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Influence of Task-Specific Processing Speed on Age Differences in Memory

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Two studies were conducted to investigate the aspect(s) of processing involved in the hypothesized speed mediation of adult age differences in memory. Both studies involved a serial memory task in which information was to be recalled either in the original order of presentation, or in a reordered sequence. Results from both studies indicated that task-specific processing durations were slower among older adults than among young adults, but that the attenuation of the age-related variance in memory was nearly as great after statistical control of a task-independent speed measure as after control of task-specific speed measures. These findings are consistent with the hypothesis that a substantial proportion of the adult age-related differences in memory is associated with a decrease with increased age in the speed of executing many cognitive processes, and not simply the speed of one or two specific processes.

THE goal of the studies described in this report was to investigate how processing speed contributes to the relations between age and memory. The relations of interest have been documented, and some initial evidence relevant to this issue has been provided, with data from earlier research (Salthouse, 1983, in press). The memory tasks in the previous studies were free recall of two lists of 12 unrelated nouns presented auditorily at a rate of ~2 seconds/word, and paired associate recall of six pairs of unrelated nouns also presented at ~2 seconds/word. The speed measures were derived from three paper-and-pencil tests of perceptual speed: digit symbol substitution, letter comparison, and pattern comparison. The average of the *z*-scores in the three tests served as a composite index of the speed with which the individual could execute elementary operations.

The results of these earlier studies are summarized in Table 1. Notice that in the first study there was a large attenuation of the age-related variance in the memory measures when the variance associated with the processing speed measure was statistically controlled (i.e., 87% attenuation with free recall, from an R^2 for age of .162–.021, and 85% attenuation with paired associates, from an R^2 for age of .162–.024).

An extreme-groups design was used in the second study, which resulted in larger age-related effects than those in the first study because of the omission of the variance associated with the intermediate ages. [The memory data were not reported in the Salthouse (1993) article, but most of the subjects from the second study in that project performed these tasks after completing the tasks reported in the article.] The speed and memory tasks were identical to those of the first study, but also included were measures of associational fluency that might be expected to be important in the performance of many memory tasks if effectiveness of elaborative encoding is related to the number of relevant associations that can be produced in a limited time. The measures were from tasks requiring the generation of as many words as possible, beginning with one of two stems (pro- and sub-) or ending with one of two terminations (-ay and -ow), and the average of the *z*-scores in the two tasks served as the measure of associational fluency.

It is apparent in the bottom panel of Table 1 that the major findings of the first study were replicated, as there was 91% attenuation of the age-related variance in free recall performance and 88% attenuation of the age-related variance in paired associates performance after control of the same composite speed measure. However, it was surprising that the attenuation of the age-related variance in memory was smaller after control of the presumably more specific fluency measure than after control of the more general speed measure; that is, only 44.5% attenuation with free recall performance and 37.1% attenuation with paired associates performance. Taken together, the results of these earlier studies suggest that processing speed, as indexed by various perceptual comparison tasks, is involved in the mediation of age differences in memory, and that the speed influence appears to be fairly general, in that it does not seem to be restricted to measures postulated to reflect memory-relevant processes. The existence of significant residual age-related variance even when the variation in speed is controlled indicates that other factors also contribute to the age differences evident in these tasks. Nevertheless, the discovery that influences independent of speed are associated with <15% of the total age-related variance for free recall and paired associate measures of memory suggests that some aspect of speed plays a major role in the relations between age and memory.

The purpose of the current project was to conduct a more detailed examination of the relation between speed and memory with a simpler task in which it might be possible to identify the mechanisms responsible for the apparent speed mediation of age-related differences in memory. The research strategy consisted of three distinct steps or phases. The first step was to determine the amount of age-related variance in the criterion measure of memory before and after controlling the variance in an index of processing speed derived from independent tasks. The goal of these analyses

Table 1. Regression Results From Previous Studies

		Free Recall			Paired Associates		
Equation		Cum. R^2	Incr. R^2	F for Incr. R^2	Cum. R^2	Incr. R^2	F for Incr. R^2
Salthouse (in press) — (N = 305, age 19–84, mean age = 51)							
1	Age	.162	.162	58.67*	.162	.162	58.65*
2	Speed	.225	.225	90.07*	.214	.214	84.57*
	Age	.246	.021	8.53*	.238	.024	9.53*
Salthouse (1993) — (N = 77, age 19–26, N = 69, age 57–89)							
3	Age	.546	.546	173.25*	.596	.596	212.07*
4	Speed	.518	.518	170.92*	.540	.540	197.16*
	Age	.567	.049	16.12*	.609	.069	25.17*
5	Fluency	.297	.297	106.15*	.247	.247	93.21*
	Age	.600	.303	108.48*	.622	.375	141.73*
6	Speed	.518	.518	184.43*	.540	.540	203.38*
	Fluency	.536	.018	6.37*	.543	.003	1.42
	Age	.601	.065	23.32*	.623	.080	30.06*

Cum. = cumulative; Incr. = increment.
$*p < .05$.

was to obtain an estimate of the magnitude of the overall speed influence on the age-memory relations, in a manner analogous to that described above.

The second step in the research strategy consisted of identifying measures of task-specific processing speeds, and then examining the relations of these measures to the criterion memory measure, and determining the extent to which the age-related variance in the memory measure was reduced after controlling the variance in the task-specific speed measures. The rationale for these analyses was that the mechanisms by which speed influenced relations between age and memory might be better understood by examining the duration of various components presumed to be involved in a given memory task. That is, in order for processing speed to influence performance it must affect quantitative or qualitative aspects of processing, and information about the duration of particular processing components may indicate which aspects of processing are affected in what manner. Also included in this phase are comparisons of the influence of the task-specific processing speed measures before and after controlling the variance in the speed measures derived from independent tasks. These comparisons are expected to be informative about the extent to which the influence of the task-specific speed measures is unique, and distinct from that associated with the speed measures obtained from independent tasks.

The third step in the research strategy involved using the task-specific speed measures as the criterion or predicted variable, and age and the speed measures from independent tasks as the predictor variables. Of interest in these analyses was the amount of unique age-related variance in the task-specific processing speed measures, as inferred by the residual age-related variance after control of the variation in the speed measures derived from independent tasks.

