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The Nature of the Influence of Speed on Adult Age Differences in Cognition

Timothy A. Salthouse

Two studies were conducted to determine the relations among age, motor speed, perceptual speed, and 3 measures of cognitive performance: study time, decision time, and decision accuracy. Each study involved over 240 adults between 18 and over 80 years of age who all performed a battery of tests, including computer-administered tests of memory, reasoning, and spatial ability. The results indicated that (a) increased age was associated with lower accuracy as well as with longer study time and decision time and (b) some of the relations between age and decision accuracy and between age and decision time appear to be mediated by a slower rate of executing cognitive operations.

A convincing argument that a construct is involved in the mediation of the relations between age and cognition could be based on the following combination of evidence: (a) demonstration of a negative relation between age and measures of the hypothesized mediator, (b) demonstration of a positive relation between measures of the mediator and measures of cognition, and (c) substantial attenuation of the relations between age and cognition after measures of the mediator are statistically controlled. Several theoretical constructs have been proposed as potential mediators of the relations between age and cognition, with reduced attention (e.g., Stankov, 1988) and failure of inhibition (e.g., Hasher & Zacks, 1988) among the most prominent at the current time. Most of the research concerning these particular constructs has been focused on establishing relations between age and measures of the hypothesized mediators. The linkage between these constructs and cognitive functioning has seldom been directly investigated, and little or no evidence is available concerning the magnitude of the attenuation of the age differences in cognition when the variance in the measures of the hypothesized mediator is held constant.

Two theoretical constructs in which each type of evidence is available are working memory capacity and speed of processing (e.g., Salthouse, 1991, 1992a, 1992b, 1992e; Salthouse & Babcock, 1991). However, there is also evidence that the attenuation of the age–cognition relations is greater after measures of processing speed are controlled than after measures of working memory are controlled, and that the relations between age and working memory are substantially attenuated when processing speed measures are controlled (Salthouse, 1991, 1992a, 1992e; Salthouse & Babcock, 1991). Taken together, these results suggest that processing speed may be more fundamental than working memory as a mediator of age–cognition relations.

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Correspondence concerning this article should be addressed to Timothy A. Salthouse, School of Psychology, Georgia Institute of Technology, Atlanta, Georgia 30332-0170.

Considerable evidence now exists indicating that a large proportion of the age-related variance in many different cognitive variables is shared with a measure of perceptual speed. Among the most pertinent results are the findings that the age-related differences in various measures of cognitive functioning are greatly reduced when statistical control procedures are used to adjust for differences in perceptual speed. As an illustration of this phenomenon, Table 1 in Salthouse (1993b) contains 44 comparisons across a wide range of cognitive variables. Age was associated with a mean of 16.2% of the total variance in the variables, but after the variance associated with measures of perceptual speed was held constant, age was associated with only 3.6% of the variance in the cognitive variables.

One interpretation of this pattern of results is based on the assumption that the well-documented finding that increased age is associated with lower scores on many measures of speeded performance reflects an age-related reduction in the speed with which many cognitive operations can be executed. All cognitive processes are not necessarily affected by this age-related slowing, and there may be more than one distinct speed factor operating. However, it is assumed that when the required operations are very simple, as in many perceptual speed tasks, much of the variation in performance is associated with the speed with which many elementary cognitive operations can be executed. It is also hypothesized that this slower processing impairs higher order processes such as integration and abstraction because less relevant information is simultaneously available when needed. This argument was illustrated abstractly in a computer simulation described in Salthouse (1988), and the ideas have been elaborated in Salthouse (1992a) and Salthouse and Babcock (1991). A basic premise is that if decay rate remains constant across age but there is an age-related slowing of the rate of activation, then some of the early information will no longer be available by the time that later information has been processed, and that this will be true to a greater extent in older adults than in young adults. A fundamental implication of this interpretation is that slower processing leads to an impairment in the quality of decisions and not simply in a longer time to reach and communicate decisions.

The present project had three major goals. The first goal was to determine whether there is comparable speed mediation of the age relations on cognitive measures obtained without time limits. Most of the previous studies have used timed paper-and-pencil tests, and thus it is possible that the attenuation of the age relations after control of measures of perceptual speed might be smaller with power tests in which there are no external time limits. There is some evidence that this is not the case, but the relevant data are based on only a few small-scale studies (e.g., Salthouse, 1993a).

