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Decomposing Adult Age Differences in Working Memory

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Two studies, involving a total of 460 adults between 18 and 87 years of age, were conducted to determine which of several hypothesized processing components was most responsible for age-related declines in working memory functioning. Significant negative correlations between age and measures of working memory (i.e., from −.39 to −.52) were found in both studies, and these relations were substantially attenuated by partialing measures hypothesized to reflect storage capacity, processing efficiency, coordination effectiveness, and simple comparison speed. Because the greatest attenuation of the age relations occurred with measures of simple processing speed, it was suggested that many of the age differences in working memory may be mediated by age-related reductions in the speed of executing elementary operations.

Working memory is generally defined as the preservation of information while simultaneously processing the same or other information. It is distinguished from other forms of memory because the assumption that it reflects both processing and storage implies that it plays an important role in many cognitive tasks (e.g., Baddeley, 1986; Carpenter & Just, 1989; Salthouse, 1990).

An illustration of the hypothesized functioning of working memory in one cognitive task, mental arithmetic, is presented in Figure 1. The left column in this figure indicates the operations to be performed, and the right column represents the intermediate products that must be temporarily stored while carrying out those operations. This figure is useful because it graphically illustrates both the importance and the complexity of working memory. That is, it is clear from this example that effective storage of information is essential in order for the successful performance of certain cognitive tasks. Figure 1 also suggests that it may be fruitful to think of working memory not as a single discrete structure, but rather as a dynamic interchange among three conceptually distinct aspects or components—processing efficiency, storage capacity, and coordination effectiveness. Processing is represented by the series of operations in the left column, storage is represented by the entries in the right column, and coordination can be assumed to correspond both to the sequencing of operations and to the arrows portraying the exchange of information between processing and storage.

A primary purpose of this article was to investigate the contribution of these three hypothesized components to age-related differences in measures of working memory. Each of the components has been hypothesized to be an important source of adult age differences by one or more researchers, but few definitive conclusions have been possible because the currently available evidence is both weak and inconsistent. To illustrate, Parkinson and his colleagues (e.g., Parkinson, 1982; Inman & Parkinson, 1983; Parkinson, Inman, & Dannenbaum, 1985; Parkinson, Lindholm, & Inman, 1982) have argued that limitations of storage are a major factor contributing to age differences in various memory and, presumably, cognitive tasks. Although they have reported that age differences in certain memory tasks are reduced in magnitude when young and old adults are matched on a digit span measure postulated to reflect storage capacity, this storage-mediation effect has only been demonstrated for a few tasks. Several researchers have discussed the possibility that difficulties in coordinating concurrent activities are a potential source of age differences in working memory (e.g., Kirchner, 1958; Rabbitt, 1981; Talland, 1968; Taub, 1968; Welford, 1958), but there is apparently not yet any evidence directly relevant to this interpretation. Perhaps the most popular interpretation in recent years has been the view that many of the age differences in working memory are attributable to age-related reductions in processing efficiency (e.g., Baddeley, 1986; Craik & Rabinowitz, 1984; Gick, Craik, & Morris, 1988; Morris, Gick, & Craik, 1988). However, empirical support for this interpretation has been mixed. For example, it has sometimes been found that the magnitude of the age differences increase as processing requirements increase (e.g., Wingfield, Stine, Lahar, & Aberdeen, 1988), but in other studies it has also been reported that age differences remain constant as processing demands are varied (e.g., Babcock & Salthouse, 1990; Light & Anderson, 1985; Salthouse, Babcock, & Shaw, 1991).

In keeping with the theoretical definition of working memory as involving the simultaneous storage and processing of information, most of the tasks explicitly designed to assess working memory require the research participant to carry out specified processing and to remember particular pieces of information. Examples are the reading span and listening span tasks used by Daneman and Carpenter (1980), the counting task used by Case, Kurland, and Goldberg (1982), the computation span task used by Salthouse and colleagues (e.g., Babcock & Salthouse, 1990; Salthouse, Mitchell, Skovronek, & Babcock, 1989; Salthouse & Prill, 1987), and various tasks used by Turner and Engle (1989).

Although each of these tasks appears to satisfy the theoretical

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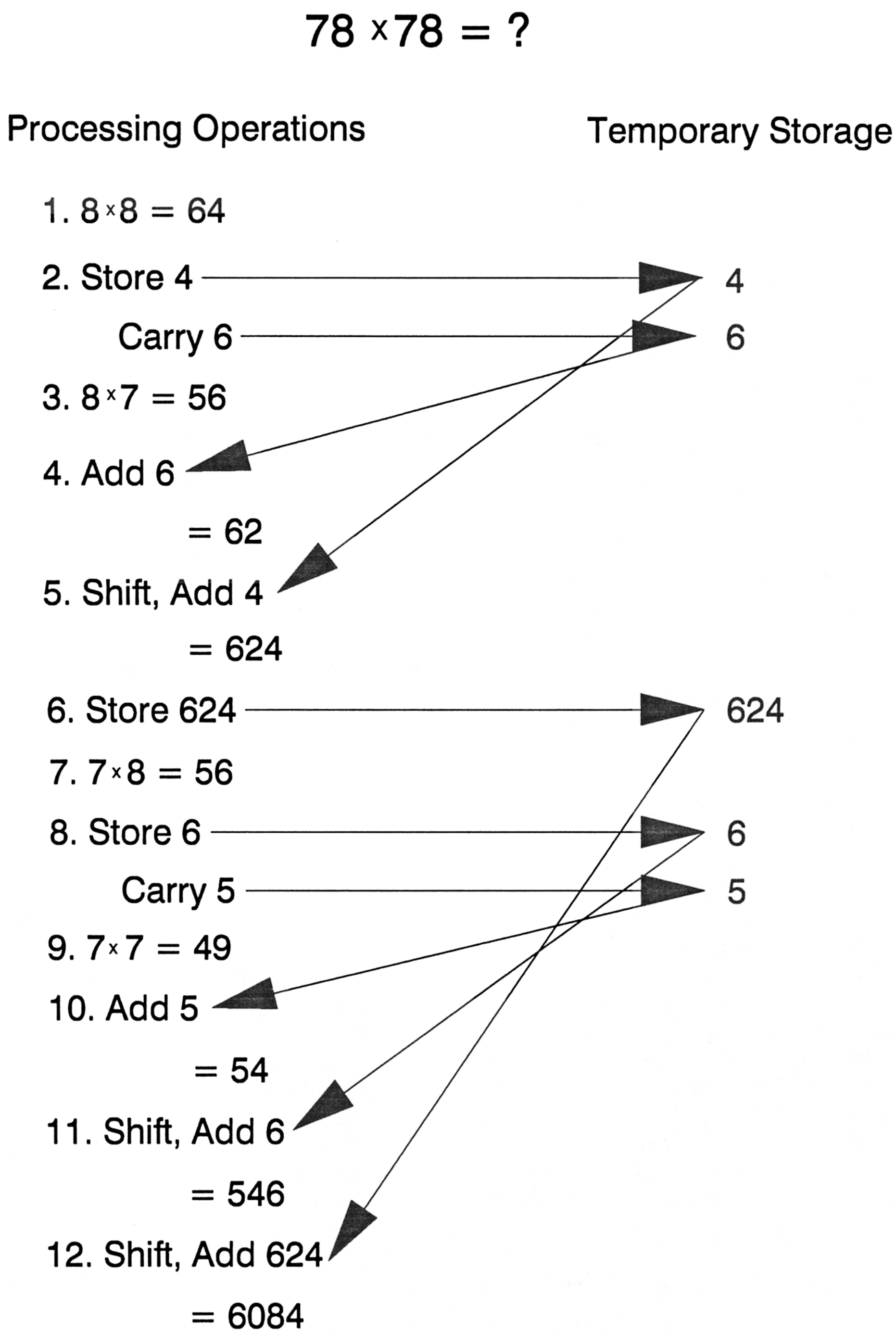

