Memory & Cognition
1993, 21 (5), 699-710

Decomposing adult age differences in symbol arithmetic

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A componential analysis was conducted to determine the locus of adult age differences in symbol arithmetic. Measures of the duration of two proposed components, substitution of digits for symbols and the addition or subtraction of the digits resulting from these substitutions, were obtained from 52 young adults and 52 older adults. Tests of working memory, perceptual speed, motor speed, and associative learning were also administered to all subjects. The results were most consistent with an interpretation postulating that the speed of many different cognitive processes decreases with increased age. Considerable age-related variance remained in the measures of symbol arithmetic performance after statistical control of working memory and associative learning performance, casting doubt on alternative hypotheses of the source of age-related differences in this task.

A potentially productive method of attempting to understand age-related influences on cognitive functioning is to begin with a moderately complex cognitive task that can be analyzed into discrete components. The goal is then to specify as precisely as possible the source or locus of the age differences in the complex task in terms of influences on single or multiple components. This analytical strategy was employed in the present study, with symbol arithmetic as the criterion task. That is, young and older adults were required to verify arithmetic problems of the form

$$\text{(symbol) [operator] (symbol)} = \text{digit},$$

with addition and subtraction as the arithmetic operations.

Performance on this task can be hypothesized to be determined by the efficiency of arithmetic processes and of processes responsible for substituting digits for symbols. Furthermore, it is postulated that the duration of these processes can be estimated from performance in three additional tasks (see Figure 1). That is, an estimate of the duration of arithmetic processes can be obtained from the time needed to perform a digit arithmetic (DA) task of the form

$$\text{(digit) [operator] (digit)} = \text{digit}.$$

And the duration required to substitute digits for symbols can be estimated from the difference between the response times in two tasks: digit-symbol (DS) substitution and digit-digit (DD) comparison. Both of these tasks involve yes/no decisions with respect to whether a pair of items matches, either according to a code table associating digits with symbols (i.e., DS), or according to physical identity (i.e., DD). Because the digit-symbol and digit-digit tasks are very similar (except that the digit-symbol task additionally requires substitution or transformation of the symbols into digits), the difference between the mean times in the two tasks can be postulated to represent the time needed to substitute digits for symbols.

According to this simple two-component model, therefore, the time to perform symbol arithmetic should be equal to the time required to perform arithmetic with digits plus the time required to carry out two symbol-digit substitutions. (Because processes associated with responding are common to all of the tasks, they are not represented as a separate component in this model.) Of course, to the extent that the arithmetic and substitution processes can overlap in their execution when performed together, the observed time may be less than that predicted from the sum of the durations of the components. On the other hand, the observed symbol arithmetic time could be greater than the sum of the durations of the hypothesized components, perhaps because the speed of certain operations depends on the familiarity of the elements upon which they operate (Gonzalez & Kolers, 1982). In order to allow for both of these possibilities, an additional term labeled *overhead*, which could be either positive or negative, can be added to the prediction equation. That is, assuming minimal and nearly equal error rates in all tasks, symbol arithmetic (SA) time should be decomposable into the following terms:

$$\text{SA} = \text{DA} + 2(\text{DS}-\text{DD}) + \text{overhead}.$$

The preceding analysis of the symbol arithmetic task allows four possible hypotheses for (the expected) adult age differences in symbol arithmetic performance to be investigated. These attribute the poorer performance of older adults relative to young adults to (1) less effective simultaneous, or overlapping, processing of component operations, (2) impaired working memory functioning,

This research was supported by National Institute on Aging Grant AG06824 to T.A.S. Correspondence should be addressed to T. A. Salthouse, School of Psychology, Georgia Institute of Technology, Atlanta, GA 30332-0170.

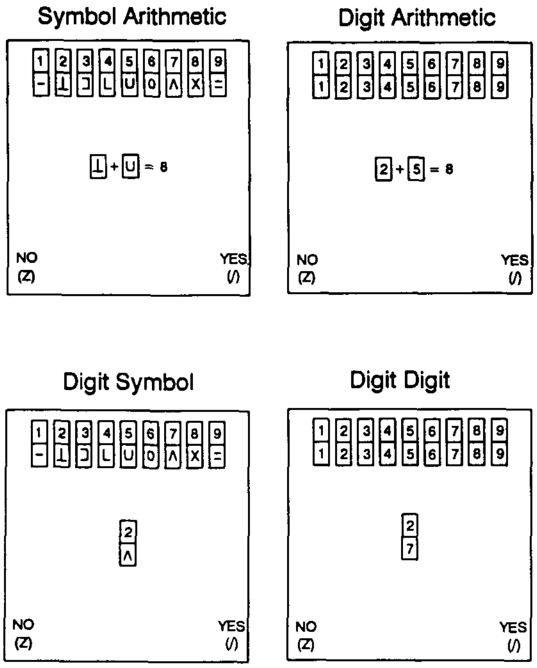

Figure 1. Illustration of the display for a sample trial in each of the four primary tasks.

(3) a deficiency in a critical process responsible for learning and using associations between digits and symbols, and (4) a reduction in the speed with which many processing operations can be executed.

The interpretation that adult age differences in symbol arithmetic might be attributable to variations in the efficiency with which processes can be executed simultaneously is based on the assumption that the duration of relevant processes can overlap, such that the actual time to perform the complete task is less than the sum of the estimated durations of the arithmetic and substitution processes. The primary expectation from this perspective is that the overhead values, reflecting discrepancies between the observed and predicted times, would be negative, and that the values would be more negative for young adults than for older adults because of age differences in the ability to execute processes simultaneously.

The working memory interpretation is based on the assumption that older adults are impaired relative to young adults in certain aspects of working memory functioning. Because tasks such as symbol arithmetic place moderately severe demands on working memory, older adults would be expected to be at a disadvantage relative to young adults. Considerable support exists for the assumption of age differences in working memory because many studies have reported that increased age is associated with poorer performance in tests of working memory (for reviews, see Craik & Jennings, 1992, and Salthouse, 1990). Evidence relevant to the role of working memory in mental arithmetic is available in a study by Charness and Campbell (1988). In their study, subjects from three different age groups were taught an algorithm to square two-digit numbers and were assessed on additional tasks designed to allow measurement of the duration of the components presumed to be involved in the mental squaring task. One of the most interesting findings from the Charness and Campbell study was that the discrepancy between the actual mental squaring time and the predicted time from the sum of the component durations was greater for older adults than for young adults. Charness and Campbell (1988) attributed the relation between age and this discrepancy or overhead measure to age differences in the operation of working memory, or more specifically to "the cost of maintaining intermediate products in memory, time to access these products, and the time to access the next step in the algorithm" (p. 116).