The second major goal of the project was to investigate the type of speed mediation involved in the relations between age and cognition. One theoretically interesting distinction is between motor speed and perceptual speed. Motor speed tasks typically have minimal cognitive requirements and can be postulated to primarily reflect the speed of sensory and motor processes. In contrast, perceptual speed tasks involve various types of cognitive operations, such as comparison, substitution, or transformation, in addition to sensory and motor processes. Salthouse (1993b; also see Salthouse, 1992b) recently reported that the attenuation of the age–cognition relations was larger when perceptual speed measures were controlled than when motor speed measures were controlled. One purpose of this project was to attempt to replicate this pattern with the same paper-and-pencil speed measures used earlier and to extend it to new speed measures derived from computer-administered tasks.

The degree of cognitive involvement in computer-administered speed tasks was varied by altering the number of cognitive operations required to perform the task. That is, the number of digit-symbol pairs was manipulated in a digit-symbol substitution test, and the number of memory set items was manipulated in a memory search test. Cognitive involvement was assumed to be minimal in the simplest versions of the task but progressively greater in tasks requiring multiple comparison, association, memory search, or substitution operations. The degree of cognitive involvement was also postulated to be minimal in the intercept parameter of the regression functions relating number of operations to reaction time, but substantial in the slope parameter of those functions because the latter can be presumed to reflect the duration of cognitive operations such as association or memory search.

A third major goal of the project was to examine the relation among age, various measures of speed, and three measures of performance derived from computer-administered cognitive tests, namely, study time, decision time, and decision accuracy. There are several possible ways in which these variables could be interrelated, and each has different implications for the manner in which a slower speed of processing mediates the relations between age and measures of cognitive functioning. For example, increased age might be associated with longer study or solution time and with longer decision time, but not with lower decision accuracy. A pattern of this type would suggest that despite an age-related slowing of certain types of processing, adults of all ages may be equally able to achieve the same level of decision accuracy when allowed sufficient time. Conversely, negative relations might exist between age and decision accuracy independent of any relations between age and study time or decision time. An outcome of this type would obviously be consistent with the theoretical perspective outlined earlier because age-related effects would be evident in the quality of the decisions in addition to effects on the time to reach or communicate decisions.

Relations might also exist among the study time, decision time, and decision accuracy variables. For example, a speed–accuracy trade-off might be evident in the form of a positive relation (higher accuracy associated with longer time) between decision accuracy and either study time, decision time, or both. Alternatively, the relation could be negative, indicating that people who are slow are also not very accurate. Finally, it is also of interest to determine the nature of the relations between various speed measures and both study time and decision time. If a common speed factor influences every time measure, then strong relations might be expected among all measures.

Because the pattern of relations among the various measures could vary across tests, it is important that analyses of the type just described be conducted with several different cognitive tests. Moreover, it is always desirable to examine the reliability of the major findings by attempting to replicate them in an independent sample of subjects. This project therefore consisted of two separate studies, both containing paper-and-pencil and computer-administered speed tests, and three computer-administered cognitive tests. Within each study, the computer-administered cognitive tests, which were assumed to require memory, reasoning, or spatial ability, were designed to yield separate measures of study time, decision time, and decision accuracy. Three analytical methods were used: hierarchical multiple regression to determine the amount of age-related variance before and after control of the variance in different speed measures; commonality analysis to partition the age-related variance into portions unique to age and shared with motor speed, perceptual speed, or both; and path analysis to examine the interrelations among the age, speed, study time, decision time, and decision accuracy variables.

Study 1

Method

Subjects. Table 1 summarizes the characteristics of the 246 adults between 18 and 84 years of age who participated in Study 1. (Adults in their 70s and 80s are reported together because of the small number of individuals in each of these age decades.) The subjects were recruited from a variety of sources, such as personal acquaintances, clubs, organizations, or neighborhood newspapers, and each was paid for participating in a single session lasting approximately 2 to 3 hr. None of the subjects was currently attending school on a full-time basis.