Figure 1. Illustration of hypothesized influence of working memory in the performance of a cognitive task. (The mental arithmetic example is taken from Charness, 1985, and the figure is from *Theoretical perspectives in cognitive aging* (p. 334) by T. A. Salthouse, 1991, Hillsdale, NJ: Erlbaum. Copyright 1991 by Lawrence Erlbaum Associates. Reprinted by permission.

criteria for the assessment of working memory, no single one of them is likely to provide a pure or completely accurate estimate of the working memory construct because of the influence of task-specific factors. That is, the variance on any given measure can be postulated to involve variance associated with the theoretical construct, variance associated with the specific manner (e.g., procedures, stimulus materials, etc.) in which the construct is assessed, and unsystematic or error variance.

Some indication of the proportion of common or construct-relevant variance in measures of working memory from earlier studies is available by examining the magnitude of the correlation coefficients between different measures of working memory. Most of the reported values have ranged from .38 (for a sentence–word measure and an arithmetic–digit measure in Turner & Engle, 1989) to .88 (for oral and silent reading span measures in Daneman & Carpenter, 1980), with intermediate values of .40 (for computation span and spatial line span in Babcock & Salthouse, 1990), .44 (for counting span and reading span in Baddeley, Logie, Nimmo-Smith, & Brereton, 1985), and .57 (for assorted tasks with complex processing requirements in Daneman & Tardif, 1987). Although these correlations are moderate in magnitude, they are likely attenuated because of a restricted range of ability (most of the studies involved college students) and less than perfect reliabilities of the measures (few of the cited studies reported reliabilities). Procedural variations associated with the methods of ensuring that the relevant processing was actually carried out, and with the specific criteria used to assess a given individual's working memory capacity, may have also contributed to underestimates of the true relations between alternative measures of working memory in the earlier studies.

To emphasize the variance associated with the working memory construct, and to minimize variance specific to the particular procedures or stimulus materials used to assess working memory, it is desirable to obtain multiple measures of the important constructs. These measures can then be combined to form composite scores that can be presumed to be better reflections of the relevant theoretical constructs. This procedure was followed in this study by having all research participants perform two independent, but theoretically parallel, sets of tasks related to working memory.

The two tasks used to measure working memory, and the tasks used in the assessment of the three hypothesized components of working memory, are portrayed in Figure 2. Notice that the two sets of tasks are structurally similar, but one set involves arithmetic problems and memory for numbers, whereas the other set involves sentence comprehension questions and memory for words. In both cases the working memory tasks required both processing and storage, the storage capacity tasks emphasized storage, the processing efficiency tasks emphasized processing, and the coordination tasks required two activities to be performed simultaneously. That is, the computation span and listening span tasks required the participant to select the correct answer to the arithmetic problems or to the questions about sentences while simultaneously remembering digits or words. These processing requirements were eliminated in the digit span and word span tasks postulated to provide relatively pure measures of storage capacity. The efficiency with which the individual could carry out the relevant processing was assessed in the arithmetic and sentence comprehension tasks. Finally, effectiveness of coordinating two simultaneous activities was evaluated by measures of performance with two concurrent processing tasks.

Two studies, involving independent groups of adults between 18 and 87 years of age, are reported. The goal in both studies was to attempt to decompose age differences in working memory into presumably more fundamental components, but the studies differed in the particular combination of tasks performed by each individual.

Study 1

Research participants in the first study performed all the tasks illustrated in Figure 2. The hypothesized components of working memory investigated in this study were therefore processing efficiency, storage capacity, and coordination effectiveness.

Method

Subjects

Newspaper advertisements requesting healthy adults to participate in a research project concerned with aging and memory were used to recruit research participants. A total of 227 adults between 20 and 87 years of age contributed complete data to the project. Seven additional adults did not complete all the tasks or did not understand the instructions, and hence their data were not included in the analyses. The final sample consisted of 116 women and 111 men, with between 24 and 67 individuals in each decade. The average years of education in the sample was 14.8. The average self-assessed health rating, on a scale ranging from *excellent* (1) to *poor* (5), was 2.10. Correlations with age were −.17 ($p < .05$) for the education variable and .22 ($p < .01$) for the health variable.

Procedure

All research participants were tested in 90-min sessions in groups of 10 to 40 people. Each individual received $10 compensation for his or her participation. The tasks, in the order in which they were administered to the participants, were computation span, digit span, arithmetic, listening span, word span, sentence comprehension, and the coordination task, with the arithmetic problems and the sentences presented orally. All participants received the tasks (and the items within the tasks) in the same order to avoid confoundings of the individuals with a task order that would complicate analyses of individual differences. Examples of the stimulus materials used in each task are shown in Figure 2. All the visual materials were assembled in booklets distributed to each research participant.

Tasks

Computation span. In this task a series of arithmetic problems was presented for the participants to solve while also remembering the last digit from each problem. The arithmetic problems were presented orally at a normal speaking rate. After each problem was presented, the examinee selected the correct answer from the three alternatives listed on an answer sheet in his or her test booklet. On completion of the designated number of problems, the examinee was instructed to turn to the back of the answer page in the test booklet and write the target digits. The time allowed for recall was approximately 4 s per target digit, which pilot research indicated was sufficient for people of all ages. Instructions emphasized that answering the problems correctly was to have the highest priority and that the recall would not be considered correct unless the processing task was performed accurately.

The number of arithmetic problems presented on each trial increased successively from one to seven, with three trials presented at each series length. The arithmetic problems were all of the form $X + Y =$ or $X - Y =$, with the following restrictions: (a) X and Y were one-digit numbers between 1 and 9; (b) answers to the problems could not be negative; (c) the final number, Y, could not be the same for two adjacent problems in a trial; and (d) the answer to the problem could not equal Y.