On the basis of the Charness and Campbell (1988) result and the Campbell and Charness (1990) results of error analyses, working memory effectiveness could be hypothesized to be a major factor contributing to adult age differences in relatively complex mental arithmetic tasks. Two specific predictions from the working memory hypothesis are examined in the present study. The first prediction is that if the overhead (i.e., discrepancy between predicted and observed times in symbol arithmetic) measure reflects the operation of working memory, then a significant positive correlation would be expected between the overhead measure and other measures of working memory. The second prediction is that statistical control of the overhead measure, or of other measures of working memory, should greatly reduce the magnitude of the age-related variance in symbol arithmetic performance. That is, if the age differences in symbol arithmetic are due to age-related variations in working memory, then those differences should be substantially attenuated when the variation in working memory is controlled.

The specific-deficit hypothesis in this study focused on the efficiency of substitution processes. Three recent studies (Salthouse, 1992b, in press-a), each involving adults from a wide range of ages, found evidence that increased age is associated with less efficient substitution processes. Correlations between age and the difference in the median times in the digit–symbol and digit–digit tasks, which is hypothesized to correspond to the duration required to carry out a substitution operation, were .33 for the sample of 131 adults in Study 3 of Salthouse (1992b) and .48 for both Study 1 (n = 246) and Study 2 (n = 258) of Salthouse (in press-a). It therefore seems reasonable to conclude that older adults are slower than young adults in carrying out the substitution processes needed to convert symbols into their corresponding digits. Thus, even if young and older adults are equivalent in their efficiency in performing arithmetic with digits, differences in the duration of this important component could be responsible for any age differences that exist in symbol arithmetic.

One prediction from the substitution inefficiency hypothesis is that statistical control of the estimated duration of substitution processes should greatly reduce the age-related variation in symbol arithmetic performance. The rationale is that if the age differences in symbol arithmetic are largely attributable to differences in the efficiency in substituting digits for symbols, then eliminating the variation in substitution duration would be expected to greatly attenuate the age-related differences in symbol arithmetic time.

Two further predictions can be derived if it is additionally assumed that reduced knowledge of digit-symbol associations contributes to the lower efficiency of older adults relative to young adults in substitution operations. First, in order to verify the basic assumption, older adults should exhibit poorer performance than young adults in a test of knowledge of digit-symbol associations and in a measure of the efficiency of learning the associations across successive trials. Second, the age differences in symbol arithmetic should be greatly reduced after the variation in associative learning performance is controlled. The reasoning for this latter prediction is identical to that with working memory or substitution efficiency as the controlled variable, except that in this case knowledge of digit-symbol associations is hypothesized to be the critical factor responsible for the age differences in symbol arithmetic performance.

The fourth hypothesis investigated in this study is based on the idea that many cognitive processes are slowed with increased age (e.g., Cerella, 1990), and that the slowing evident in some processes (such as the operations required for a particular cognitive task) is not independent of that evident in other processes (such as those involved in relatively simple perceptual speed tasks). There are two related predictions from this processing speed interpretation. The first is that statistical control of measures of processing speed, derived either from the component tasks or from completely separate tasks, should greatly reduce the magnitude of the age-related variance in symbol arithmetic performance. Again, the reasoning is that if the age differences in the criterion task are attributable to age-related variations in some construct (in this case, processing speed as indexed by performance in perceptual speed tasks), then eliminating the variation in measures of that construct should attenuate the age differences in the criterion task.

A second prediction is based on a quantitative adjustment for the overall speed difference on the group differences in symbol arithmetic time. The underlying assumption is that if young and older adults differ only with respect to the rate at which relevant operations are executed, then no age differences should remain when the times are adjusted for the overall rate difference as estimated from performance in other tasks. One means by which this prediction can be investigated involves determining the parameters of the regression equation relating the mean times of one group to the mean times of the other group, and then using those parameters to create simulated subjects from the other age group (see Madden, Pierce, & Allen, 1992). For example, the equation relating the mean times of older adults to the mean times of young adults could be applied to the data of each individual young adult to create a sample of simulated older adults. The times of these simulated older subjects could then be contrasted with the times of the actual older subjects to determine whether there are significant group differences in any of the speed measures after this "global" adjustment. In an analogous manner, simulated young subjects could be created by determining the regression equation relating the mean times of young subjects to the mean times of older subjects, and then applying the parameters from this equation to the data of individual older subjects. An even stronger test of the processing speed interpretation involves using performance in paper-and-pencil tests of perceptual speed, rather than performance in the component tasks, as the basis for adjusting the times to create simulated subjects. With both types of adjustment, the expectation from the slower processing speed interpretation is that there will be little or no difference in symbol arithmetic times between the actual and simulated subjects.

The simulation procedure differs from the hierarchical regression statistical control procedure in two important respects. First, it relies on the relation between group means as an indication of the nonspecific slowing influence, in accord with several recent proposals (e.g., Cerella, 1990; Madden et al., 1992). Second, it uses the relation determined at the group level to adjust the scores of each individual, both on new criterion variables (e.g., symbol arithmetic time) and on the same variables used to derive the general relation (e.g., times for the hypothesized components).

To summarize, four possible factors—degree of simultaneous processing of component operations, effectiveness of working memory functioning, efficiency of a specific process concerned with substitution, and relatively general speed of processing—that might account for adult age differences in symbol arithmetic performance were investigated. In order to test the predictions, samples of young and older adults performed a battery of tasks consisting of paper-and-pencil speed tests, tests of working memory, associative learning/testing of digit-symbol pairings, and the following tasks both before and after the associative learning: digit-digit, digit-symbol, digit arithmetic, and symbol arithmetic.

METHOD

Subjects

Fifty-two young adults (29 males and 23 females between 18 and 27 years of age, with a mean age of 20.2) received extra credit in a psychology course for their participation, and 52 older adults (26 males and 26 females between 60 and 80 years of age, with a mean age of 68.3) were recruited through advertisements or referrals and were paid for their participation. The average years of education completed by the young adults was 14.1 (SD = 1.4) and by the older adults was 15.5 (SD = 2.1). Each research participant evaluated his or her health on a 5-point scale ranging from 1 for *excellent* to 5 for *poor*. The average for the young adults was 2.0 (SD = 0.7), and that for the older adults was also 2.0 (SD = 0.9). These data indicate that the subjects in both age groups were highly educated and in good to excellent health.

Experimental Tasks

Four paper-and-pencil speed tests were administered to provide independent measures of each individual's processing speed. On the basis of previous research (Salthouse, in press-b), two of the tests, *boxes* and *digit copying*, were postulated to represent motor speed, and two other tests, *pattern comparison* and *letter comparison*, were assumed to reflect perceptual speed. All four tests were administered using booklets containing instructions and examples and a single test page for each test. The time allowed to work on the test page in each test was 30 sec, with a stopwatch used for timing.

The first paper-and-pencil test, boxes, contained 10 rows of 10 squares each, with one side missing from each square. The subjects were instructed to draw in the missing side for as many of the items as possible.

The second test, pattern comparison, contained two columns of 15 test items each. Each test item consisted of a pair of patterns composed of either three, six, or nine line segments. In half of the pairs, the two patterns were identical; in the other half, the two patterns differed in the position of one line segment. The subjects were instructed to write an S between each matching pair and a D between each different pair.