Two studies are reported, both involving a serial memory task in which (immediate) recall is either in the original order of presentation, or in a different order (numerical order with digit stimuli and alphabetical order with letter stimuli). Of particular interest is the condition in which reordering of the stimuli is required because the necessity of simultaneous processing and storage satisfies the criterion of a working memory task, and working memory has been implicated as an important factor in the age differences in many cognitive tasks (Salthouse, 1990). Because the amount of required processing is greater with reordered sequences, the age difference might be expected to be larger in that condition relative to recall in the original order if some of the age-related deficit is attributable to less efficient processing on the part of older adults (Babcock & Salthouse, 1990; Gick, Craik, & Morris, 1988; Morris, Gick, & Craik, 1988; Salthouse, 1990; Stine & Wingfield, 1987).

Study 1

Individual digits or letters were presented at a fixed rate, but subjects were encouraged to respond (by typing on a keyboard) both rapidly and accurately, and the interval between each successive keystroke in recall was monitored to obtain measures of the duration of task-relevant processing. Because the instruction about the order in which the items were to be recalled was not presented until after the last item in the sequence, the time required to conduct the processing associated with reordering the items could be estimated from the difference in recall time between original and reordered sequences. A baseline estimate of entry time when there was no memory requirement was also obtained by monitoring the time required to copy the items when they were displayed simultaneously on the screen. In order to obtain measures of a more general processing speed, all research participants also performed two computer-administered versions of the Digit Symbol Substitution Test (Salthouse, 1992).

METHOD

Subjects. — Characteristics of the 38 young and 38 old adults who participated in this study are summarized in Table 2.

Procedure. — All subjects performed the tasks in the same fixed order: Digit Symbol, Digit Digit, Copy Digits, Copy Letters, Memory Digits, and Memory Letters. Each task was preceded by a set of practice trials, 18 each in the Digit Symbol and Digit Digit tasks, and 6 each in the other tasks. The set of digit stimuli included the digits from 1 to 9, and the letter stimuli consisted of the first nine consonants in the alphabet. (Vowels were excluded to avoid the occurrence of easily remembered words.)

Measures of task-independent processing speed were obtained from computer-administered versions of the Digit Symbol Substitution and Digit Digit tasks (Salthouse, 1992). These tasks consisted of the presentation of either a digit and a symbol (Digit Symbol) or two digits (Digit Digit) that the subject was to classify as matching or not matching according to physical identity (Digit Digit), or according to a code table presented at the top of the display (Digit Symbol). Because accuracy averaged >94% for young and old adults in both tasks (cf. Table 2), the median response time across 90 trials, 10 repetitions of each digit, served as the primary performance measure in each task.

All items for a given trial were presented simultaneously on the computer screen in the copy tasks, and were to be typed on the keyboard either in the original (left-to-right) order of presentation or in a different order (alphabetic for letters, numeric for digits). The instruction about the order of entry (i.e., the word "Original" or the word "Reordered") was displayed simultaneously, and timing for the first keystroke started when the items were displayed.

The items in the Memory tasks were presented sequentially for 1 second each, with the prior item removed on presentation of each successive item. The task was to recall the items either in the order in which they were presented, or in a different order (alphabetic or numeric sequence). The instruction about the order in which the items were to be recalled was displayed immediately after the last item in the sequence, and timing of the keystroke entry started at that moment.

Table 2. Background Characteristics of Research Participants

	Study 1		Study 2	
	Young	Old	Young	Old
N	38	38	38	38
% Males	55.3	44.7	44.7	44.7
Age (range)	20.2 (18–23)	69.7 (58–80)	20.1 (18–25)	68.4 (55–78)
Education *(SD)*	14.2 (1.4)	15.2 (2.8)	13.9 (1.6)	15.0 (2.6)
Health *(SD)*	1.7 (.9)	1.8 (.8)	1.7 (.8)	1.7 (.7)
Digit Symbol				
Accuracy *(SD)*	95.2 (3.3)	94.5 (9.5)	96.2 (2.2)	95.4 (3.2)
Time *(SD)*	1,126 (215)	1,845 (363)	1,186 (226)	1,891 (445)
Digit Digit				
Accuracy *(SD)*	96.6 (2.2)	98.4 (1.7)	97.4 (2.0)	98.0 (2.7)
Time *(SD)*	523 (61)	767 (213)	551 (86)	768 (202)

Note. Education refers to number of years of formal education completed, and Health refers to self-rating of health on a 5-point scale with 1 = excellent and 5 = poor. Digit Symbol and Digit Digit accuracy values are percentage correct responses, and time values are in msec.

Each combination of task (copy, memory), stimuli (letters, digits), order (original, reordered), and number of items (3, 5, or 7) was represented by eight trials. The trial types were blocked according to task and stimulus type, but the number of items presented and the order of recall were randomly mixed within blocks. All variables except age were manipulated within subjects.

RESULTS AND DISCUSSION

Figure 1 displays the percentage of correctly recalled trials in each memory condition. An Age × Stimuli × Number × Order analysis of variance (ANOVA) was conducted on the data summarized in the figure. All main effects in this analysis were significant ($p < .05$): Age, $F(1,74) = 11.15$, $MS_e = 16.62$; Stimuli, $F(1,74) = 252.42$, $MS_e = 3.09$; Number, $F(2,148) = 703.05$, $MS_e = 2.62$; and Order, $F(1,74) = 31.30$, $MS_e = 5.03$. Only two interactions involving age were significant ($p < .05$): Age × Number, $F(2,148) = 8.29$, $MS_e = 2.62$; and Age × Number × Stimuli, $F(2,148) = 5.41$, $MS_e = 1.78$. It is noteworthy that the Age × Order interaction was not significant, $F(1,74) = 1.80$, $MS_e = 5.03$, $p > .15$, indicating that the overall age differences were not significantly larger when the processing demands were increased by requiring that the items be recalled in a different order from that in which they were presented.

The significant three-way interaction was decomposed by conducting Age × Stimuli ANOVAs on the data with each number of items. The Stimulus effect was significant in each analysis (i.e., $Fs > 10.2$), but neither the Age main effect nor the Age × Stimulus interaction was significant in the