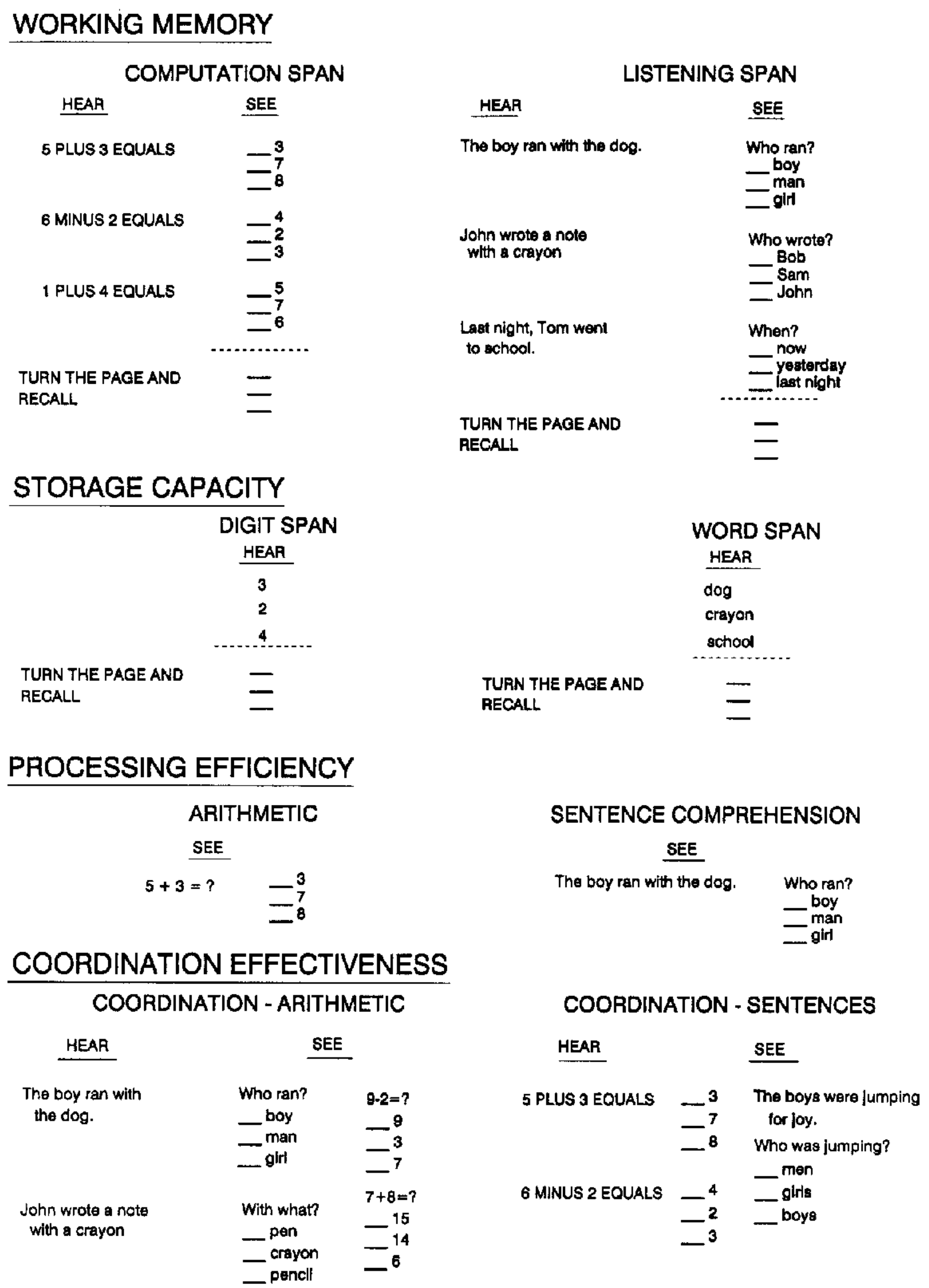

Figure 2. Examples of trials in the eight tasks performed by all research participants in Study 1.

The two incorrect alternatives for the problems were randomly selected numbers between 1 and 20.

Listening span. The listening span task consisted of the oral presentation of simple sentences; the research participant was instructed to answer a question about the sentence in the booklet while also remembering the last word in each sentence. Sentences were read at a normal speaking rate, and the examinee was requested to select the correct answer from one of three alternatives listed on an answer sheet in the test booklet. On completion of the designated number of problems, the examinee was instructed to turn to the back of the answer page in the test booklet and write the target words. The recall time was approximately 4 s per target word—a time more than adequate for people of all ages in the pilot research. As in the computation span task, the instructions emphasized that the questions had to be answered correctly or the recall responses would not be evaluated.

The sentences were between 6 and 10 words long and were generated with the following restrictions: (a) The final word was not longer than two syllables, (b) the final word was common enough to be found in a children's dictionary (Simon & Schuster, 1984), and (c) no word appeared more than once in the session as the final word of a sentence. An attempt was made to keep the comprehension questions for each sentence very simple (e.g., who?, when?, and where?), and neither the question nor the answer alternatives contained the to-be-remembered target word from the sentence.

Digit span and word span. Both digits and words were presented at a rate of approximately 1 per s, with a duration of about 4 s per presented item allowed for recall. The number of items presented on each trial increased from 3 to 11, with three trials at each series length. Words used in the word span task were selected with the same constraints used in the selection of words for the listening span task.

Arithmetic and sentence comprehension. These tasks involved the presentation of a single page of items (27 arithmetic problems or 25 sentences) with three answer alternatives for each item. The examinee was instructed to answer as many of the items as possible in 20 s. There were two separately timed administrations of each task.

Coordination. Two versions of the coordination task were administered. One version involved participants attempting to solve visually presented arithmetic problems while simultaneously answering questions concerning orally presented sentences. The second version involved the participants attempting to answer questions about visually presented sentences while simultaneously solving arithmetic problems that were orally presented. There were two separately timed (20 s) administrations of each version. Figure 2 shows that the stimuli for the visual portions of the coordination tasks were presented in a manner identical to that for the arithmetic and sentence comprehension tasks. The stimuli for the auditory portions of the tasks were presented in a manner identical to that for the computation span and listening span tasks. Participants were instructed to give highest priority to answering the questions concerning the auditorily presented material but also to complete as many of the visually presented items as possible in the time allowed.

Results and Discussion

Spans were estimated in the same manner for the computation span, listening span, digit span, and word span tasks. The procedure consisted of scoring each recall attempt as correct (all items recalled in original sequence) or incorrect and then designating the span as the highest number of target items recalled correctly on at least two of the three trials with that sequence length. An additional requirement in the computation span and listening span tasks was that in order for a trial to be considered correct, no errors could have been committed on the relevant arithmetic (for computation span) or sentence comprehension (for listening span) problems. The span estimates in these tasks therefore represented successful recall and successful performance on the required processing.

Performance in the remaining tasks was assessed in terms of the number of items answered correctly in the allotted time. Two scores were available in the coordination tasks, corresponding to the measures on the visual task and the auditory task. However, there were very few errors, and consequently little variability, in the performance of the auditory tasks, and as a result, this measure was not subjected to further analyses.