The third test, letter comparison, contained one column of 21 items. Each item consisted of two strings of either three, six, or nine letters. In half of the items, the two letter strings were identical; in the other half, the two strings differed in the identity of one letter. The subjects were instructed to write an S between each matching pair and a D between each different pair.

The fourth test, digit copying, contained 10 rows of 10 items each. Each item consisted of a pair of squares with a digit between 1 and 9 in the upper square and nothing in the lower square. The subjects were instructed to copy the digit from each upper square in the empty square below it.

Five tasks were administered on computers, although instructions and sample problems for each task were presented in booklets that could be studied, and referred to, as long and as frequently as desired. In addition, several practice trials were presented at the beginning of each task to ensure that the subjects understood exactly what they were supposed to be doing.

The reading span task was based on a task introduced by Daneman and Carpenter (1980), and is very similar to that described by Salthouse (1992a). The task required the subject to remember the last word of each of a number of short sentences while answering questions about those sentences. For example, the initial trial consisted of the presentation of one sentence along with a question about that sentence. The up and down arrow keys on the keyboard were then used to position an arrow in front of one of three possible answers to the question. After the ENTER key was pressed to register the response, the sentence disappeared from the screen, and the subject was to type the last word of the sentence. The number of sentences (and associated questions) per trial increased after every third trial as long as the subject correctly answered the questions and recalled all the to-be-remembered words on at least two of the three trials with a given number of sentences. The highest number of sentences at which the subject achieved this criterion served as the reading span measure.

The computation span task was based on a task described by Salthouse (1992a). In this task, the subject was required to solve simple arithmetic problems while remembering the last digit in each problem. The arithmetic problems consisted of a digit, a plus or a minus sign, another digit, and an equals sign. As in the reading span task, selection of the correct answer was indicated by using the arrow keys to move an arrow in front of the correct answer from among a set of three alternatives presented below the arithmetic problem. The number of items increased after every third trial as long as the subject correctly answered the arithmetic problems and recalled all of the to-be-remembered digits on at least two of three trials with a given number of problems. The highest number of problems at which the subject achieved this criterion served as the computation span measure.

The digit-digit and digit-symbol tasks were identical to those described by Salthouse (1992b). In both cases, a trial consisted of a display of a code table at the top of the screen and two boxes containing symbols or digits in the middle of the screen (see Figure 1 for an illustration). The task for the subject was to decide as rapidly as possible whether the items in the middle of the screen were equivalent, either with respect to physical identity in the digit-digit task or because the digit and the symbol matched according to the code table at the top of the screen in the digit-symbol task. The code table was present in both tasks, but in the digit-digit task it contained the same digits in both the top and the bottom box. In the digit-symbol task, the top boxes in the code table contained digits and the bottom boxes contained symbols. The probe stimuli, which were presented in the middle of the screen, were either two digits in the digit-digit task or a digit and a symbol in the digit-symbol task. Each block of trials in both tasks consisted of five repetitions of each digit in the top box, with three (or two) trials containing a matching item and two (or three) trials containing a mismatching item in the bottom box. Mismatching items were randomly selected from the noncorresponding digits (for the digit-digit task) or symbols (for the digit-symbol task). Responses were communicated by pressing the / key for yes when the probe items matched and by pressing the Z key for no when the probe items did not match. The subjects were encouraged to respond as rapidly and accurately as possible. Both median time per trial (in milliseconds) and percentage of error responses served as dependent variables.

The digit arithmetic and symbol arithmetic tasks were designed to be similar to the digit-digit and digit-symbol tasks with respect to the presence of the code table and the nature of the binary response, but to require the verification of an arithmetic equation rather than a comparison of physical identity or associational equivalence (see Figure 1). That is, the probe stimuli consisted of arithmetic equations of the form: $a + b = c$, or $a - b = c$. The c term was always a positive digit, and the a and b terms were either digits between 1 and 9 (in the digit arithmetic task) or the symbols corresponding to the digits between 1 and 9 (in the symbol arithmetic task). Constraints in the creation of the problems were that a was never equal to b, that a was always greater than b for the subtraction problems, and that on half of the problems the c term was the correct result of the left side of the equation and on half of the problems it differed by a value of 1 in either direction. Each block of trials contained five trials in which each digit (or its corresponding symbol) was in either the a or the b position in the arithmetic equation. Approximately one half of the trials involving each digit (or its corresponding symbol) were correct equations, and the remainder were incorrect equations. The subjects were instructed to press the / key if the equation was true and to press the Z key if the equation was false, and to respond as rapidly and accurately as possible. Median time per trial (in milliseconds) and percentage of error responses served as dependent variables.

Trials in the associative learning task involved the presentation of individual digits on the left of the display and the set of nine symbols in a column on the right of the display. The symbols and the pairings of symbols to digits were identical to those in the digit-symbol and symbol arithmetic tasks. The task for the subject was to use the arrow keys on the keyboard to position an arrow in front of the symbol that was associated with the probe digit. Ordering of the symbols varied from trial to trial to ensure learning of associations between digits and symbols rather than between digits and

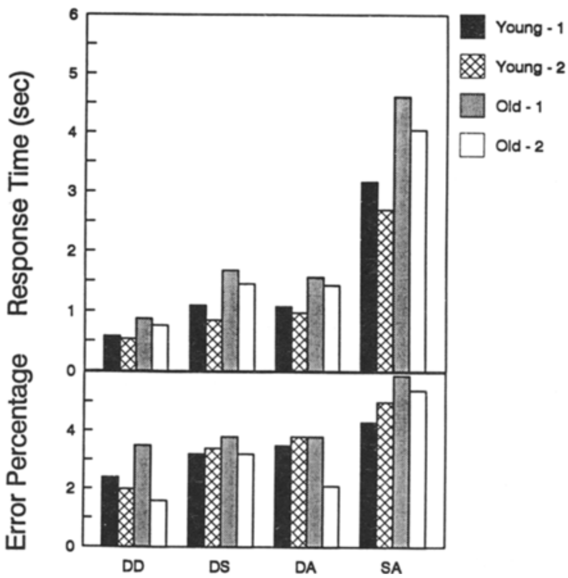

Figure 2. Mean response time (top panel) and mean error percentage (bottom panel) for young and older adults in the four primary tasks. The 1 refers to the first assessment, before associative learning, and the 2 refers to the second assessment, after associative learning.

positions. Accuracy feedback (i.e., highlighting of the correct alternative accompanied by an auditory tone) was presented after each response. The subjects were allowed to take as long as they wanted to make their selections in this task. A total of 90 trials were presented, one with each probe digit in each successive set of nine trials.