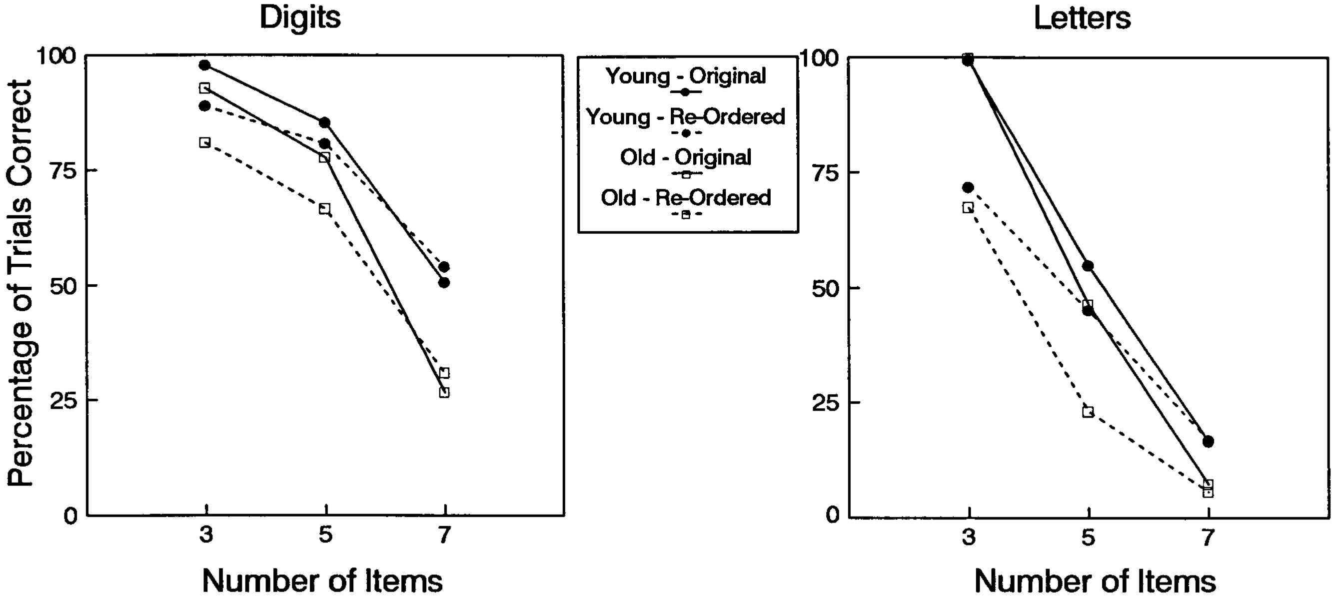

Figure 1. Mean percentage correct across original and reordered sequences for 3, 5, and 7 items for young and old adults, Study 1.

data based on 3 items, and only the main effect of Age was significant with 5 items, $F(1,74) = 8.31$, $MS_e = 5.00$. Both the main effect of Age, $F(1,74) = 22.56$, $MS_e = 3.06$, and the Age × Stimuli interaction, $F(1,74) = 8.86$, $MS_e = 1.22$, were significant with 7-item sequences. Inspection of Figure 1 reveals that this latter interaction is attributable to a larger age difference with digits than with letters, but the low level of performance with letters raises the possibility that the interaction is an artifact of a measurement floor with the letter stimuli.

A detailed examination was also conducted of processing times obtained during the performance of the task. Very few subjects were accurate on many trials involving 7 items, and thus the analyses were restricted to 5-item sequences. The analyses were further limited to subjects with at least one correct trial in both the original and the reordered sequence with each type of material, in order to ensure complete data from each subject. This resulted in subsamples of 29 young adults and 25 older adults. The ages of the subjects in the subsample were similar to those in the entire sample (i.e., young 20.1 vs 20.2, and old 68.6 vs 69.7), although both age groups in the subsample had somewhat faster Digit Symbol scores than the total sample. That is, the means were 1,079 msec in the subsample vs 1,126 msec in the total sample for young adults, and 1,792 msec in the subsample vs 1,845 msec in the total sample for older adults.

The means across subjects of the median time per item in correct memory trials and correct copy trials for each serial position are displayed in Figure 2. Separate Age × Order × Serial Position ANOVAs conducted on the copy and memory data with digit and letter stimuli revealed that all main effects and interactions were significant ($p < .05$), except for the Order effect in the Digit Copy condition. The data in Figure 2 indicate that the first entry is rather slow, and that the remaining items are entered quite rapidly except when the items must be reordered from memory, and particularly with letter stimuli. Both young and old adults were somewhat slower in the recall of the third item, possibly because the items were initially reordered in two-item groups. (Results from a similar analysis based on the data from 16