Two background questions concerned the subject's education: "How many years of formal education have you completed?" and "Which of five categories (<12, 12, 13–15, 16, >16) best describes the highest grade (or degree) you have completed?" The correlation between responses to these items was .93. The entry in Table 1 represents the results from the question of how many years of education had been completed. This variable had a correlation with age of −.20 ($p < .01$).

Six background questions were designed to assess health. One question asked for an evaluation of one's health on a scale ranging from 1 = *excellent* to 5 = *poor.* Three additional questions also used a 5-point scale and asked for ratings of overall health, satisfaction with health, and degree of limitations of daily activities owing to health status. Correlations among these measures were moderate to high (.47 to .78). Two yes/no questions asked whether the individual had had surgery for cardiovascular problems or was taking medication for high blood pressure.

Table 1
Demographic Characteristics of Research Participants

Decade	n	Age (years)	% female	Eduation (years) *M*	Eduation (years) *SD*	Health[a] *M*	Health[a] *SD*
			Study 1				
20s	48	23.4	46	14.7	2.1	1.8	0.7
30s	43	33.9	58	15.5	1.6	2.2	0.9
40s	48	44.2	69	14.8	2.1	2.0	0.9
50s	40	54.7	72	14.1	2.2	2.6	1.2
60s	44	64.6	61	14.0	2.6	2.0	1.0
70s+	23	75.0	65	13.1	2.2	2.4	0.8
Total	246	46.6	61	14.5	2.2	2.1	1.0
			Study 2				
20s	35	25.1	46	15.0	1.7	1.8	0.7
30s	58	34.0	59	15.8	2.3	1.8	0.8
40s	50	44.6	66	15.6	2.3	2.0	0.9
50s	33	54.2	73	14.9	2.2	2.0	0.8
60s	46	64.5	52	15.7	2.5	1.9	0.9
70s+	36	75.8	69	14.3	2.4	2.0	1.0
Total	258	48.7	60	15.3	2.3	1.9	0.8

[a] From 1 = *excellent* and 5 = *poor.*

Responses to these items had very low correlations with the other items (.04 to .27). The health variable in Table 1 refers to the first overall health rating, which had a correlation with age of .13 ($p > .01$).

Procedure. Subjects were tested in groups of 1 to 4, and for the computer-administered tests a separate personal computer was provided for each subject. All subjects performed the tests in the following order: Boxes, Pattern Comparison, Number Series Completion, Name Number, Cube Assembly, Letter Comparison, Digit Copying, Digit Symbol, Paper Folding, Matrix Reasoning, and Associative Memory. The abilities postulated to be assessed by the tests were motor speed (Boxes and Digit Copying), perceptual speed (Pattern Comparison, Letter Comparison, and Digit Symbol), reasoning (Number Series Completion and Matrix Reasoning), spatial visualization (Cube Assembly and Paper Folding), and memory (Name Number and Associative Memory).

The first seven tests were in a paper-and-pencil format. The Boxes test was from Salthouse (1993b). The form for this test consisted of 10 rows of 10 three-sided squares with the top, bottom, left, or right side open. The task for the subject was to draw a line across the open side to make a closed box, and the measure of performance was the number of boxes drawn within 30 s.

The Digit Copy test was also from Salthouse (1993b). The form in this test consisted of 10 rows of 10 pairs of boxes with a digit in the top box and nothing in the bottom box. The task was to copy the digit from the top box in the box immediately below it, and the measure of performance was the number of digits copied within 30 s.

The Letter Comparison test was from Salthouse (1991, 1993b) and Salthouse and Babcock (1991), and it required the subject to inspect pairs of three, six, or nine letters and then write an S if the two pairs are the same and a D if they are different. The test form consisted of a single column of 21 pairs of letters with a blank line between them. The measures of performance were the numbers of correct and incorrect responses produced within 30 s.

The Pattern Comparison test was also from Salthouse (1991, 1993b) and Salthouse and Babcock (1991). Subjects in this test were asked to inspect pairs of line patterns composed of three, six, or nine line segments and then to write an S if the pair of patterns is the same and a D if they are different. The test form consisted of two columns of 15 pattern pairs, each with a blank line between the two members of the pair. The number of correct responses and the number of incorrect responses produced within 30 s served as the measures of performance in this test.

