and the information loss measure (i.e., $r = -.17$). In fact, the negative correlation suggests that, if anything, increased age was associated with smaller losses of information over time. It was therefore concluded that "the processes responsible for the relations among age, speed, and working memory seem to involve the speed at which relevant information can be activated, and not the rate at which information decays or is displaced" (Salthouse, 1992a, p. 168).

In two recent studies, a continuous paired-associates task was used to investigate the distinction between speed of encoding and rate of information loss as possible mechanisms responsible for the age differences in working memory. In this task the stimulus and response pairs keep changing, and thus the subject must continuously monitor and update new information while also preserving the status of earlier information.

Two variables have been manipulated in this task: the presentation time per pair, and the number of pairs intervening between the presentation and test of a given stimulus–response pair. It was assumed that the time to encode information could be inferred by the effects of presentation time on accuracy with no intervening items and that the rate of loss of information could be determined by the effects of the number of intervening items on decision accuracy at the longest presentation time.

Two different versions of the task were used in separate studies (see Figure 6, A and B). One study involved common words as the stimulus terms and digits from 1 to 3 as the response terms, with the subject required to recall the correct response (Figure 6A). The other study involved

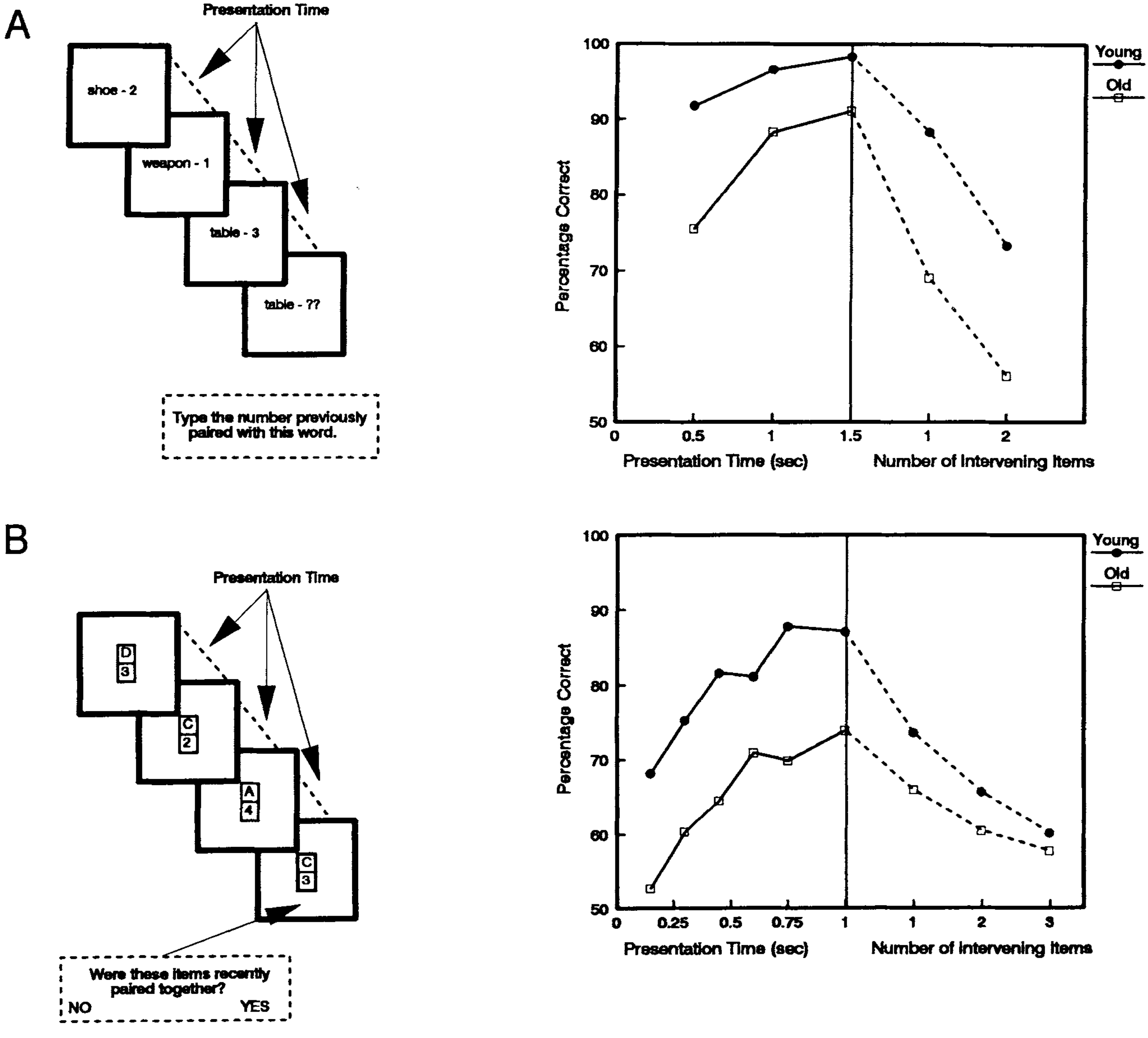

Figure 6. Schematic illustration of the task structure and results from continuous paired-associates tasks in two studies. (A) Data from Salthouse (in press-c), and (B) data from Study 1 in Salthouse (in press-a). The number of intervening items between presentation and test was 0 in the example in A and 1 in the example in B.

letters from A to F as the stimulus terms and digits from 1 to 6 as the response terms, with subjects required to decide whether a particular letter–digit pair had been recently presented together (Figure 6B). Fifty college students and 50 older adults participated in the study with word–digit pairs (Salthouse, in press-c), and 64 college students and 72 older adults participated in the study with letter–digit pairs (Salthouse, in press-a).