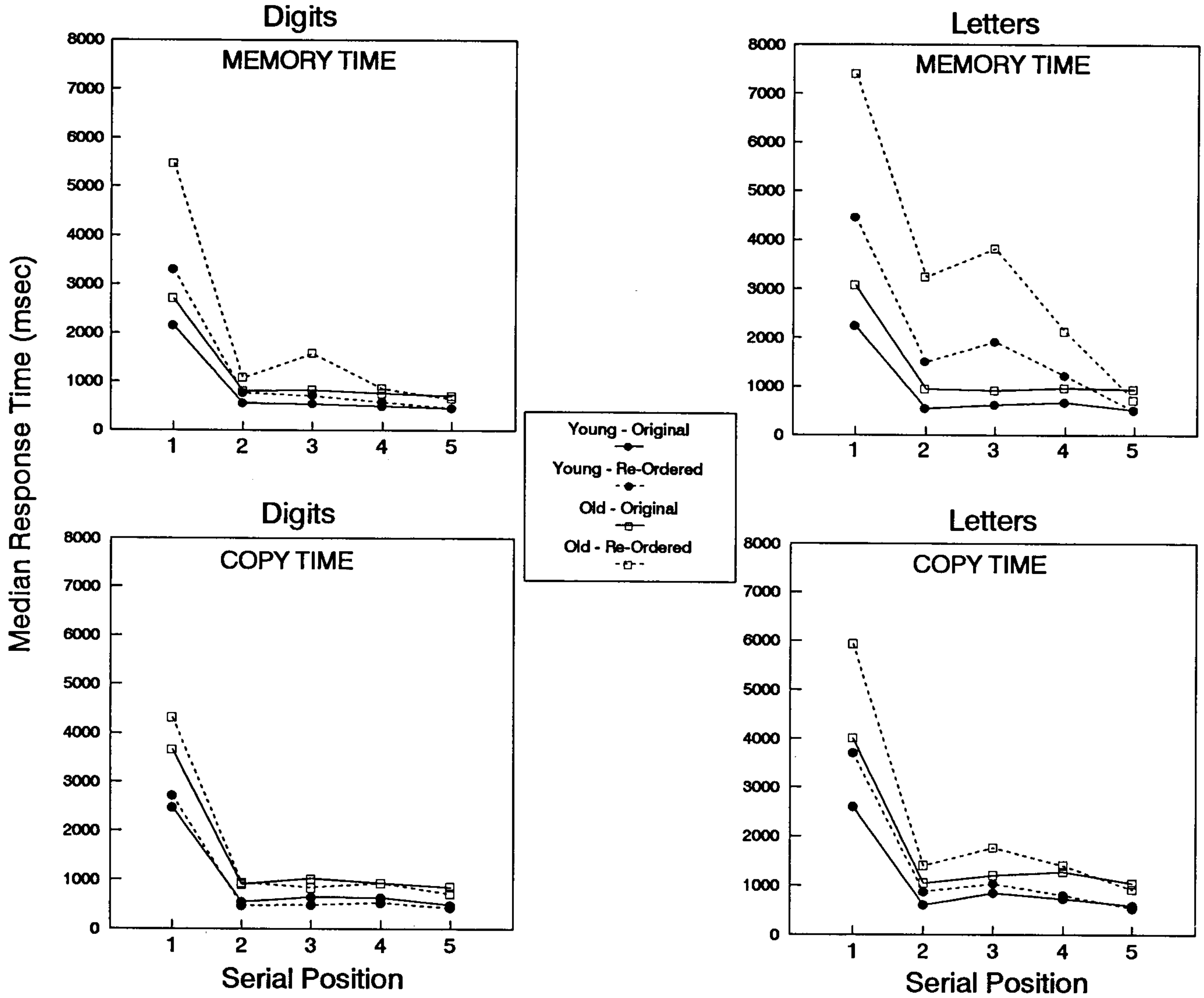

Figure 2. Median response time in 5-item copy and memory trials with original and reordered sequences for young and old adults, Study 1.

young subjects with at least one correct trial on the 7-item lists in every condition were consistent with this interpretation because there were two peaks in the recall times of 7-letter lists, one at the third item and another at the fifth item.) The slower entry on the third item is largely restricted to memory processing, because it is not pronounced in the copy task. Perhaps the most important point to be noted from the data in Figure 2 is that, although the older adults were generally slower than the young adults, the overall pattern appears very similar in the two groups.

The median entry times in the copy and memory tasks with original and reordered recall were used as predictors of recall accuracy with 5-item lists. (Data from 3-item and 7-item lists were not included to avoid measurement ceilings and floors.) An additional predictor was a composite measure of task-independent processing speed created by averaging the *z*-scores for the time measures from the Digit Symbol and Digit Digit tasks, which has a correlation of .71 with each other. The results of the hierarchical regression analyses for the 54 subjects with complete data are summarized in Table 3. Regression analyses including the task-specific speed measures were designed such that the times for the simplest or most fundamental processes were entered first, followed by times representing more complex processes. That is, the entry time in the copying condition preceded the entry time in the memory condition in the prediction of both original and reordered recall accuracy, and the entry time in original recall preceded the entry time in reordered recall in the prediction of reordered recall accuracy. Analyses were also conducted with component durations derived by subtracting one time from another (e.g., entry time with recall in original order was subtracted from entry time in reordered recall to yield a measure of reordering time). However, the results of those analyses are not reported because these difference score measures had low reliability and exhibited very weak relations to the criterion memory performance measures.

Five major points should be noted about the results in Table 3. First, there is no significant age-related variance in the accuracy of recalling 5 items in their original order of presentation (Equation 1). Second, there is significant age-related variance in the accuracy of recalling items in a different order (Equation 5), and it is still significant after recall accuracy in the original order is controlled (Equation 7). Third, both the age-related variance (Equation 6) and the influence of recall in the original order (Equation 8) are reduced when the task-independent speed measure is controlled. In fact, examination of Equations 6 and 8 reveals that there was no residual age-related variance in the measure of reordered recall after eliminating the variation in the task-independent speed measure.

The fourth point to note from Table 3 is that significant relations were evident between the task-specific speed measures and memory performance (Equations 3, 9, and 10). Furthermore, the age-related variance in reordered recall was substantially reduced after controlling the variation in these task-specific measures (Equations 9 and 10). However, the fifth point to be noted is that the reduction in the age-related variance was greater, and the relations between memory and the task-specific speed measures weaker, after the task-independent speed measure was controlled (Equations 11 and 12).

The relation of age on the task-specific processing durations before and after control of the task-independent speed index was also examined in regression analyses, with the results summarized in Table 4. Only in recall time for letters in their original order (Equation 6 with letter stimuli) was the age-related variance significantly greater than zero after the task-independent speed index was controlled. Even in this case, however, the degree of attenuation after control of the variance associated with the task-independent speed mea-

Table 3. Prediction of Performance With 5-Item Memory Lists (N = 54), Study 1

		Digits			Letters		
Equation		Cum. R^2	Incr. R^2	F for Incr. R^2	Cum. R^2	Incr. R^2	F for Incr. R^2
Original							
1	Age	.019	.019	1.03	.052	.052	2.84
2	Speed	.052	.052	2.82	.053	.053	2.86
	Age	.064	.012	.69	.056	.003	.18
3	CopyTime-O	.096	.096	5.42*	.099	.099	5.47*
	MemTime-O	.115	.019	1.12	.099	.000	.00
	Age	.117	.002	.06	.099	.000	.03
4	Speed	.052	.052	2.89	.053	.053	2.88
	CopyTime-O	.096	.044	2.46	.099	.046	2.51
	MemTime-O	.116	.020	1.16	.099	.000	.00
	Age	.123	.007	.39	.099	.000	.01
Reordered							
5	Age	.124	.124	7.39*	.194	.194	12.49*
6	Speed	.150	.150	9.05*	.227	.227	15.05*
	Age	.152	.002	.08	.230	.003	.21
7	Original	.100	.100	6.32*	.185	.185	13.66*
	Age	.197	.097	6.17*	.309	.124	9.11*
8	Speed	.150	.150	9.51*	.227	.227	17.13*
	Original	.205	.055	3.44	.336	.109	8.19*
	Age	.209	.004	.25	.337	.001	.11
9	CopyTime-R	.183	.183	11.71*	.173	.173	11.84*
	MemTime-R	.205	.022	1.42	.178	.005	.34
	Age	.219	.014	.89	.268	.090	6.09*
10	MemTime-O	.250	.250	16.74*	.148	.148	9.46*
	MemTime-R	.252	.002	.09	.148	.000	.00
	Age	.253	.001	.09	.218	.070	4.46*
11	Speed	.150	.150	9.44*	.227	.227	15.48*
	CopyTime-R	.199	.049	3.01	.256	.029	1.98
	MemTime-R	.214	.015	.99	.274	.018	1.21
	Age	.219	.005	.30	.281	.007	.50
12	Speed	.150	.150	9.90*	.227	.227	15.00*
	MemTime-O	.254	.104	6.83*	.248	.021	1.35
	MemTime-R	.255	.001	.06	.258	.010	.66
	Age	.255	.000	.01	.258	.000	.01

Note. Cum. = cumulative; Incr. = increment; CopyTime-O = median entry time in copy condition with original sequence; CopyTime-R = median entry time in copy condition with reordered sequence; MemTime-O = median entry time in memory condition with original sequence; MemTime-R = median entry time in memory condition with reordered sequence.