All subjects performed the tasks just described in the following order: boxes, pattern comparison, letter comparison, digit copying, reading span, computation span, digit-digit, digit-symbol, digit arithmetic, symbol arithmetic, symbol arithmetic, digit arithmetic, digit-symbol, digit-digit, associative learning, digit-digit, digit-symbol, digit arithmetic, symbol arithmetic, symbol arithmetic, digit arithmetic, digit-symbol, and digit-digit. Note that the primary experimental tasks were presented in a counterbalanced order before and after the associative learning, thus allowing pre- and post-associative learning to be used as an additional experimental factor in the analyses.

RESULTS

The results will be reported in four sections, beginning with the means and analyses of variance, followed by the correlations among the variables, then by the multiple regression analyses, and finally by the comparisons between actual and simulated subjects. A significance level of .05 was used for all statistical comparisons.

Analyses of Variance

Age (young, older) × pre/post (before and after associative learning) analyses of variance (ANOVAs) were conducted on the time and accuracy measures from the digit-digit, digit- symbol, digit arithmetic, and symbol arithmetic tasks. The means of these measures are displayed in Figure 2, and the results of the ANOVAs are summarized in Table 1.

The only significant effect in the analyses on the error measures was a main effect of age in the digit arithmetic task. As can be seen in Figure 2, this is attributable to greater errors (3.7%) by young adults than by older adults (2.4%). In contrast, the age effect was significant in all of the analyses of the time measures. Furthermore, the pre/post associative learning effect was significant on the digit-symbol, digit arithmetic, and symbol arithmetic measures. Because symbol-digit associations were not relevant in the digit arithmetic task, the pre/post improvement in this case is likely due to effects of the additional practice rather than greater knowledge of the symbol-digit associations. The age × pre/post interaction was signifi-

Table 1
F ratios (and MS_e terms) from Age × Pre/Post Associative Learning Analyses of Variance

	Age	MS_e	Pre/Post	Age × Pre/Post	MS_e
df:	1	102	1	1	102
Errors					
DD	0.80	.001	0.00	3.11	.001
DS	0.67	.001	1.23	2.83	.000
DA	9.01*	.001	1.23	2.27	.000
SA	2.72	.003	1.90	1.99	.001
Time					
DD	161.56*	23,012	0.55	11.34*	5,474
DS	144.30*	136,182	67.20*	0.36	11,380
DA	87.24*	149,637	20.77*	1.64	5,141
SA	125.36*	869,605	19.22*	1.51	107,716
Substitution Measure					
	60.77*	103,235	43.87*	6.39*	15,309
Overhead Measures					
Difference	10.20*	324,075	2.29	7.24*	121,308
Ratio	8.23*	.093	31.10*	22.03*	.035

Note—DD=digit-digit, DS=digit-symbol, DA=digit arithmetic, SA=symbol arithmetic. $*p < .05$.

cant on the digit-digit measure, reflecting a larger reduction for older adults (from 880 to 767 msec) than for young adults (from 586 to 542 msec). Because the digit-digit task was the first task of this type performed in the session, the interaction may be attributable to a longer period of becoming familiar with the overall situation, and with the requirement of speeded responding, for older adults relative to young adults.

Table 1 also reports results of analyses conducted on the estimated substitution duration, derived by subtracting the digit-digit time from the digit-symbol time. As expected, these times were longer for older adults than for young adults, and the durations were reduced after associative learning. The significant interaction is attributable to a greater reduction in the values for young adults, from 518 to 316 msec (39% reduction), than for older adults, from 809 to 697 msec (14% reduction).

Results of analyses conducted on the overhead measures are also presented in Table 1. Two methods can be used to compute the overhead measure. One is in terms of the difference between the observed (symbol arithmetic) and the predicted (digit arithmetic plus twice the difference between the digit-symbol and digit-digit) scores, and the other is in terms of the ratio of the observed and predicted scores. The latter method was used by Charness and Campbell (1988), apparently because of an assumption that proportions were more meaningful than absolute differences when there are group differences in baselines. As can be seen in Table 1, the pattern of results is different with the two measures. Means of the absolute differences were 1,045 msec before associative learning and 1,087 msec after associative learning for young adults, and 1,423 and 1,212 msec for older adults before and after associative learning, respectively. Means of the ratios were 1.50 and 1.70 for young adults before and after associative learning, and 1.51 and 1.47 for older adults before and after learning. With the difference score method, therefore, the interaction reflects a reduction in the overhead measure for older adults but not for young adults, whereas with the ratio method the interaction reflects no change for older adults but an increase for young adults. Because the componential model described in the introduction was based on the assumption of additive durations, the absolute difference method of computing the overhead measure was used in all subsequent analyses.

An age (young, older) × trial (10 successive presentations of each probe digit) ANOVA conducted on the number of correct digit-symbol associations in the associative learning test revealed that all effects were significant [age, $F(1,102) = 20.10$, $MS_e = 24.87$; trial, $F(9,918) = 19.78$, $MS_e = 0.74$; age × trial, $F(9,918) = 3.31$]. The interaction is a consequence of the age differences decreasing across successive trials, at least in part because of near-ceiling levels of performance for young adults (i.e., for young adults, Trial 1 = 90.3% and Trial 10 = 98.6%; for older adults, Trial 1 = 71.1% and Trial 10 = 86.7%). Not only is the interaction a possible measurement artifact, but the F ratios for age in separate analyses on each trial were all greater than 9, indicating that the accuracy of young adults was significantly higher than that of older adults on every trial. Furthermore, the correlation between number correct in the first trial (AL-1) and number correct in all trials (AL-All) was high (.83), and the correlations between age and performance on the first trial and performance across all trials were identical (both = −.39). When considered in combination, this pattern of results suggests that older adults relative to young adults have less incidental learning of the associations (as reflected by poorer performance in the first trial), possibly somewhat less intentional learning of the associations (as revealed by the significant age × trials interaction), and considerably lower levels of overall performance in the test of digit-symbol associations.

Correlations

The correlation matrix for the primary variables is presented in Table 2. Four points should be noted regarding the entries in this table. First, it is apparent that the reliabilities of the time measures are very high. The only value below .95 is with the initial digit-digit measure, which may be due to the fact that this was the first task performed in the session and performance may have been unstable because of unfamiliarity with the apparatus, with the response assignments, or with the appropriate emphasis on speed relative to accuracy.

Second, the correlations between the working memory measures and the overhead measures were quite small (i.e., $r = -.15$ to $-.22$). (It should be noted that the relations were similar for the computation span and reading span measures of working memory, and thus the low correlations are apparently not attributable to domain specificity of working memory.) The correlations with a composite measure of working memory, formed by averaging the z scores from the computation span and reading span measures, were of approximately the same magnitude—that is, −.21 for the preassociative learning overhead measure and −.23 for the postassociative learning overhead measure (both $ps < .05$). These results are therefore inconsistent with the hypothesis that the overhead measure represents the operation of working memory.