The distribution of the computation span and listening span estimates by decade are illustrated in Figure 3. It is clear in these data that the distribution of spans systematically shifts toward lower values with increased age. This shift is reflected in the age correlations of −.47 for the computation span estimates and −.52 for the listening span estimates. These results can therefore be viewed as establishing the phenomenon of age-related reductions in working memory functioning that we intend to explain.

Table 1 contains correlations and estimated reliabilities for the major measures in Study 1. Reliabilities of the spans were

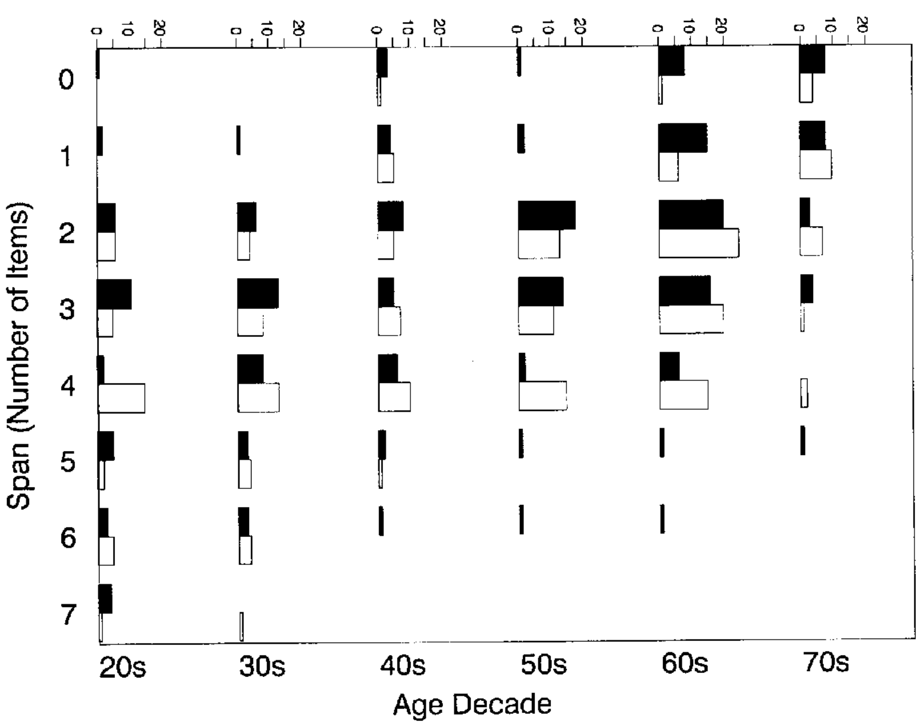

Figure 3. Distribution of estimated spans for the computation span (solid bars) and listening span (open bars) measures in Study 1.

Table 1
Correlation Matrix for Study 1

Measure	1	2	3	4	5	6	7	8	9
1. Age	—	−.47	−.52	−.34	−.42	−.57	−.52	−.66	−.49
2. CS		(.90)	**.68**	.55	.59	.64	.57	.62	.49
3. LS			(.86)	.45	.62	.60	.62	.61	.57
4. DS				(.89)	**.57**	.42	.42	.43	.41
5. WS					(.84)	.53	.56	.53	.50
6. Ar						(.92)	**.68**	.79	.58
7. Se							(.89)	.75	.71
8. ArD								(.94)	**.77**
9. SeD									(.82)
M	50.67	2.58	3.00	6.61	4.08	12.33	7.26	5.74	1.98
SD	16.82	1.57	1.35	1.50	1.16	4.67	2.66	3.82	1.85

Note. $N = 227$. Entries in parentheses are estimated reliabilities derived by boosting split-half correlations by the Spearman-Brown formula. Values in boldface represent correlations between variables postulated to assess the same construct. CS = computation span; LS = listening span; DS = digit span; WS = word span; Ar = arithmetic speed; Se = sentence speed; ArD = arithmetic speed in dual condition; SeD = sentence speed in dual condition.

computed by determining the correlation between the average number of correct responses on trials with even numbers of to-be-remembered items and the average number of correct responses on trials with odd numbers of to-be-remembered items, and then the Spearman-Brown formula was used to estimate the reliability of all the trials. Although the span estimates were not directly based on the total number of correct trials, correlations between the total correct measure and the actual span estimates ranged from .90 to .94 across the four span measures. (Corresponding values for these same measures in Study 2 ranged from .87 to .92). Reliabilities for the remaining measures in Table 1 were determined by applying the Spearman-Brown formula to predict reliability of the average score from the correlation between scores of two separate assessments.

Three important points should be noted about Table 1. The first is that the reliabilities for all measures were respectable, with a median of .89 and a range from .82 to .94. The second point is that although all the correlations among measures are moderately positive, the largest correlations are generally between measures hypothesized to reflect the same theoretical construct. In particular, the correlation of .68 between the computation span and listening span tasks was the highest for each of these measures. This finding is consistent with the interpretation that the two measures reflect a common construct, in addition to any specific processes that might be involved with each task. Finally, it is noteworthy that the age correlations with all measures were negative and moderate to large in magnitude.

To evaluate the potential mediating influence of different variables on the age-related effects on other variables, a series of hierarchical regression analyses were performed. The logic of the analyses was that the contribution of a variable to the age differences on a given measure could be estimated by contrasting the amount of age-associated variance before and after removing the variance associated with that variable. The variable can be inferred to be important as a potential mediator of the age relations to the extent that there is a substantial attenuation of the age-associated variance after it is statistically controlled.

Three separate sets of parallel analyses were conducted; the primary one based on composite scores created by averaging the *z* scores from corresponding measures in the two sets of tasks, and one each on the measures from each set of tasks. Results of these analyses, expressed in terms of the increment in R^2 for age after control of other variables, are summarized in Table 2.

For the sake of simplicity, we describe the major findings from Table 2 in terms of the results based on the composite scores. However, the table can be inspected to verify that a qualitatively similar pattern is evident in the measures from each set of tasks. First, it is apparent that there is only slight attenuation of the age differences after statistical control of the health and education variables. However, the age-associated variance was substantially reduced, to less than 7%, by controlling for the variable corresponding to storage capacity, to about 2% by controlling for the variable reflecting processing efficiency, and to just over 1% by controlling for both the storage capacity and processing efficiency variables.

A second noteworthy aspect of the results in Table 2 is that the degree of attenuation of the age-related influences on the hypothesized components varied according to the other components treated as potential mediators. For example, statistical control of the processing efficiency component reduced the age-associated variance in the storage capacity component to 1.3%, but statistical control of the storage capacity component only reduced the age-associated variance in the processing efficiency component to 12.3%. The asymmetric nature of these effects provides a clue to the causal relations among the variables because variables functioning as mediators of a relation would be expected to result in greater attenuation of the relation when they are controlled than variables representing the outcome, or consequence, of the relation.

The pattern of results just described suggests that efficiency of processing may be a major determinant of the age differences in working memory. Storage capacity and coordination effectiveness also contribute to the age differences, but since they are themselves influenced by processing efficiency, processing efficiency seems to be the primary factor responsible for many of the age differences in working memory.