Results from both studies are illustrated in Figure 6, A and B. It is clear from these results that in each study older adults required considerably more time than young adults to achieve a similar level of accuracy but that the amount of decrease in accuracy with intervening items was generally similar for young and old adults. In both respects the results of these studies are consistent with those of the Salthouse (1992a) study despite the use of quite different procedures and materials. It therefore appears that the speed influence occurs because older adults are slower than young adults at encoding information or establishing an adequate internal representation, and not because of an age difference in the rate at which information is lost over short intervals.

In summary, the research on processing speed has revealed large and robust influences of speed on the relations between age and working memory. The statistical control results summarized in Figure 5 indicate that between 71% and 96% of the age-related variance in measures of working memory is shared with measures of processing speed. The mechanism for this relation is still not well understood, but there is some support for the interpretation that increased age is associated with a reduction in the speed of encoding or activating information and that the subsequent preservation of information over short intervals is relatively unaffected by increased age.

Conclusion

A large body of research, only a small portion of which has been described here, indicates that the working memory construct is theoretically useful and that something similar to it is involved in the adult age differences often reported in various measures of cognitive functioning. However, the research summarized above suggests that a simpler construct may be responsible for much of the adult age differences in working memory—namely, the speed at which relevant processing operations, and particularly those related to encoding or activation of information, can be executed. Furthermore, processing speed may be the common factor inferred to be contributing to the shared age-related influences on what are often considered to be distinct types of memory measures. At the very least, the available research seems to imply that some construct related to speed of processing needs to be incorporated into explanations proposed to account for age-related variations in working memory.

References

Baddeley, A. D. (1986). *Working memory.* Oxford, England: Oxford University Press.

Baddeley, A. (1992). Working memory. *Science, 255,* 556–559.

Baddeley, A., & Hitch, G. (1974). Working memory. In G. Bower (Ed.), *The psychology of learning and memory* (Vol. 8, pp. 47–90). San Diego, CA: Academic Press.

Baddeley, A., Logie, R., Bressi, S., Della Sala, S., & Spinnler, H. (1986). Dementia and working memory. *Quarterly Journal of Experimental Psychology, 38A,* 603–618.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior, 19,* 450–466.

Raven, J. (1962). *Advanced Progressive Matrices, Set II.* London: H. K. Lewis.

Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. *Developmental Review, 10,* 101–124.

Salthouse, T. A. (1991). Mediation of adult age differences in cognition by reductions in working memory and speed of processing. *Psychological Science, 2,* 179–183.

Salthouse, T. A. (1992a). Influence of processing speed on adult age differences in working memory. *Acta Psychologica, 79,* 155–170.

Salthouse, T. A. (1992b). What do adult age differences in the Digit Symbol Substitution Test reflect? *Journal of Gerontology: Psychological Sciences, 47,* P121–P128.

Salthouse, T. A. (1992c). Why do adult age differences increase with task complexity? *Developmental Psychology, 28,* 905–918.

Salthouse, T. A. (1993). Influence of working memory on adult age differences in matrix reasoning. *British Journal of Psychology, 84,* 171–199.

Salthouse, T. A. (in press-a). Aging associations: Influence of speed on adult age differences in associative learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition.*

Salthouse, T. A. (in press-b). How many causes are there of aging-related decrements in cognitive functioning? *Developmental Review.*

Salthouse, T. A. (in press-c). Selective influences of age and speed on associative memory. *American Journal of Psychology.*

Salthouse, T. A., & Babcock, R. L. (1991). Decomposing adult age differences in working memory. *Developmental Psychology, 27,* 763–776.

Salthouse, T. A., & Coon, V. E. (1994). Interpretation of differential deficits: The case of aging and mental arithmetic. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20,* 1172–1182.

Salthouse, T. A., Kausler, D. H., & Saults, J. S. (1988). Investigation of student status, background variables, and the feasibility of standard tasks in cognitive aging research. *Psychology and Aging, 3,* 29–37.

Salthouse, T. A., & Kersten, A. W. (1993). Decomposing adult age differences in symbol arithmetic. *Memory & Cognition, 21,* 699–710.

Salthouse, T. A., Rogan, J. D., & Prill, K. A. (1984). Division of attention: Age differences on a visually presented memory task. *Memory & Cognition, 12,* 613–620.

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