$^*p < .05$.

Table 4. Prediction of Recall (or Entry) Time Measures With 5-Item Lists from Age and Speed (N = 54), Study 1

		Digits			Letters		
Equation		Cum. R^2	Incr. R^2	F for Incr. R^2	Cum. R^2	Incr. R^2	F for Incr. R^2
Copy-Original							
1	Age	.409	.409	36.06*	.446	.446	41.88*
2	Speed	.554	.554	63.28*	.465	.465	46.52*
	Age	.554	.000	.00	.490	.025	2.46
Copy-Reordered							
3	Age	.289	.289	21.14*	.254	.254	17.73*
4	Speed	.487	.487	49.99*	.340	.340	26.28*
	Age	.503	.016	1.68	.340	.000	.00
Memory-Original							
5	Age	.421	.421	37.86*	.422	.422	37.89*
6	Speed	.464	.464	45.44*	.311	.311	27.46*
	Age	.479	.015	1.43	.422	.111	9.70*
Memory-Reordered							
7	Age	.200	.200	13.00*	.214	.214	14.12*
8	Speed	.275	.275	19.35*	.188	.188	12.29*
	Age	.275	.000	.01	.218	.030	1.96

Cum. = cumulative; Incr. = increment.
$^*p < .05$.

sure was considerable (i.e., 74%, from an R^2 of .422 to .111).

To summarize, the results of this study replicated the finding of substantial shared variance among age, perceptual comparison speed, and memory performance. In addition, the results indicated that although some of the task-specific speed measures were significantly related to the measures of memory performance, only a small proportion of those relations was independent of a presumably more general speed index derived from separate tasks. Moreover, nearly all of the age-related variance in the task-specific speed measures was shared with the task-independent speed measure.

Study 2

Kliegl and colleagues have recently provided convincing evidence that input processing time is an important factor in the age differences in serial recall by the finding that older adults need more time to achieve the same level of recall performance as young adults (Kliegl, Smith, & Baltes, 1989; Thompson & Kliegl, 1991). Furthermore, Thompson and Kliegl (1991) cite an unpublished study by Kliegl and Lindenberger as having found that the "age differences in recall accuracy were completely accounted for by individual differences in criterion-referenced encoding times" (p. 544). What is not clear from the Kliegl studies is whether the influence of input processing time is independent of a more general, or task-independent, processing speed, and whether a similar relation between encoding time and recall performance exists among untrained subjects (i.e., research participants in the Kliegl studies received extensive training with the method-of-loci mnemonic strategy).

The present study therefore included manipulations of stimulus presentation time to determine the relation between a measure of encoding time and recall accuracy. The stimulus duration required to achieve a specified level of accuracy was then used as the measure of the individual's stimulus encoding time. In most other respects the study was similar to Study 1. That is, the number of subjects was the same, they were recruited in the same manner, and the Digit Symbol and Digit Digit tasks were again used to provide an index of task-independent processing speed. However, because of the time needed to examine the effect of variations in stimulus presentation time, only the memory task with the 5-item letter sequences was administered.

METHOD

Subjects. — Characteristics of the subject samples, 38 adults in each of two age groups, are summarized in Table 2. None of these individuals had participated in Study 1.

Procedure. — The tasks were performed in the following order by all subjects: Digit Symbol, Digit Digit, and Memory Letters. The Digit Symbol and Digit Digit tasks were identical to those of Study 1. Mean levels of accuracy were >95% in both tasks and both age groups (cf. Table 2), and thus median time per response served as the primary dependent variable in these tasks.

The memory task differed from that in Study 1 by using only 5-letter stimulus sequences and by replacing the fixed stimulus duration of 1 second/item with a duration that varied across trial blocks. A different range of presentation times was used for young and old adults, because pilot research revealed that the older adults were seldom successful with presentation durations of 100 msec. Young adults therefore received durations of 100, 200, 400, 800, and 1,600 msec/item, whereas older adults received durations of 200, 400, 800, 1,600, and 3,200 msec/item. Blocks of 16 trials each were presented from the slowest to the fastest durations, and then again in the reverse order such that each presentation duration was represented by 32 trials. All trials in a given block had the same presentation time, but on a randomly selected half of the trials within each block the letters were to be recalled in the original order, and on half of the trials they were to be recalled in alphabetic order.

RESULTS AND DISCUSSION

The mean percentage of 5-letter trials recalled correctly as a function of stimulus presentation duration is displayed in Figure 3. An Age × Order × Duration ANOVA was conducted on the accuracy for trials with presentation durations common to both age groups (i.e., 200, 400, 800, and 1,600 msec). All three main effects were significant ($p <$ .05); Age, $F(1,74) = 46.18$, $MS_e = 57.71$; Order, $F(1,74) = 21.77$, $MS_e = 7.59$; and Duration, $F(3,222) = 146.73$, $MS_e = 6.03$, but none of the interactions involving age was significant (i.e., all $F < 1.3$).

Two methods were used to derive estimates of each individual's input processing time or task-specific encoding duration. One method was based on the fact that the means summarized in Figure 3 could be accurately (i.e., all R^2

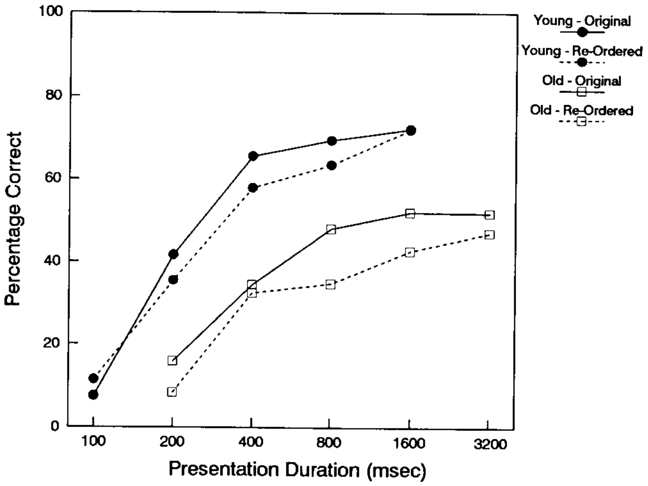

Figure 3. Mean percentage correct for original and reordered 5-letter sequences as a function of presentation duration for young and old adults, Study 2.