Third, the correlations between the number of correct digit-symbol associations in the initial trial of the associative learning test and the first digit-symbol, symbol arithmetic, and substitution measures were all moderately large (i.e., $rs = -.49$, $-.44$, and $-.50$, respectively). Subjects who perform faster in the tasks requiring substitution of symbols and digits, and who have shorter estimated substitution durations, therefore exhibit greater knowledge of the digit-symbol associations in a later test.

Fourth, the correlations between the number of correct digit-symbol associations across all trials of the associative learning test and the second digit-symbol, symbol arithmetic, and substitution measures were also relatively high (i.e., $rs = -.65$, $-.63$, and $-.74$, respectively). These results indicate that subjects with greater knowledge of the digit-symbol associations subsequently re-

Table 2
Correlation Matrix for Primary Variables ($n = 104$)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1 DD1	(78)	85	73	69	69	69	66	65	34	50	39	18	−27	−26	−23	−24
2 DD2		(96)	84	79	78	80	74	74	58	56	22	23	−26	−28	−29	−25
3 DS1			(96)	93	85	87	87	88	89	84	08	10	−49	−50	−29	−31
4 DS2				(98)	78	79	83	90	83	95	13	06	−61	−65	−31	−30
5 DA1					(95)	96	83	81	72	66	09	11	−35	−36	−31	−28
6 DA2						(98)	81	80	73	67	06	03	−33	−33	−29	−26
7 SA1							(95)	90	76	75	48	30	−44	−46	−38	−34
8 SA2								(98)	78	85	27	42	−62	−63	−37	−36
9 SUB1									—	82	−15	01	−50	−52	−25	−27
10 SUB2										—	06	−04	−70	−74	−28	−29
11 OH1											—	49	−03	−06	−22	−15
12 OH2												—	−15	−12	−20	−20
13 AL-1													—	83	20	27
14 AL-All														—	26	29
15 CS															—	54
16 RS																—
M	.73	.65	1.40	1.16	1.33	1.21	3.89	3.38	.66	.51	1.23	1.15	7.27	79.3	4.05	2.70
SD	.21	.15	.42	.40	.38	.36	1.05	.96	.30	.29	.56	.41	2.22	17.0	2.16	1.52
r_{age}	74	78	72	79	67	67	72	73	50	67	35	15	−39	−39	−30	−29

Note—Decimal points are omitted in the matrix. Correlations with absolute values greater than .20 are significantly ($p < .05$) different from zero. Values in parentheses on the diagonal are estimated reliabilities derived by applying the Spearman-Brown formula to the correlation between the measures from the two administrations of each task. The 1 and 2 after the letters refer to measures before and after associative learning. DD is digit-digit time, DS is digit-symbol time, DA is digit arithmetic time, SA is symbol arithmetic time, SUB is substitution defined as DS-DD, and OH is (absolute difference) overhead. AL-1 is the number of correctly associated symbols in the first trial of associative learning, AL-All is the number of correctly associated symbols across all trials of associative learning, CS is computation span, and RS is reading span.

spond faster in the tasks requiring substitution of symbols and digits and have shorter estimated durations for the substitution component.

Multiple Regression Analyses

Results of the multiple regression analyses with symbol arithmetic time as the criterion variable are summarized in Table 3. The left columns report the results of analyses on symbol arithmetic time before associative learning, and the right columns report the results of analyses on symbol arithmetic time after associative learning. In order to determine the influences on performance in the second assessment independent of those affecting the first assessment, symbol arithmetic time from the first assessment was entered as the initial predictor in all of the multiple regression equations predicting postassociative learning symbol arithmetic time.

Consider the results from the left columns first. It is apparent that the overhead measure (Equation 2), the composite working memory measure (Equation 3), the substitution duration measure (Equation 4), and associative learning performance (Equation 5) are all related to symbol arithmetic performance. However, there is still a relatively large, and statistically significant, amount of residual age-related variance when these variables are controlled. In contrast, the residual age-related variance is much smaller when measures of the component tasks (digit-digit, digit-symbol, and digit arithmetic) are controlled (Equations 6–10), and there is very little relation between working memory or associative learning and symbol arithmetic performance when the component measures are controlled (Equations 11 and 12). (It is not meaningful to include the overhead measure or the substitution measure in addition to the component measures as predictors of symbol arithmetic time because these measures are linearly dependent on the other predictors.) Because only a small proportion of age-related variance remains after the component measures are controlled, it can be inferred that unexplained age-related influences, although significantly greater than zero, are responsible for very little of the total age-related variance in symbol arithmetic performance. That is, the total proportion of age-related variance in symbol arithmetic time is .518 (Equation 1), but it is reduced by more than 97% (i.e., to .014, in Equation 10) after the variance in the measures of the hypothesized components was controlled. Because the reduction in age-related variance was much smaller after controlling the measures of working memory, substitution efficiency, and associative learning, these results provide little support for the working memory and substitution inefficiency interpretations discussed in the introduction.

The results in the right column of Table 3 indicate the variables associated with significant increments in variance in the second (postassociative learning) symbol arithmetic measure after the variance in the first (preassociative learning) symbol arithmetic measure had been removed. It can be seen that there is significant residual age-related variance when only the first symbol arithmetic measure is controlled (Equation 1′), but not when either the second digit-digit (Equation 6′) or the second digit-symbol

Table 3
Proportions of Variance in Symbol Arithmetic Time Associated With Various Predictors

Before Associative Learning				After Associative Learning			
Eq.	Pred.	R^2	Incr. R^2	Eq.	Pred.	R^2	Incr. R^2
				0	SA1	.804	.804*
1	Age	.518	.518*	1′	Age	.818	.014*
2	OH1	.227	.227*	2′	OH2	.828	.024*
	Age	.577	.350*		Age	.846	.018*
3	WM	.166	.166*	3′	WM	.807	.003
	Age	.550	.384*		Age	.820	.013*
4	SUB1	.581	.581*	4′	SUB2	.873	.069*
	Age	.734	.134*		Age	.875	.002
5	AL-All	.216	.216*	5′	AL-All	.860	.056*
	Age	.558	.342*		Age	.869	.009*
6	DD1	.434	.434*	6′	DD2	.817	.013*
	Age	.554	.120*		Age	.821	.004
7	DS1	.760	.760*	7′	DS2	.884	.080*
	Age	.777	.017*		Age	.885	.001
8	DA1	.692	.692*	8′	DA2	.818	.014*
	Age	.739	.047*		Age	.827	.009*
9	DD1	.434	.434*	9′	DD2	.817	.013*
	DS1	.761	.327*		DS2	.885	.068*
	Age	.778	.017*		Age	.885	.000
10	DD1	.434	.434*	10′	DD2	.817	.013*
	DS1	.761	.327*		DS2	.885	.068*
	DA1	.788	.027*		DA2	.886	.001
	Age	.802	.014*		Age	.886	.000
11	DD1	.434	.434*	11′	DD2	.817	.013*
	DS1	.761	.327*		DS2	.885	.068*
	DA1	.788	.027*		DA2	.886	.001
	WM	.798	.010*		WM	.888	.002
	Age	.810	.012*		Age	.888	.000
12	DD1	.434	.434*	12′	DD2	.817	.013*
	DS1	.761	.327*		DS2	.885	.068*
	DA1	.788	.027*		DA2	.886	.001
	AL-All	.792	.004		AL-All	.898	.012*
	Age	.804	.012*		Age	.898	.000
13	MS	.267	.267*	13′	MS	.819	.015*
	Age	.545	.278*		Age	.827	.008*
14	PS	.525	.525*	14′	PS	.823	.019*
	Age	.593	.068*		Age	.826	.003
15	MS	.267	.267*	15′	MS	.819	.015*
	PS	.544	.277*		PS	.830	.011*
	Age	.601	.057*		Age	.832	.002