Three of the paper-and-pencil tests were administered for 2 min each. The Number Series test was similar to the Number Series Completion test described by Salthouse and Prill (1987). The test form consisted of 20 problems, each involving a series of five elements. First-order problems were based on a simple continuation (e.g., 2-4-6-8-10-??), second-order problems were based on a relation among the differences between elements rather than among the elements themselves (e.g., 2-4-7-11-16-??), and alternating-order problems consisted of two interleaved relations (e.g., 2-13-4-11-6-??). Each successive set of 5 problems had 1 first-order problem, 2 second-order problems, and 2 problems with alternating relations. Subjects answered the problems by writing the best continuation of the series on the test form.

The Cube Assembly test was originally based on a task described by Shepard and Feng (1972), and it has been used previously in Salthouse (1991, 1992d). Problems in the test consist of a pattern of six connected squares representing an unfolded cube. One of the squares is marked as the base of the cube, and two squares contain arrows pointing to one side of the square. The task is to decide whether the arrows would be pointing at one another if the squares were assembled into a cube. The test contains 24 problems, with an equal number of problems in which one, two, or three folds were required to assemble the cube. One problem of each type was presented before another of the same type. Decisions were communicated by placing a check in a column labeled YES (indicating the arrows would touch) or in a column labeled NO (indicating they would not touch), located adjacent to the problem on the test form.

The Name–Number test consisted of the presentation of 10 first names (5 male and 5 female), each paired with a number between 10 and 99. The pairs were presented together for 1 min, and then the subject was presented with the list of names in a reordered sequence and was allowed 1 min to write the numbers associated with the names. Performance was assessed in terms of the numbers of correct and incorrect name–number pairs.

All computer-administered tests were preceded by written instructions and several practice trials, and all except the first test had a primary emphasis on accuracy rather than speed. The Digit Symbol test was based on the test described in Salthouse (1992c). Nine, 6, 3, or 0 digit-symbol pairs were presented in a code table in the top of the computer screen, and a pair of items, either a digit and a symbol or two digits, appeared in the middle of the screen. The subjects were instructed to respond with the rightmost slash (/) key on the bottom row of the keyboard if the items were physically identical or matched according to the code table, and with the leftmost (Z) key on the bottom row of the keyboard if the items did not match. One practice block of 18 trials was presented with nine digits and nine symbols, followed by eight experimental blocks of 90 trials each. The number of symbols across the eight blocks were 9, 6, 3, 0, 0, 3, 6, and 9, respectively. In conditions with either 3 or 6 symbols, one of the blocks had the symbols paired with the first n digits (where n is 3 or 6), and the other block had the symbols paired with the last n digits. The remaining digits had the symbol in the code table replaced with identical digits (e.g., 2 with 2, 4 with 4, and so on). Trial selection was based on all nine digits regardless of condition, and thus approximately one third and two thirds of the trials in the conditions with 6 and 3 symbols, respectively, involved comparisons of pairs of digits rather than a digit paired with a symbol. One half of the trials in each block required a positive response (because the members of the pair matched), and one half required a negative response (because the members of the pair did not match). Subjects were instructed to respond as rapidly and accurately as possible.

The computer-administered Paper Folding test was based on the test of the same name described in several earlier articles (i.e., Salthouse, Babcock, Mitchell, Palmon, & Skovronek, 1990; Salthouse, Babcock, Skovronek, Mitchell, & Palmon, 1990; Salthouse, Mitchell, Skovronek, & Babcock, 1989). Trials in this task were initiated by pressing the ENTER key on the keyboard. This led to a dynamic display of the first fold, and subsequent folds or the location of the hole punch were displayed after each successive press of the ENTER key. After the display of the punch location, another press of the ENTER key resulted in a display of a pattern of holes accompanied by the words NO on the lower left of the screen and YES on the lower right of the screen. Decisions were communicated by pressing the Z or slash key, respectively. Three trial types were distinguished on the basis of the number of folds (one, two, or three) presented before the display of a hole punch. Subjects could inspect each display of the product of a fold or the hole punch as long as desired and could take as long as necessary to make a decision. The total time inspecting the folds and examining the position of the hole punch served as the measure of study time, and the time to respond to the pattern of holes served as the decision time. A practice block of 3 trials contained a detailed explanation of the task, and it could be repeated as often as desired. This was followed by two blocks of 24 trials each, composed of 8 trials with each number of folds arranged in a random order.