>.99) described by negative exponential functions of the form:

$$\text{Proportion Correct} = C * (1 - \exp(-(\text{time} - \text{A})*\text{B})).$$

The C parameter in this equation corresponds to the asymptotic level of accuracy, the A parameter to the time at which accuracy begins to increase, and the B parameter to the rate of increase in accuracy with additional time. Analyses based on the group means revealed that relative to older adults, young adults had smaller A parameters (i.e., .086 and .065 for original and reordered recall for young adults, and .100 and .151 for original and reordered recall for older adults), larger B parameters (i.e., 7.79 and 5.28 for original and reordered recall for young adults, and 3.63 and 4.73 for original and reordered recall for older adults), and larger C parameters (i.e., .711 and .689 for original and reordered recall for young adults, and .520 and .428 for the corresponding values for older adults). Because the asymptotic level of accuracy was only .428 with reordered recall in the older group, the time corresponding to an accuracy of .25 (i.e., correct recall of 25% of the lists) served as the measure of encoding time. (See Appendix, Note 1.) The times based on the equations from the group means were 142 msec for original recall in young adults, 150 msec for reordered recall in young adults, 281 msec for original recall in older adults, and 337 msec for reordered recall in older adults.

Because the goal was to derive encoding time estimates from each subject, attempts were made to fit negative exponential functions to the original and reordered recall data of each subject. Data of some subjects could not be fit because of small or unsystematic accuracy variations, and time estimates could not be derived in five additional cases because the accuracy asymptotes were less than the criterion value of .25. Age × Order ANOVAs were conducted on the parameters, and on the estimated encoding times corresponding to an accuracy of .25, for the 32 young adults and 27 older adults with relevant data. No effects were significant in the analyses of the A, B, or R^2 parameters, and only the Age effect was significant ($p < .05$) on the C parameter, $F(1,57) = 22.83$, $MS_e = .037$. All three effects were significant ($p < .05$) in the analysis of estimated encoding time: Age, $F(1,57) = 10.33$, $MS_e = .133$; Order, $F(1,57) = 13.52$, and Age × Order, $F(1,57) = 9.69$, $MS_e = .041$. Means of the estimated times were 169 msec for young adults with recall in the original order, 195 msec for young adults with recall in alphabetic order, 355 msec for older adults with recall in the original order, and 512 msec for older adults with recall in alphabetic order.

The second method used to estimate each individual's task-specific encoding time was based on linear regression equations relating log presentation time to accuracy across the three shortest durations (i.e., 100, 200, and 400 msec for young adults, and 200, 400, and 800 msec for older adults). These equations were then used to predict the duration required to recall 25% of the lists correctly. Data from five subjects, one young and four old, are omitted from these analyses because the encoding duration estimates were not meaningful due to correct recall of <25% of the lists across all three of the shortest presentation durations. Means of the correlations representing the goodness-of-fit of the regression equations were .92 and .90 for original and reordered trials, respectively, for the 37 young adults, and .81 and .80 for the two types of trials for the 34 older adults. An Age × Order ANOVA on the correlations revealed that only the Age effect was significant, $F(1,69) = 7.32$, $MS_e = .051$, $p < .05$, indicating that the relations between stimulus presentation time and accuracy were somewhat less precise for the older adults. The predicted durations corresponding to 25% accuracy averaged 139 msec for recall in the original order and 160 msec for recall in alphabetic order for the 37 young adults, and 412 msec and 626 msec, respectively, for the 34 older adults. Only the Age main effect was significant in the Age × Order ANOVA, $F(1,69) = 24.03$, $MS_e = .42$. Although the pattern of means suggests that an interaction might be present, the Age × Order interaction was not significant, $F(1,69) < 1.0$.

Correlations computed between the predicted times corresponding to correct recall of 25% of the trials derived from the two methods were very high, with $r = .95$ for the estimates in the original order condition and $r = .86$ for estimates in the reordered condition. Because estimates were available for more subjects when the linear regression method was used (i.e., 71 compared with 59), subsequent analyses were based on the encoding times derived from the linear regression procedure. It should be noted, however, that the high correlations between the two sets of estimates suggest that very similar results would have been obtained with encoding times derived from negative exponential functions.

Figure 4 displays the mean of the median recall times (averaged across trials with 1,600 and 800 msec presentation durations) by serial position. (These presentation durations were selected because they were the largest durations common to both age groups.) An Age × Order × Serial Position ANOVA revealed that all main effects and interactions except for the three-way interaction were significant (F's > 3.9, $p < .05$). Inspection of Figure 4 reveals that the pattern is very similar to the top right panel of Figure 2, in that the older adults were always slower than the young adults, and recall

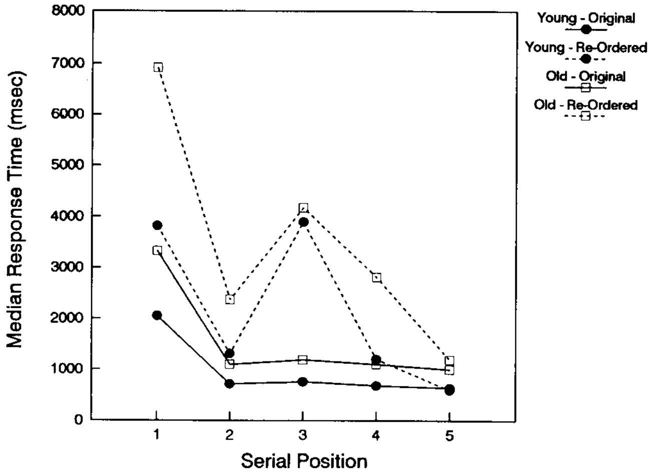

Figure 4. Median response time in 5-letter memory trials with original and reordered sequences for young and old adults, Study 2.