Note—The regression equations in the right column all contain SA1 as the first predictor and the listed variables as subsequent predictors. The 1 and 2 after the letters refer to measures before and after associative learning. DD is digit-digit time, DS is digit-symbol time, DA is digit arithmetic time, SA is symbol arithmetic time, SUB is the estimated duration of substitution derived by subtracting DD from DS, and OH is (absolute difference) overhead. AL-1 is the number of correctly associated symbols in the first trial of associative learning, AL-All is the number of correctly associated symbols across all trials of associative learning, WM is the composite (Computation Span and Reading Span) measure of working memory, MS is the composite (Boxes and Digit Copy) measure of motor speed, and PS is the composite (Letter Comparison and Pattern Comparison) measure of perceptual speed. $^*p < .05$.

(Equation 7′) measure was also controlled. This suggests that most of the age-related variance in the second assessment of symbol arithmetic is attributable to age differences in the measures used to estimate substitution efficiency. The fact that the age-related variance was also reduced to near zero when the substitution measure was controlled (Equation 4′) is also consistent with this interpretation. Performance in the associative learning test was also significantly related to the residual symbol arithmetic measure (Equations 5′–12′), but significant age-related variance remained after control of associative learning performance when the component measures were not additionally controlled.

The postulated distinction between motor speed and perceptual speed in the paper-and-pencil measures was supported by the pattern of correlations among these measures. That is, the correlations were higher between measures postulated to represent the same construct (i.e., .70 between boxes and digit copy, and .70 between letter comparison and pattern comparison) than between measures postulated to represent different constructs (i.e., .33 to .57). Composite measures of motor speed (boxes and digit copy) and perceptual speed (letter comparison and pattern comparison) were therefore created by averaging z scores, and these composite measures were then used as predictors of symbol arithmetic time. It is apparent in Equations 13, 14, and 15 that significant age-related variance remains after these paper-and-pencil speed measures are controlled. However, it is noteworthy that the amount of age-related variance was reduced from over 50% (Equation 1) to less than 7% (Equation 14) when the perceptual speed composite measure was controlled. The finding that the magnitude of the reduction in age-related variance in measures of cognitive functioning was greater after control of a measure of perceptual speed (Equation 14) than after control of a measure of motor speed (Equation 13) is consistent with several recent studies (Salthouse, in press-a, in press-b).

Hierarchical multiple regression analyses were also performed on the associative learning, working memory, and digit-symbol measures in an attempt to identify the primary sources of the age-related differences in these variables. Results of multiple regression analyses conducted with performance in the associative learning test and the composite working memory measure as the criterion variables are summarized in Table 4. Notice that no significant age-related variance remained in associative learning performance after controlling for the variation in digit-symbol performance (Equation 4). Although this particular finding could reflect the common element of digit-symbol associations in both tasks, the similar reduction of the age-related variance after control of the paper-and-pencil perceptual speed measures (Equation 8) suggests that it is the speed with which elementary operations can be executed, and not merely knowledge of digit-symbol associations, that is primarily responsible for this attenuation.

The regression analyses with working memory as the criterion also reveal that the age-related variance was greatly reduced when either the digit-symbol measure (Equation 12) or the paper-and-pencil perceptual speed measure (Equation 15) was controlled. The discovery that most of the age-related variance in these types of working memory measures is shared with measures of perceptual speed is consistent with earlier research (Salthouse, 1991, 1992a; Salthouse & Babcock, 1991).

Results of regression analyses with digit-symbol time before and after associative learning as the criterion variable are summarized in Table 5. As in Table 3, the left column contains analyses of performance before associative learning, and the right column displays analyses of performance after associative learning with performance before associative learning as the initial predictor. Several points should be noted regarding the results in the left column. First, the significant residual age-related variance after digit-digit time was controlled (Equation 2) indicates that age differences in digit-symbol performance are attributable to more than the sensorimotor aspects of the digit-digit task. Second, the significant influence of performance in the associative learning test (Equations 3 and 4) suggests that knowledge of the digit-symbol associations contributes to digit-symbol performance. Third, the significant residual age-related variance after both associative learning performance and digit-digit performance are controlled (Equations 6 and 7) indicates that not all of the determinants of the age differences in digit-symbol performance have yet been identified. Nevertheless, it is important to recognize that over 93% (i.e., an R^2 associated with age of .521 [Equation 1] relative to .034 [Equation 6] of the age-related variance in digit-symbol performance is shared with measures of digit-digit and associative learning performance.

The most interesting results from the right column in Table 5 are that significant age-related variance in the second digit-symbol measure remains even after the first digit-symbol measure (Equation 1′), the digit-digit measure (Equation 2′), or the associative learning measures (Equations 3′ and 4′) have been controlled, either alone or in combination (Equations 6′ and 7′). All of the factors contributing to the age differences in the postassociative learning digit-symbol measure therefore cannot yet be specified.

The discovery that the age-related variance in digit-symbol performance was greatly reduced (i.e., by nearly 87%, from .521 to .068) when measures of perceptual speed were controlled is similar to reports from previous

Table 4
Proportion of Variance in Associative Learning and Working Memory Associated With Different Predictors

Eq.	Pred.	R^2	Incr. R^2
	Associative Learning		
1	Age	.152	.152*
2	WM	.096	.096*
	Age	.189	.093*
3	DD1	.067	.067*
	Age	.154	.087*
4	DS1	.252	.252*
	Age	.254	.002
5	DD1	.067	.067*
	DS1	.278	.211*
	Age	.294	.016
6	DD1	.067	.067*
	DS1	.278	.211*
	WM	.300	.022
	Age	.311	.011
7	MS	.083	.083*
	Age	.162	.079*
8	PS	.144	.144*
	Age	.169	.025
9	MS	.083	.083*
	PS	.153	.070*
	Age	.173	.020
	Working Memory		
10	Age	.111	.111*
11	DD1	.071	.071*
	Age	.112	.041*
12	DS1	.119	.119*
	Age	.134	.015
13	DD1	.071	.071*
	DS1	.120	.049*
	Age	.135	.015
14	MS	.041	.041*
	Age	.112	.071*
15	PS	.200	.200*
	Age	.200	.000
16	MS	.041	.041*
	PS	.202	.161*
	Age	.202	.000

Note—The 1 and 2 after the letters refer to measures before and after associative learning. DD is digit-digit time, DS is digit-symbol time, WM is the composite (Computation Span and Reading Span) measure of working memory, MS is the composite (Boxes and Digit Copy) measure of motor speed, and PS is the composite (Letter Comparison and Pattern Comparison) measure of perceptual speed. $^*p < .05$.