The Matrix Reasoning test was based on the test described in Salthouse (1993a), which in turn was based on the Raven Progressive Matrices test. Problems consisted of a 3 × 3 matrix with geometric patterns in each of eight cells and a set of eight patterns representing possible completions of the missing cell in the matrix. The matrix and the completion alternatives were presented successively in separate screens on the computer. Study time was measured as the time to inspect the matrix, and decision time was measured as the time from the presentation of the answer alternatives to the registration of the numeric response indicating which of the answer alternatives was selected. Subjects could inspect the matrix and the set of alternatives as long as desired but could not return to the matrix after advancing to the display of the answer alternatives.

The practice block of 3 trials was repeatable, and it was followed by two experimental blocks of 18 trials each. Three trial types were distinguished by the number of relevant relations among the elements in the matrix (cf. Salthouse, 1993a). Six trials in each experimental block contained each number of relations, and they were presented in a random order.

The Associative Memory test was a continuous paired-associate task designed to measure the ability to remember associations between words and digits. The test involved the presentations of either a word paired with a digit (from the set of one, two, or three) or a single word. When a word and a digit were presented, the subject was allowed to inspect the pair for as long as desired. When a word was presented alone, the subject was to type the digit that had been previously presented with that word. The time devoted to the initial inspection of the word–digit pair was used as the measure of study time, and the time to enter a digit in response to the test word was used as the measure of decision time.

A practice list of 6 pairs was presented, followed by an experimental list of 90 pairs with 24 tests (8 each at lags of zero, two, or four intervening items). The stimulus words were nouns between four and eight letters in length with Kucera-Francis frequencies of 10 or greater with above average ratings in concreteness and imagery, from the Toronto Word Pool (Friendly, Franklin, Hoffman, & Rubin, 1982).

Results and Discussion

Because of the many statistical comparisons and the relatively large sample size, an alpha level of .01 was adopted for all statistical significance tests reported in this article.

Table 2
Summary Statistics for Primary Dependent Variables, Study 1

Variable	*M*	*SD*	Est. Rel.	R^2 Linear age	R^2 Quadratic age
Boxes	50.5	13.1	.78[a]	.290*	.006
Digit Copy	51.5	11.2	.84[a]	.281*	.030*
Letter Comparison	9.4	3.4	.38[a]	.251*	.018
Pattern Comparison	15.4	3.9	.52[a]	.374*	.001
Digit Symbol-0 (s)	0.76	0.23	.94[b]	.262*	.046*
Digit Symbol-9 (s)	1.50	0.40	.95[b]	.374*	.021*
Intercept (s)	1.05	0.30	.86[b]	.284*	.027*
Slope (s)	0.05	0.03	.44[b]	.115*	.001
Correct − incorrect					
Number Series	2.49	4.23	.67[a]	.118*	.004
Cube Assembly	4.02	4.70	.70[a]	.091*	.012
Name Number	1.15	3.81	.46[a]	.070*	.006
% correct					
Paper Folding	69.7	11.9	.72[c]	.215*	.007
Matrix Reasoning	57.5	21.9	.88[c]	.149*	.009
Associative Memory	67.5	12.2	.45[c]	.071*	.002
Decision time (in s)					
Paper Folding	2.41	0.82	.89[c]	.336*	.005
Matrix Reasoning	6.00	3.94	.93[c]	.241*	.009
Associative Memory	2.88	1.46	.93[c]	.231*	.050*
Study time (in s)					
Paper Folding	6.24	3.55	.93[c]	.057*	.001
Matrix Reasoning	26.89	14.42	.90[c]	.067*	.017
Associative Memory	1.76	1.17	.96[c]	.023	.007

Note. Est. Rel. = estimated reliabilities.
[a] Alternate-forms correlation from a sample of 212 college students. [b] Correlation between scores from first and second administrations boosted by the Spearman-Brown formula. [c] Computed from correlations across three levels of complexity with formula in Kenney (1979, p. 132): Reliability = n(average r)/[1 + (n − 1)(average r)].
* $p < .01$.