Table 5. Prediction of Performance With 5-Item Memory Lists From 1,600 and 800 Msec Presentation Duration Trials (N = 71), Study 2

Equation		Cum. R^2	Incr. R^2	F for Incr. R^2
Original				
1	Age	.279	.279	26.72*
2	Speed	.167	.167	15.75*
	Age	.280	.113	10.69*
3	Encoding Time	.301	.301	34.84*
	Age	.412	.111	12.88*
4	MemTime-O	.326	.326	34.88*
	Age	.365	.039	4.25*
5	Speed	.167	.167	19.102*
	Encoding Time	.376	.209	24.02*
	Age	.415	.039	4.42*
6	Speed	.167	.167	17.82*
	MemTime-O	.326	.159	17.06*
	Age	.373	.047	4.99*
7	Speed	.167	.167	20.12*
	Encoding Time	.376	.209	25.31*
	MemTime-O	.432	.056	6.67*
	Age	.453	.021	2.58*
Reordered				
8	Age	.381	.381	42.46*
9	Speed	.307	.307	34.96*
	Age	.403	.101	10.88*
10	Original	.512	.512	85.12*
	Age	.591	.079	13.21*
11	Speed	.307	.307	52.57*
	Original	.594	.287	49.14*
	Age	.609	.015	2.47
12	Encoding Time	.590	.590	120.52*
	Age	.667	.077	15.88*
13	MemTime-O	.375	.375	47.65*
	MemTime-R	.418	.043	5.49*
	Age	.473	.055	7.08*
14	Speed	.307	.307	62.61*
	Encoding Time	.644	.337	68.62*
	Age	.671	.027	5.66*
15	Speed	.307	.307	38.49*
	MemTime-O	.410	.103	12.89*
	MemTime-R	.431	.021	2.68
	Age	.473	.042	5.27*
16	Speed	.307	.307	61.93*
	Encoding Time	.644	.337	67.87*
	MemTime-O	.657	.013	2.64
	MemTime-R	.658	.001	.27
	Age	.678	.020	3.96

Note. Cum. = cumulative; Incr. = increment; Encoding Time = predicted stimulus presentation time required to achieve 25% accuracy; MemTime-O = median entry time in memory condition with original sequence; MemTime-R = median entry time in memory condition with reordered sequence.

$^*p < .05$.

time for reordered sequences was slower than recall in the original sequence, particularly in the third serial position.

Table 5 contains results of the analyses paralleling those reported in Table 3 for recall with presentation durations of 800 and 1,600 msec, which most closely correspond to the 1-sec presentation duration used in Study 1. Several points should be noted about the entries in this table. First, the age-related effects in letter recall were much larger in this study than in the previous study, both for recall in the original order (i.e., R^2 for age of .279 vs .052) and for recall in alphabetic order (i.e., R^2 for age of .381 vs .194). The reasons for the larger age relations in this study compared with those in Study 1 are not obvious because the procedure was generally similar and the samples appear comparable in most respects (see Table 2). The fact that more trials were administered in the relevant conditions in this study compared with the previous one (i.e., 32 vs 8) may have contributed to the difference across studies, either because of differential practice effects or increased reliability of the memory measure. (See Appendix, Note 2.) Second, although control of the composite perceptual speed measure substantially reduced the age-related variance (i.e., percentage attenuations of 59% and 73% for original and reordered recall, respectively), the residual age-related variance (Equations 2 and 9) was significantly > 0. This indicates that, unlike Study 1, control of the task-independent speed index is not sufficient to account for all of the significant age-related variance in immediate recall in this study. Third, significant age-related variance remains in the measure of reordered recall after the measure of recall in the original order is controlled (Equation 10), but not after the task-independent speed measure is also controlled (Equation 11). Both of these findings are consistent with the results of Study 1.

Another important finding to note from Table 5 is that statistical control of the task-specific (i.e., Encoding Time and Recall Time; Equations 3, 4, 12, and 13) speed measures resulted in substantial attenuation of the age-related variance in memory performance. That is, the percentage attenuation of the age-related variance was 60.2% and 86.0% after control of the encoding time and recall time speed measures for recall in the original order, and 79.8% and 85.6%, respectively, after control of these measures for recall in alphabetic order. The residual age-related variance was significantly greater than zero, indicating that factors independent of both these speed measures contributed to the age-related differences in memory performance. In this respect, the current results differ from those of Kliegl and Lindenberger, as reported in Thompson and Kliegl (1991). Another noteworthy result from Table 5 is that the relations between the task-specific speed measures and memory were smaller after control of the composite task-independent speed measure (i.e., Equations 3 vs 5, 4 vs 6, 12 vs 14, and 13 vs 15). This suggests that only a portion of the variance shared between memory and the task-specific speed measures was distinct from the presumably more general, task-independent speed measure.

A final set of regression analyses were similar to those of Table 4 in that they examined the extent to which the age-related variance in the task-specific speed measures could be accounted for by the task-independent speed measure. Results of these analyses are presented in Table 6. Notice that only with recall time for reordered recall (Equation 8) was there not significant residual age-related variance in the task-specific measures after control of the presumably more general measures of perceptual speed. However, it should also be noted that each of the task-specific speed measures had considerable age-related variance in common with the perceptual speed measure because control of the task-independent speed measure resulted in attenuations of 39.2%, 78.1%, 86.5%, and 94.4%, respectively, for the measures of original encoding time, reordered encoding time, original recall time, and reordered recall time.

Table 6. Prediction of Task-Specific Processing Times From Age and Speed (N = 71), Study 2

Equation		Cum. R^2	Incr. R^2	F for Incr. R^2
Encoding Time Measure				
Original				
1	Age	.166	.166	13.74*
2	Speed	.068	.068	5.58*
	Age	.169	.101	8.29*
Reordered				
3	Age	.237	.237	21.41*
4	Speed	.204	.204	18.64*
	Age	.256	.052	4.74*
Recall Time Measure				
Original				
5	Age	.443	.443	54.77*
6	Speed	.462	.462	65.72*
	Age	.522	.060	8.40*
Reordered				
7	Age	.338	.338	35.23*
8	Speed	.437	.437	54.65*
	Age	.456	.019	2.45*

*$p < .05$.

General Discussion

The primary question of interest in this project was, how does a slower processing speed contribute to age-related differences in memory? The research strategy consisted of trying to measure the durations of components postulated to be involved in a particular memory task, and then examining how these task-specific speed measures were related to age and to performance in the memory task, and how both sets of relations were influenced by speed measures derived from independent tasks.

Figure 5 illustrates a framework within which the present research can be interpreted. A major purpose of the studies reported herein was to examine the plausibility of each of the relations represented in this figure.

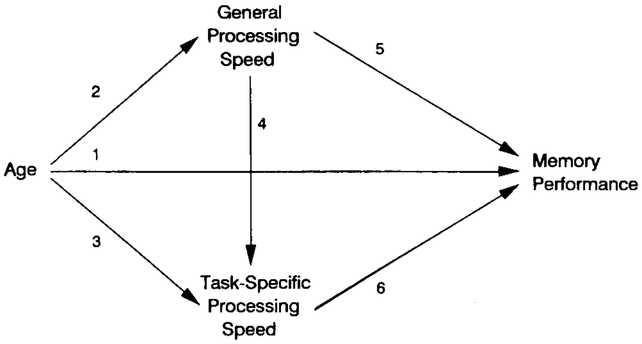

Figure 5. Illustration of hypothesized relations among age, memory performance, and general and specific measures of processing speed.