One method of summarizing the empirical relations among

Table 2
Increment in R^2 for Age After Statistically Controlling for Other Variables (Study 1)

Control	Working memory R^2	Working memory F	Computation span R^2	Computation span F	Listening span R^2	Listening span F
None	.297	94.93*	.224	64.91*	.275	85.36*
Health	.261	84.31*	.197	57.27*	.243	75.87*
Education	.244	86.11*	.185	56.96*	.226	76.61*
H & E	.222	78.43*	.167	51.61*	.206	69.89*
H, E, & storage	.068	34.11*	.070	27.00*	.079	33.76*
H, E, & process	.021	10.49*	.017	6.54	.055	22.60*
H, E, & coord.	.028	12.53*	.007	2.79	.067	26.42*
H, E, storage, & process	.011	6.47	.007	3.30	.032	15.04*
H, E, storage, & coord.	.014	8.00*	.003	1.38	.036	16.77*
H, E, process, & coord.	.011	6.76*	.004	1.56	.040	16.93*
H, E, storage, process, & coord.	.008	4.62	.001	0.69	.025	13.67*
	Storage capacity		Digit span		Word span	
None	.188	52.08*	.119	30.35*	.180	49.43*
Health	.169	46.87*	.116	29.48*	.152	42.11*
Education	.146	44.41*	.097	25.49*	.134	41.75*
H & E	.136	41.39*	.098	25.61*	.118	36.76*
H, E, & process	.013	4.53	.018	5.02	.024	8.68*
H, E, & coord.	.014	4.68	.007	2.22	.031	10.86*
H, E, process, & coord.	.006	2.29	.006	1.65	.016	5.84
	Coordination effectiveness		Arithmetic dual		Sentence dual	
None	.376	135.86*	.435	173.17*	.244	72.70*
Health	.347	125.18*	.403	160.39*	.224	66.45*
Education	.325	125.83*	.377	163.46*	.210	64.88*
H & E	.307	118.57*	.358	154.74*	.197	60.74*
H, E, & process	.026	19.46*	.066	48.04*	.023	10.95*
H, E, & storage	.161	71.14*	.258	118.69*	.094	32.36*
H, E, process, & storage	.023	17.08*	.060	43.83*	.017	8.06*
	Processing efficiency		Arithmetic		Sentence comprehension	
None	.353	122.69*	.330	110.65*	.265	81.32*
Health	.305	108.29*	.285	97.37*	.230	71.18*
Education	.293	114.27*	.278	101.33*	.217	72.67*
H & E	.261	103.08*	.247	91.11*	.193	65.25*
H, E, & storage	.123	57.56*	.164	64.83*	.088	33.99*
H, E, & coord.	.011	8.47*	.004	2.55	.029	14.65*
H, E, storage, & coord.	.008	6.06	.003	1.97	.018	9.52*

Note. H = health; E = education; coord. = coordination effectiveness; *dfs* = 1 and 225 minus the number of controlled variables.
* $p < .01$.

the theoretical constructs consists of expressing those relations in a path diagram. To the extent that the composite measures accurately reflect the theoretical constructs of interest, structural diagrams of this type are valuable in allowing all the hypothesized causal connections to be represented, including those that are indirect or mediated, as well as those that are direct. A path diagram illustrating the relations among the composite variables in this study, with the path coefficients derived from the EZPath (Steiger, 1989) computer program, is portrayed in Figure 4. Because the comparisons of primary interest are those between different variables and not those between different samples, standardized path coefficients are reported. An initial analysis revealed that the paths between the age and storage capacity variables and between the coordination effectiveness and working memory variables had coefficients less than twice their standard errors. Those paths were therefore deleted, and the analysis was repeated with only the relations displayed in Figure 4. This model provided a good fit to the data because the 90% confidence intervals ranged from .000 to .147 for the Steiger-Lind Adjusted root mean square (RMS) Index (Steiger, 1989) and ranged from .872 to 1.000 for the Adjusted Population Gamma Index.

These path analysis results serve to reinforce the conclusion that variations in processing efficiency are an important factor contributing to age differences in working memory. Particularly relevant to this conclusion are the relatively small coeffi-

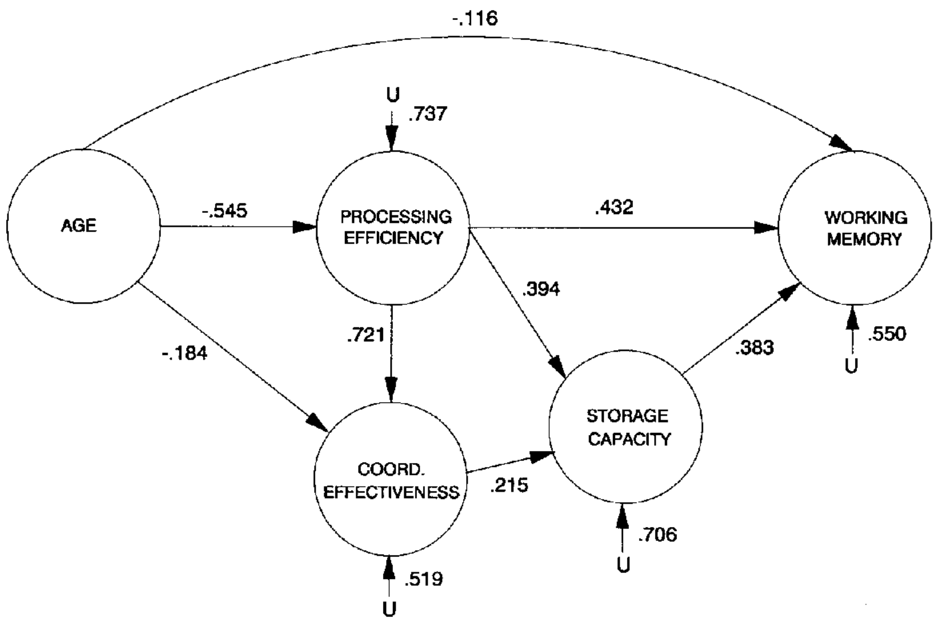

Figure 4. Path analysis model of relations among age and hypothesized components of working memory based on results of Study 1.

cients (−.116) for the direct path linking age to working memory, the relatively large coefficients for the paths linking age to processing efficiency (−.545) and processing efficiency to working memory (.432), and the absence of a direct path between age and storage capacity.