Table 5
Proportion of Variance in Digit-Symbol Time Associated With Different Predictors

Before Associative Learning				After Associative Learning			
Eq.	Pred.	R^2	Incr. R^2	Eq.	Pred.	R^2	Incr. R^2
				0	DS1	.873	.873*
1	Age	.521	.521*	1′	Age	.899	.026*
2	DD1	.539	.539*	2′	DD2	.873	.000
	Age	.610	.071*		Age	.902	.029*
3	AL-1	.244	.244*	3′	AL-1	.903	.030*
	Age	.576	.332*		Age	.927	.024*
4	AL-All	.252	.252*	4′	AL-All	.917	.044*
	Age	.578	.326*		Age	.940	.023*
5	WM	.119	.119*	5′	WM	.874	.001
	Age	.533	.414*		Age	.899	.025*
6	DD1	.539	.539*	6′	DD2	.873	.000
	AL-1	.634	.095*		AL-1	.910	.037*
	Age	.668	.034*		Age	.927	.017*
7	DD1	.539	.539*	7′	DD2	.873	.000
	AL-All	.643	.104*		AL-All	.925	.052*
	Age	.674	.031*		Age	.940	.015*
8	DD1	.539	.539*	8′	DD2	.873	.000
	WM	.563	.024*		WM	.874	.001
	Age	.620	.057*		Age	.903	.029*
9	MS	.250	.250*	9′	MS	.878	.005*
	Age	.541	.291*		Age	.900	.022*
10	PS	.530	.530*	10′	PS	.875	.002
	Age	.598	.068*		Age	.900	.025*
11	MS	.250	.250*	11′	MS	.878	.005*
	PS	.544	.294*		PS	.879	.001
	Age	.602	.058*		Age	.902	.023*

Note—The regression equations in the right column all contain DS1 as the first predictor and the listed variables as subsequent predictors. The 1 and 2 after the letters refer to measures before and after associative learning. DD is digit-digit time, DS is digit-symbol time, WM is the composite (Computation Span and Reading Span) measure of working memory, MS is the composite (Boxes and Digit Copy) measure of motor speed, and PS is the composite (Letter Comparison and Pattern Comparison) measure of perceptual speed. $^*p < .05$.

studies (Salthouse, 1992b, in press-b). Of particular interest in this study is the finding that the reduction in age-related variance in the computer-administered digit-symbol task when the paper-and-pencil measure of perceptual speed (Equation 10) was controlled was nearly equivalent to that when the computer-administered measure of digit-digit time (Equation 2) was controlled.

To summarize the regression results, the largest reduction of the age-related variance in the symbol arithmetic measure occurred after controlling the measures representing the component durations, with much less attenuation of the age-related effects after controlling measures of working memory or associative learning. Furthermore, there was no significant residual age-related variance in the working memory and associative learning measures after controlling the measures representing the component durations. The apparent implication of this pattern of results is that speed factors play an important role in the age differences in working memory and associative learning as well as those in symbol arithmetic.

Comparisons of Simulated Subjects

The influence of a widespread or relatively general age-related slowing on the age differences in symbol arithmetic performance was examined by adjusting the times of one group of subjects by a factor determined by the mean performance differences between the two groups in other speeded tasks. An assumption of these analyses is that the effect of a relatively general age-related slowing can be eliminated by adjusting the observed times of young (or older) adults to create simulated older (or young) adults. Any performance differences that remain between the simulated and actual subjects can therefore presumably be attributed to specific influences that are distinct from any general age-related slowing that might exist.

Two methods of forming simulated subjects were used to create both simulated young adults and simulated older adults. One method is based on the regression equation relating the mean times in the two groups across six component measures (digit-digit, digit-symbol, and digit arithmetic before and after associative learning), and the other method is based on the ratio of the scores in the paper-and-pencil perceptual speed measures. (Actually, it is the inverse of the paper-and-pencil measures because these measures are in units of items per time rather than in time per item.) Simulated older subjects were created by adjusting the times of actual young subjects, and simulated young subjects were created by adjusting the times of actual older subjects. The regression equations relating the mean times of the two groups in the computer-administered component tasks were

$$\text{older}' = -.005 + 1.52\ (\text{young}),\ R^2 = .95$$

and

$$\text{young}' = .046 + .62\ (\text{older}),\ R^2 = .95.$$

The means for the sum of the letter comparison and pattern comparison measures were 34.48 for the young adults and 23.23 for the older adults. These values led to adjustment factors of (34.48/23.23) = 1.48 to relate the times of older adults to the times of young adults, and (23.23/34.48) = .68 to relate the times of young adults to the times of older adults.

The t test values for all of the relevant contrasts are reported in Table 6. The top row indicates results based on differences between actual young and older adults, the second and third rows represent contrasts of actual young subjects with simulated young subjects created by reducing the times of each older subject by a specified amount, and the fourth and fifth rows contrast actual older subjects with simulated older subjects created by increasing the times of each young subject by a specified amount.

It can be seen that the group differences evident in row 1 are eliminated on most of the measures in the contrast of actual and simulated subjects, with the notable exception of the second digit-symbol measure. The actual-simulated differences with the symbol arithmetic measure in the second row and with the digit-digit measure in the fourth row are in the opposite direction of the observed young-older differences, indicating that the adjustment in these cases was too large. However, because these discrepancies are not consistent across the different types of simulations, they should probably not be considered very reliable. In contrast, the underadjustment for the second digit-symbol measure was evident in all simulations, and thus it appears to be quite robust. This discrepancy is also

Table 6
***T* Values in Comparisons of Original and Simulated Data**

	DD1	DD2	DS1	DS2	DA1	DA2	SA1	SA2
				Actual				
Young vs. Older	−10.43*	−11.50*	−9.79*	−11.96*	−8.36*	−8.37*	−9.70*	−10.01*
				Simulated				
Young vs. Y'_1	−0.27	1.42	0.26	−2.73*	1.41	0.97	2.18*	1.42
Young vs. Y'_2	−0.58	1.34	−0.96	−3.68*	0.32	0.01	0.24	−0.49
O'_1 vs. Older	0.20	2.30*	−0.22	−2.97*	1.01	0.67	1.05	0.32
O'_2 vs. Older	−0.40	1.57	−0.81	−3.52*	0.47	0.15	0.40	−0.33

Note—Y'_1 = Simulated young adults created by adjusting each older adult's times by the equation: Y′ = .046 + 0.62 (Time). Y'_2 = Simulated young adults created by adjusting each older adult's times by the equation: Y′ = .68 (Time). O'_1 = Simulated older adults created by adjusting each young adult's time by the equation: O′ = −.005 + 1.52 (Time). O'_2 = Simulated older adults created by adjusting each young adult's times by the equation: O′ = 1.48 (Time). *$p < .05$.

evident in the ratios of the mean time of older adults to the mean time of young adults because the ratios were between 1.42 and 1.53 for all measures except for the second digit-symbol measure, which was 1.71. It can therefore be inferred that the age differences in the post-associative learning digit-symbol measure are larger than expected by the overall pattern of age-related slowing. Of greatest importance in the present context, however, is the discovery that the age differences in the symbol arithmetic measures were eliminated, or possibly even reversed, after adjusting for the age-related slowing apparent in other speed measures.