Three measures of task-specific processing speed were examined in these studies. The speed of initial registration and encoding of the items was represented by the stimulus presentation duration needed to correctly recall a specified percentage of lists, the speed of accessing or retrieving items from memory was represented by the additional time required to enter items from memory compared with entering them from the display (i.e., Equations 3, 4, 9, and 11 in Table 3), and the speed of reordering the items was represented by the additional time to enter items in a different order relative to entering them in the original order (i.e., Equations 10 and 12 in Table 3, and Equations 13 and 15 in Table 4). The measures of a presumably more general processing speed were derived from independent tasks requiring decisions about the physical identity or associational equivalence of a pair of items. Previous research (e.g., Salthouse, 1992) has suggested that memory factors contribute very little to the age-related variation in these tasks, and that performance on the tasks can be interpreted as primarily reflecting the speed with which relatively simple perceptual and cognitive operations can be executed.

Although path analytic or structural equation methods were not used in this project because of the small sample sizes, results from the current studies nonetheless allow a number of inferences to be drawn concerning the relations represented in Figure 5. First, consider the paths linking age to memory performance either directly (Path 1) or indirectly by means of a reduction in general, or task-independent, processing speed (Paths 2 and 5). (Note that a direct influence in this context merely means that it is independent of the other variables being considered, and not that it is unmediated by any factor.) The substantial reduction in the age-related variance in memory after the variation in the index of general processing speed was controlled implies that Paths 2 and 5 are involved in the relations between age and memory. However, the discovery that significant residual age-related variance remained in Study 2 after control of the index of general speed suggests that Path 1 sometimes contributes to the age-memory relations. Both of these pathways can be viewed as representing unexplained influences, because the mechanisms by which increased age, or a slower speed of performing perceptual comparison tasks, contributes to lower levels of memory performance cannot yet be specified.

Second, similar types of comparisons with the task-specific speed measures suggest that Paths 3 and 6 in Figure 5 are also involved in the relations between age and memory. That is, because the age-related variance in memory was reduced when the task-specific speed measures were controlled, it can be inferred that some of the age differences in memory are mediated through reductions in the speed of memory-specific processing. The causal mechanisms linking these task-specific speed measures to memory performance may be related to impaired quality of encoding, or to a greater loss of information. That is, the degree of elaboration of encoded information might be less, or the proportion of displaced or decayed information greater, when more time is required to encode, access, or process (i.e., reorder) to-be-recalled information.

And third, information about the relations between the general and specific measures of speed is available from results of regression equations predicting specific speed from age and the general speed measure (Tables 4 and 6), and predicting memory performance from age, the general speed index, and the specific speed measures (Tables 3 and 5). The former equations are relevant to the paths labeled 2, 3, and 4 because the strength of the indirect influence of age on the specific speed measures (Paths 2 and 4) can be inferred to be proportional to the degree to which the age-related variance in the task-specific speed measures is attenuated after control of the more general speed measure. The results in Tables 4 and 6 indicate that much of the relation between age and the task-specific speed measures is mediated through general speed (via Paths 2 and 4), although the existence of significant independent age-related variance in some measures indicates that Path 3 can also contribute to the relation.

Sequential examination of the influence of the general speed index, the task-specific speed measures, and age on the measures of memory performance is informative about the Paths labeled 1, 5, and 6 in Figure 5. Although there is some variation across the task-specific speed measures, it appears that all of the paths illustrated in Figure 5 can contribute to the relations between age and memory. That is, the age-related variance in memory performance is reduced when either the general or the specific speed measures are controlled, and, at least in some cases, there is still a significant relation between memory performance and the specific speed measure even after the general speed measure was controlled. Analyses with the general speed measure entered in the prediction equation after the specific speed measures were not reported in Tables 3 and 5, but results from these analyses were consistent with the preceding interpretation. That is, in at least several combinations of predictors and criterion memory measures, the influence of the general speed measure was still significant after removing the variance associated with the specific speed measures. This occurred after altering the order of entry of the variables in Equations 11 and 12 with letter stimuli in Table 3, and in Equations 5, 14, 15, and 16 in Table 5.

To summarize, the results of these studies confirm earlier findings of a large influence of processing speed on adult age differences in memory. Earlier research is also extended by revealing that increased age is associated with slower processing of several components hypothesized to be involved in the performance of these particular memory tasks. However, it is important to note that the task-independent and task-specific measures of speed have substantial age-related variance in common, and thus they are not independent. Indeed, the pattern of results is consistent with the interpretation that the age differences in the specific speed measures, including the encoding time measure based on procedures similar to those used by Kliegl and colleagues (Kliegl et al., 1989; Thompson & Kliegl, 1991), are partially caused by a more general age-related slowing.

Although these studies focused on encoding time, memory retrieval or access time, and processing or reordering time, it seems reasonable to expect similar results with other measures of relevant processing durations. For example, the reports that young and old adults differ in both memory performance and in subvocal rehearsal rate (Salthouse, 1980) or articulation rate (Kynette, Kemper, Norman, & Cheung, 1990) could be viewed as additional manifestations of the interrelations of age, a relatively general processing speed, and memory examined in these studies. Moreover, the current perspective leads to the expectation that if the durations of components such as association, elaboration, or organization could be assessed, then they would also be related to age and to more general measures of processing speed, as well as to memory. The causes of age-related differences in the postulated general processing speed have not yet been determined, and the exact manner by which slower processing reduces memory effectiveness still cannot be specified. Nevertheless, the results of these studies suggest that at least some of the age-related impairments in memory are attributable to declines with age in the speed of relevant processing, and that the speed of memory-specific processing is closely related to the speed with which the individual can perform other relatively simple tasks.

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Appendix

Notes

1. This particular level of accuracy is somewhat arbitrary, but encoding time estimates based on different levels of accuracy were highly correlated with one another. For example, the correlations in the sample of young subjects between encoding time estimates with accuracy levels of 10% and 25% were .92 (original) and .87 (reordered), and .94 (original) and .94 (reordered) between accuracy levels of 25% and 40%.

2. Reliability of the criterion memory measure could not be determined in Study 1, but the estimates in Study 2 derived by boosting the correlation between accuracy in the 800 and 1,600 msec conditions by the Spearman-Brown formula were .83 for recall in the original order and .88 for reordered recall.