The results of this study suggest that processing efficiency is the most important determinant of age-related differences in working memory. Statistically significant age-related influences are evident in the measures of storage capacity and coordination effectiveness, but those measures contribute little to the

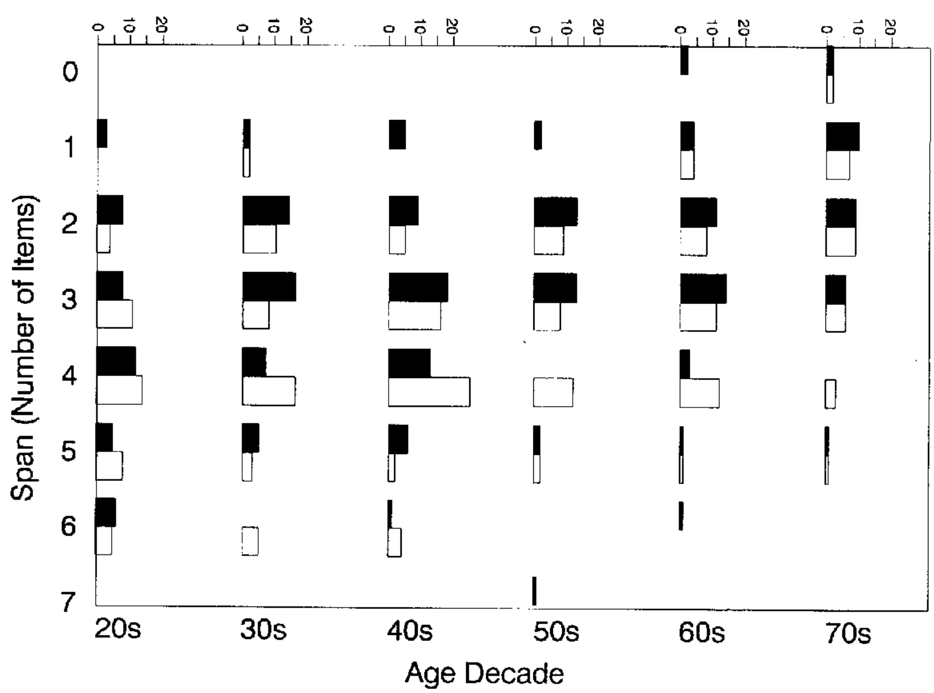

Figure 5. Distribution of estimated spans for the computation span (solid bars) and listening span (open bars) measures in Study 2.

attenuation of the age differences in working memory after partialing the influence of processing efficiency. Furthermore, although there was a small negative relation between age and ability to perform two concurrent tasks after controlling the variance associated with the measures of processing efficiency, virtually all of the age-related differences in the span measures were eliminated after statistical control of the processing efficiency measures.

Study 2

In view of the apparent importance of the processing efficiency component in the age differences in working memory, it is desirable to be more explicit about precisely what that component represents. The tasks used to operationalize the processing efficiency construct in Study 1 required the research participants to solve arithmetic problems and to answer sentence comprehension questions, which are both moderately complex tasks. Because of their complexity, it was likely that the measures from these tasks reflected a combination of factors and not just the efficiency with which processing operations were executed. In an attempt to obtain a potentially purer assessment of the efficiency of carrying out elementary processing operations, participants in this study also performed two relatively simple speeded comparison tasks.

Because no direct relation was evident between the measures of coordination effectiveness and of working memory in the path analysis results of Study 1, the tasks used to assess coordination effectiveness were not included in Study 2. The hypothesized components of working memory investigated in this study were therefore processing efficiency, storage capacity, and simple comparison speed.

Method

Subjects

Research participants were recruited in the same manner described in Study 1. Complete data were obtained from 233 adults (139 women and 94 men) ranging from 18 to 82 years of age. Each decade from the 20s to 70+ was represented by between 28 and 52 individuals. The data from 13 additional participants were not included in the analysis because they failed to understand the instructions or did not complete all tasks. The average health rating (1 = excellent, 5 = poor) for the 233 participants was 2.16, with an age correlation of .13. The average years of education was 15.1, with an age correlation of −.06.

Procedure

Both the sequence and the identity of the tasks were varied from Study 1, as the order of the repeated tasks was changed, several tasks were dropped, and new ones were added. The first task performed in the session was the arithmetic task, followed by the digit span and computation span tasks. New tasks designed to measure comparison speed were then administered, with three versions involving pairs of letters and three versions involving pairs of line-segment patterns. The sentence comprehension task was then performed, followed by the word span and listening span tasks. The final task performed in the session was the Digit Symbol Substitution test from the Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981).

Materials and procedures for the previously used tasks (i.e., those designed to measure working memory, storage capacity, and processing efficiency) were identical to those of Study 1. The new Letter Comparison and Pattern Comparison tasks consisted of pages containing pairs of letters, or pairs of line-segment patterns, that the examinee was to classify as "same" or "different" as rapidly as possible. One half of the pairs in each page were same and one half were different. Pairs requiring a *different* response were constructed by altering one of the elements (letter or line segment) in one member of the pair. The letters were randomly selected consonants, arranged in sets of three, six, or nine letters in each member of the pair. The line patterns were connected lines in an invisible 4 × 4 matrix, with three, six, or nine line segments in each member of the pair. There were two separately timed (20 s) administrations of 32 pairs for each of the versions (i.e., with three, six, or nine items) of each task.

Results and Discussion

The procedure for estimating the spans was identical to that described in Study 1. Figure 5 illustrates the distribution of the

Table 3
Correlation Matrix for Study 2

	1	2	3	4	5	6	7	8	9	10
1. Age	—	−.39	−.41	−.18	−.32	−.53	−.39	−.59	−.64	−.56
2. CS		(.84)	**.49**	.52	.46	.62	.50	.54	.52	.52
3. LS			(.86)	.45	.56	.57	.49	.47	.49	.43
4. DS				(.87)	**.50**	.44	.39	.35	.30	.29
5. WS					(.79)	.42	.48	.39	.37	.37
6. Ar						(.91)	**.68**	.70	.67	.72
7. Se							(.90)	.62	.57	.62
8. Let								(.94)	**.80**	.71
9. Pat									(.94)	.73
10. DigSym										—
M	46.92	2.89	3.35	6.88	4.30	13.72	7.68	8.61	13.13	58.79
SD	16.44	1.32	1.25	1.37	0.94	4.73	2.29	2.19	2.86	14.39

Note. $N = 233$. Entries in parentheses are estimated reliabilities derived by boosting split-half correlations by the Spearman-Brown formula. Values in bold represent correlations between variables postulated to assess the same construct. CS = computation span; LS = listening span; DS = digit span; WS = word span; Ar = arithmetic speed; Se = sentence speed; Let = speed of letter comparison; Pat = speed of pattern comparison; DigSym = digit symbol substitution.