Table 2 contains the means, standard deviations, estimated reliabilities, and R^2 values for the linear and quadratic age relations for the primary dependent variables. Quadratic trends were evaluated by an age-squared term entered after the linear age term in a multiple regression equation and after both the age and the age-squared variables had been centered to means of zero to reduce potential multicollinearity problems (Cohen & Cohen, 1983). Because the quadratic trends were always small in relation to the linear trends, they were ignored in subsequent analyses.

Most reliabilities were in the respectable range, although those for the Name Number measure and for the measure of decision accuracy in the Associative Memory test were much lower than desirable. In both cases it appears that the tasks may have been too difficult for many of the research participants because the average levels of performance were quite low. Reliability estimates for the Letter Comparison and Pattern Comparison variables were low in the pilot sample of college students, perhaps because of the restricted age range in this group. However, these variables had correlations with other variables in this sample that were higher than the estimated reliability, and thus the reliability in the present sample was likely greater than that derived from the student sample. As an example, the correlations of the Letter Comparison and Pattern Comparison variables with age were −.50 and −.61, respectively, and the correlation between the two variables was .55.

Paper-and-pencil tests. Performance in the paper-and-pencil tests was initially analyzed in terms of the number of correct responses, the number of incorrect responses, and the number of correct responses minus the number of incorrect responses. The age relations were weak with the measure of number of incorrect responses, as the age correlations were −.03 for Pattern Comparison, .09 for Letter Comparison, .13 for Number Series, .18 for Cube Assembly, and .06 for Name Number Association. Only the correlation for Cube Assembly was significantly different from zero. The age relations were similar for the measures of number correct and number correct minus number incorrect, and the correlations between the two measures were generally high: Pattern Comparison, r = .96; Letter Comparison, r = .96; Number Series, r = .86; Cube Assembly, r = .71; and Name Number, r = .86. To provide an adjustment for guessing, all subsequent analyses used the variable of number correct minus number incorrect for the paper-and-pencil tests.

Preliminary Age (by decade) × Complexity Level analyses of variance (ANOVAs) were conducted on the data from the three computer-administered cognitive tests to determine whether the age relations varied according to task complexity (i.e., number of folds in Paper Folding, number of relations among elements in Matrix Reasoning, and presentation-test lag in Associative Memory). Perhaps because of the small number of trials at each complexity level, the Age × Complexity interactions were not significant with the decision accuracy measure in any of the tests. Moreover, this was also true in restricted samples of subjects who all had accuracy in the simplest condition (i.e., one fold, one relation, or Lag 0) above the mean from the entire sample. Only the means across all three complexity levels are therefore considered in subsequent analyses.

Scores from the paper-and-pencil speed tests and the mean response times in the Digit Symbol test with zero (DigSym-0) and nine (DigSym-9) symbols were converted to standard deviation units on the basis of the entire sample distribution and were plotted as a function of decade in Figure 1. Because the Digit Symbol measures are expressed in units of time per item rather than number of items in a fixed period of time, higher scores on these measures correspond to poorer performance. Inspection of Figure 1 reveals that the patterns with each measure are very similar in that the average in the decade of the 20s is about +.5 (or −.5 for the Digit Symbol measures) and the average in the decade of the 70s is about −1.0 (or +1.0 for the Digit Symbol measures). The tendency for the function for the Digit Symbol measures to be positively accelerated accounts for the presence of the significant quadratic age trends in these measures reported in Table 2.

The same type of conversion to standard deviation units was conducted for the measures of number correct minus number incorrect in the three paper-and-pencil cognitive tests, with the means by decade plotted in Figure 2. As in Figure 1, the age trends are nearly monotonic, with means that range from about +.5 in the decade of the 20s to between −.5 and −1.0 in the decade of the 70s.