DISCUSSION

The primary question motivating this research was, what accounts for adult age differences in symbol arithmetic? Before considering the interpretation that received the most support, the interpretations with contradictory or inconsistent evidence will first be reviewed.

There was no evidence for age differences in the efficiency of parallel processing because the mean overhead, or observed-minus-predicted discrepancy, values were all positive. Moreover, only 1 out of 208 individual values (pre- and postassociative learning for each of 104 subjects) was negative. Because the actual time to perform the complex task was longer than the sum of the durations of the components, no evidence of overlapping or parallel processing exists in these data.

The working memory interpretation was also not supported because correlations between the working memory measure and the overhead measure were very weak. The relations were also quite small when the residual variance in symbol arithmetic performance after control of digit-digit, digit-symbol, and digit arithmetic (Equation 11 in Table 3) was used as an indirect measure of overhead. This pattern of results obviously raises questions about whether the overhead measure actually reflects the functioning of working memory. The results of another type of comparison lead to the same concern. That is, if the overhead measure reflects working memory functioning, then one might expect a higher correlation between the working memory measure and the overhead measure (which is the presumed working memory component in symbol arithmetic) than between the working memory measure and the measure of overall performance in the symbol arithmetic task (which should involve many determinants in addition to working memory). However, the correlations with the composite working memory measure were −.41 for the symbol arithmetic measures both before and after associative learning and only −.21 and −.23 for the overhead measures before and after associative learning. Although some of the difference in the magnitude of these correlations might be attributable to differences in the reliabilities of the symbol arithmetic and overhead measures, additional analyses suggest that this is not the major factor. That is, correlations with working memory corrected for unreliability in the symbol arithmetic and overhead measures, using the correlation between the first and second assessment as the estimate of reliability, were −.42, −.25, and −.27 with the symbol arithmetic and two overhead measures, respectively.

Another result inconsistent with the working memory interpretation of the age differences in symbol arithmetic is that the reduction of the age-related variance in symbol arithmetic time was relatively small after control of the overhead measure (Equation 2 in Table 3) or after control of the composite working memory measure (Equation 3 in Table 3). Although it could be argued that the working memory measures in this study were not very reliable or valid, the same measures have been found to have significant relations with other cognitive measures (e.g., Salthouse, 1991, 1992c). Furthermore, the correlation between age and the composite working memory measure in this study (i.e., $r = -.33$) is similar to the correlations of −.38 and −.53 reported in two samples by Salthouse (1992a).

The existence of significant age relations in the substitution measures in Tables 1 and 2 and the significant residual age-related variance in digit-symbol performance when digit-digit performance was controlled (Equation 2 in Table 5) are consistent with the interpretation that the age differences in symbol arithmetic time originate because of age differences in the efficiency of substitution processes. Furthermore, the significant age differences in the first trial of associative learning indicate that there was less incidental learning of the digit-symbol associations by older adults, and the significant age × trials interaction in the number of correct trials in the associative learning test suggests that there may be an age difference in the efficiency of intentional learning of the associations. However, there are also several important pieces of contradictory evidence. For example, a substantial amount of age-related variance in symbol arithmetic time remained when a measure of substitution efficiency was controlled (Equation 4 in Table 3). The amount of age-related variance in symbol arithmetic time was also very similar before ($R^2 = .52$) and after ($R^2 = .53$) associative learning, instead of being greatly reduced after subjects have had an opportunity to learn the associations. Furthermore, there was substantial age-related variance in symbol arithmetic after performance in the associative learning test was controlled (Equation 5 in Table 3), and the subjects were presumably equated in their knowledge of the digit-symbol associations. When considered together, therefore, the evidence is mixed with respect to the interpretation postulating a specific deficit concerned with substitution processes. There are sizable age-related differences in the measure of substitution efficiency and in several measures of association learning, but the failure of other predictions suggests that this is not the complete explanation for the age differences in the symbol arithmetic task.

The major assumption of the processing speed interpretation is that no single component is critical, but that many types of processing are slowed with increased age, and all could contribute to impairments in performance of cognitive tasks. Although some measures are postulated to be better indicators or markers of the processing speed construct than others, it is assumed that many cognitive impairments originate because of reductions in the speed of a large number of processes rather than because of deficiencies in only a few crucial processes.

Several findings in the current study are consistent with the processing speed interpretation. First, the multiple regression results in Table 3 indicate that the age-related variance in symbol arithmetic was greatly reduced when the variance in the speed of the component measures was controlled. Moreover, the attenuation of the age-related variance was substantial even when the speed measures being controlled were derived from two very short (30-sec) paper-and-pencil tests of perceptual speed (Equation 14). And second, the group differences in the symbol arithmetic measures were small to nonexistent when the times of young subjects (or older subjects) were adjusted for the overall speed differences evident in other measures. It is also noteworthy that processing speed appears to be very important in the age differences in associative learning and working memory, because the results summarized in Table 4 indicate that nearly all of the age-related variance in these measures was eliminated when the variance in the digit-symbol or perceptual speed measures was controlled.

Although speed factors appear to be involved in many of the age differences reported in this study, it is important to mention that they are not the only factors responsible for age-related differences. For example, significant age-related variance remained in the first symbol arithmetic measure after the component speed measures were controlled, and the smaller than expected reduction in digit-symbol time for older adults after associative learning could not be explained solely in terms of the available speed measures. Other types of explanation, independent of the construct of processing speed, therefore are presumably needed to account for these results.

What is the mechanism by which slower speed contributes to poorer cognitive performance? One possibility is that slower execution of component operations leads to fewer higher-order products completed in a given period of time. Furthermore, because the processing takes longer, the products of earlier processing may no longer be available by the time later processing is completed. Slower execution of the components may not lead to more errors in the symbol arithmetic task because the relevant processes are relatively simple and can be monitored and repeated if necessary. In other circumstances, however, perhaps including the present associative learning and working memory tasks, it may not be possible to maintain high levels of accuracy because earlier processing cannot be repeated, and consequently products of prior processing may be lost. Slower processing in these situations may therefore lead to lower accuracy or quality, in addition to a longer time to respond.

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(Manuscript received November 30, 1992;
revision accepted for publication April 6, 1993.)