Table 4
Increment in R^2 for Age After Statistical Control of Other Variables (Study 2)

Control	Working memory		Computation span		Listening span	
	R^2	F	R^2	F	R^2	F
None	.211	61.89*	.149	40.57*	.166	46.07*
Health	.200	58.78*	.146	39.41*	.154	42.87*
Education	.193	64.02*	.137	39.94*	.151	46.16*
H & E	.187	62.02*	.136	39.72*	.143	43.78*
H, E, & storage	.079	39.40*	.086	31.98*	.058	21.99*
H, E, & process	.021	9.67*	.006	2.37	.062	20.71*
H, E, & speed	.011	4.47	.003	1.03	.017	5.46
H, E, storage, & process	.018	10.38*	.009	3.99	.035	13.67*
H, E, storage, & speed	.008	4.36	.005	1.90	.008	3.08
H, E, process, & speed	.006	2.78	.000	0.01	.017	5.70
H, E, storage, process, & speed	.005	3.21	.001	0.40	.008	7.22*
	Storage capacity		Digit span		Word span	
None	.086	21.66*	.034	8.04*	.105	26.96*
Health	.077	19.67*	.031	7.31*	.094	24.46*
Education	.076	20.62*	.029	7.22*	.094	25.98*
H & E	.071	19.21*	.028	6.80*	.087	24.09*
H, E, & process	.001	0.32	.003	0.90	.025	7.76*
H, E, & speed	.002	0.42	.001	0.36	.011	3.05
H, E, process, & speed	.000	0.03	.007	1.92	.011	3.30
	Processing efficiency		Arithmetic		Sentence comprehension	
None	.252	77.82*	.282	90.81*	.150	40.92*
Health	.230	72.79*	.265	86.02*	.132	36.99*
Education	.227	87.32*	.258	99.83*	.133	42.33*
H, E	.213	82.88*	.248	96.04*	.120	39.04*
H, E & storage	.126	58.88*	.195	87.53*	.060	21.67*
H, E & speed	.004	2.15	.013	6.78*	.000	0.00
H, E, storage & speed	.003	1.75	.014	8.36*	.000	0.26
	Speed					
None	.419	166.47*				
Health	.404	160.49*				
Education	.400	171.89*				
H, E	.390	167.28*				
H, E & storage	.296	136.68*				
H, E & process	.102	64.43*				
H, E, storage & process	.099	63.79*				

Note. H = health; E = education; *dfs* = 1 and 231 minus the number of controlled variables.

computation span and listening span measures by decade. The pattern of the distributions shifting toward lower scores with increased age and the significant negative age correlations of −.39 for computation span and −.41 for listening span are similar to those observed in Study 1.

Performance in the speeded comparison tasks was represented by the number of pairs correctly classified in the allotted time. It was anticipated that the correlations of these measures with age, and with the measures of working memory, might become larger as the number of elements in each pair increased from three to six to nine. Although the number of correct classifications decreased as the comparisons involved more elements, no systematic trend was apparent in the magnitude of the correlations. For example, the age correlations were −.58, −.56, and −.43, respectively, for the three-, six-, and nine-element letter comparisons and −.64, −.64, and −.52, respectively, for the three-, six-, and nine-element pattern comparisons. Because the three versions appeared to exhibit similar relations with other variables, the scores for the three versions were averaged to provide a more reliable measure of performance with each type of comparison.

The correlation matrix for the major measures is shown in Table 3. As in Study 1, reliabilities were generally respectable, and each of the measures had negative correlations with age but moderately positive correlations with one another.

Hierarchical regression analyses similar to those conducted in Study 1 were performed on the primary measures, with the results summarized in Table 4. (The digit symbol substitution measure was not included in these analyses because it is planned to be the focus of a separate decompositional analysis

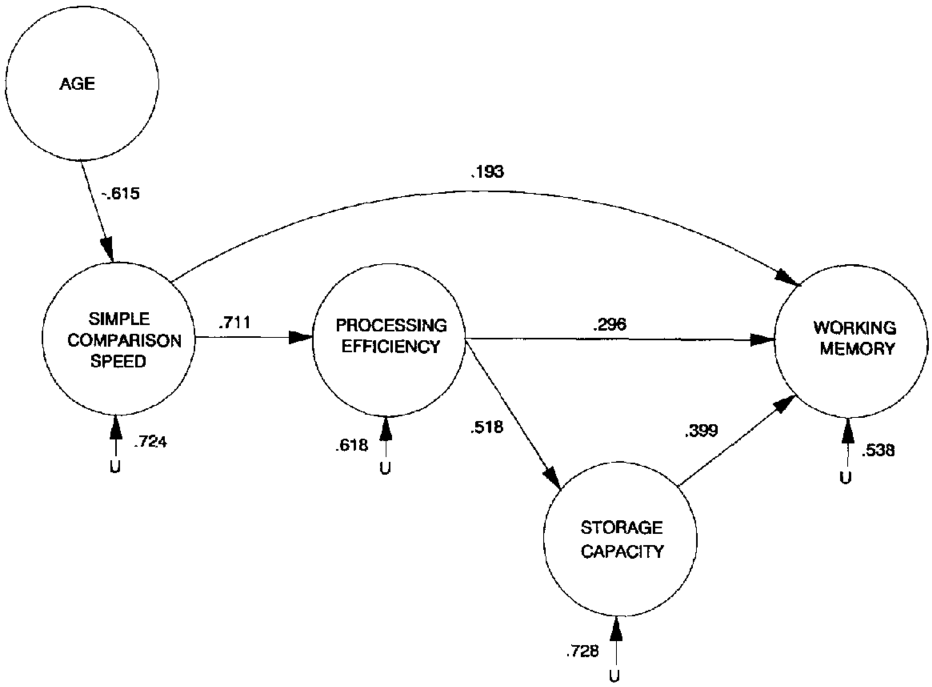

Figure 6. Path analysis model of relations among age and hypothesized components of working memory based on results of Study 2.

to be reported in a later article.) The major results from Study 1 were replicated by the findings that the age-associated variance in the measures of working memory was reduced to less than 8% after controlling for the measures of storage capacity and to almost 2% after controlling for the measures of processing efficiency. The earlier results are extended by the additional finding that the age-associated variance was reduced to nearly 1% by controlling for the measures of simple speed (letter comparison and pattern comparison). Further examination of Table 4 reveals that the interrelations among age and the measures of the hypothesized components were not symmetrical, because the greatest attenuation of the age relations occurred after statistically controlling for the simple speed measure.

A path diagram illustrating the relations among the composite variables is displayed in Figure 6. As in Figure 4, paths with coefficients less than twice their standard errors were deleted from the initial analysis, and the analysis was repeated with only the displayed paths. The goodness-of-fit indices revealed an excellent fit to the data in that the 90% confidence intervals for the Steiger-Lind Adjusted rms Index (Steiger, 1989) ranged from .000 to .093 and those for the Adjusted Population Gamma Index (Steiger, 1989) ranged from .948 to 1.000. The most interesting aspect of Figure 6 is that all the age-related effects on processing efficiency, storage capacity, and working memory are indirect, rather than direct. In other words, all the significant relations between age and measures of these constructs appear to be mediated through age-related reductions in simple speed.

General Discussion

A very robust finding across the two studies in this project is that increased age is associated with progressively lower performance on tasks designed to assess working memory. The age correlations for the computation span and listening span measures ranged from −.39 to −.52, and Figures 3 and 5 indicate that the age-related reductions are characterized by a gradual shift in the entire distribution of scores. The major question addressed in these studies was which hypothesized component of working memory is primarily responsible for these differences.

A primary assumption motivating this research is that there are some aspects of working memory that transcend specific tasks and, hence, are independent of the particular kind of processing carried out and of the particular type of information being remembered. We are not claiming that working memory functioning is completely independent of the nature of the relevant processing or of the type of information being remembered. However, the moderately large correlations between the measures from the computation span and listening span tasks in Tables 1 and 3 suggest that there are substantial commonalities in at least these particular measures of working memory. Moreover, the analyses based on the composite scores appear to yield meaningful and coherent results, even when the task-specific aspects are presumably minimized by averaging across measures from the two sets of tasks.

Measures hypothesized to reflect components concerned with processing efficiency, storage capacity, and coordination effectiveness were investigated in Study 1. The greatest attenuation of the age differences in the working memory measures was found after statistically controlling for the measures of processing efficiency. Furthermore, the relations among the component measures were asymmetrical, in that the largest attenuation of the age-related effects occurred after statistically controlling for the measures postulated to reflect processing efficiency.

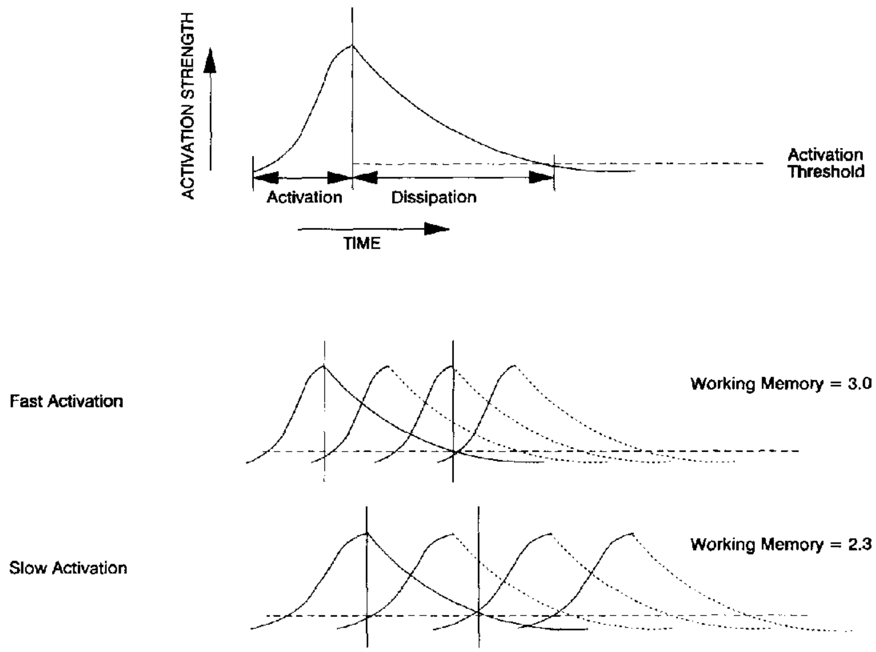

Figure 7. Schematic illustration of major assumptions of the proposed explanation for how speed of processing might influence working memory functioning.

The path analysis results also indicated that a substantial proportion of the age-related differences in working memory appear to be mediated by reductions in processing efficiency.

Components investigated in Study 2 were storage capacity, processing efficiency, and simple perceptual comparison speed. The results indicated that processing efficiency could be decomposed into as-yet-unidentified complex factors and aspects related to simple speed and that most of the age-related influences seemed to be mediated through simple speed. This was apparent in the multiple regression analyses in which statistical control of the simple speed measures resulted in substantial attenuation of the age relations in the other measures and in the path analysis results that indicated that all the significant age-related influences on the working memory, storage capacity, and processing efficiency measures appeared to be mediated through the simple speed variable.

The results of these two studies clearly suggest that the efficiency of processing, and especially processing involving very simple operations, is an important factor contributing to age-related differences in working memory. However, although the correlational data indicate that an association exists between speed-related variance and memory-related variance, these data do not by themselves provide an explanation for that relation. A satisfactory explanation requires not only that a significant relation be established, but also that mechanisms be postulated to specify why that relation exists. Our speculations in this regard are an elaboration of earlier ideas by Salthouse (e.g., 1980, 1982, 1985, 1988).

The basic assumptions are portrayed in Figure 7. Notice that information is postulated to increase in activation strength over a relatively short interval and then to dissipate gradually over a longer interval. Working memory can be conceptualized in this framework as the amount of information for which, at any given time, the activation strengths are above a threshold.

Within this general framework, individual differences in working memory can be postulated to originate either because of variations in the rate of activation or because of variations in the rate at which information is lost or dissipated. We propose that increased age is associated with a reduction in the rate at which information is activated, but not in the rate at which it is dissipated. The basis for the claim that the dissipation rate remains constant across the adult years derives from tasks such as continuous recognition (e.g., Erber, 1978; Ferris, Crook, Clark, McCarthy, & Rae, 1980; LeBreck & Baron, 1987; Lehman & Mellinger, 1986; Poon & Fozard, 1980; Wickelgren, 1975), continuous paired-associate recognition (e.g., Balota, Duchek, & Paullin, 1989), keeping track of changing variables (e.g., Salthouse et al., 1991), and Brown-Peterson interference paradigms with variable-length retention intervals (e.g., Charness, 1981; Parkinson et al., 1985; Puckett & Lawson, 1989; Puckett & Stockburger, 1988; Talland, 1967). In each of these tasks it has been found that young and old adults have nearly parallel functions relating accuracy of performance to time, number of intervening items, or number of intervening operations. It therefore seems reasonable to infer from these results that the rate at which information is lost or dissipated is unrelated to age across most of the adult life span.

No direct evidence exists concerning the influence of age-related processes on the rate at which information is activated. However, there are well-documented findings that older adults require longer intervals to escape backward masking in tachistoscopic presentations (e.g., see Salthouse, 1982, for an early review), a phenomenon sometimes interpreted as reflecting the time needed to encode a single stimulus. The major results from our studies supporting the interpretation that increased age is associated with a reduction in the rate of activation are that the largest attenuation of the age-related influences was with the measures of processing efficiency and that this tendency was especially pronounced with very simple measures of processing efficiency or speed. Because the attenuation of the age relations on working memory was greatest for the simplest measures, it is apparently not the number or complexity of the operations that is important, but the speed with which even very elementary operations can be successfully executed. These simple measures can be postulated to provide better estimates of the time needed to activate stimuli than the more complex processing efficiency measures, and it may be for this reason that the greatest mediation of the age relations was apparent with the measures of simple comparison speed. It has been suggested that linkages between measures of speed and memory functioning might be attributable to the rate at which to-be-remembered items can be rehearsed or repetitively cycled in an articulatory loop (e.g., Baddeley, 1986; Salthouse, 1980). We suspect that information can be activated in many ways, however, and that a slower rate of articulation or rehearsal is only one of a large number of consequences of a slower speed of activating internal information.

The preceding speculations must, of course, still be considered quite tentative, but they do suggest a mechanism that might be involved in producing the relation that now seems to be reasonably well established. It may therefore be productive for future research to investigate not only the nature of the relations among age, processing efficiency or speed, and working memory, but also to examine specific hypotheses, such as the one just described, for why these relations exist.

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