Digit symbol. Mean reaction time and mean percentage of errors in the Digit Symbol test are plotted as a function of number of symbols and age decade in Figure 3. Both variables were analyzed by separate repeated measures ANOVAs in which age was categorized by decade and number of symbols was a within-subjects variable. Only the main effect of number of symbols was significant in the analysis of errors, $F(3, 720) = 19.38$, $MS_e = 3.21$. All three effects were significant in the analysis of re-

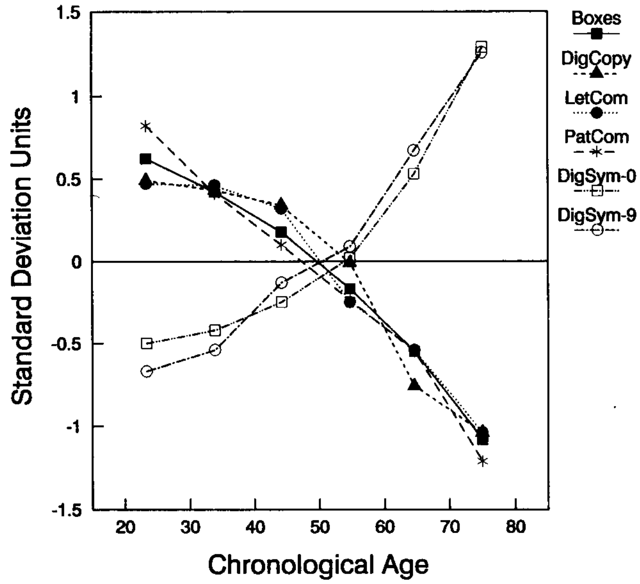

Figure 1. Mean standard deviation scores by decade for the speed measures, Study 1. DigCopy = Digit Copy; LetCom = Letter Comparison; PatCom = Pattern Comparison; DigSym-0 = Digit Symbol with zero symbols; DigSym-9 = Digit Symbol with nine symbols.

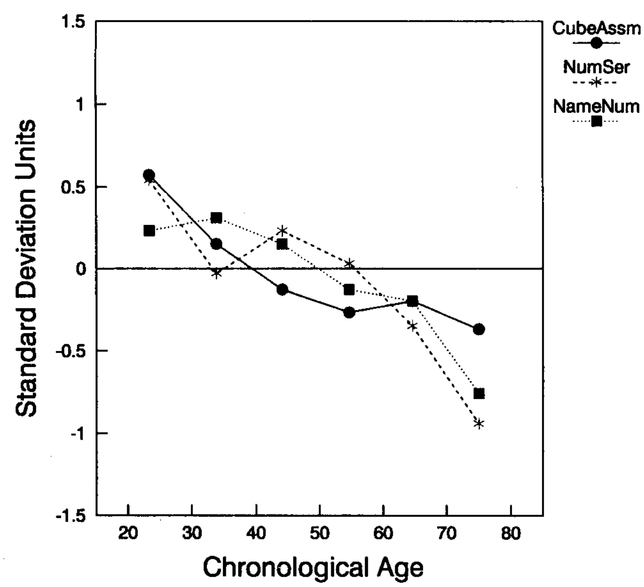

Figure 2. Mean standard deviation scores by decade for the number correct minus the number incorrect scores in three paper-and-pencil cognitive tests, Study 1. CubeAssm = Cube Assembly; NumSer = Number Series Completion; NameNum = Name–Number test.

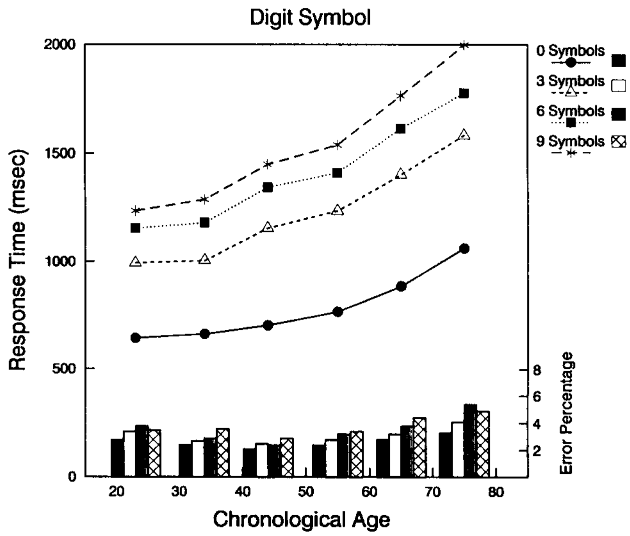

Figure 3. Mean reaction time and mean percentage of errors in the Digit Symbol Substitution test as a function of the number of digit-symbol pairs by decade, Study 1.

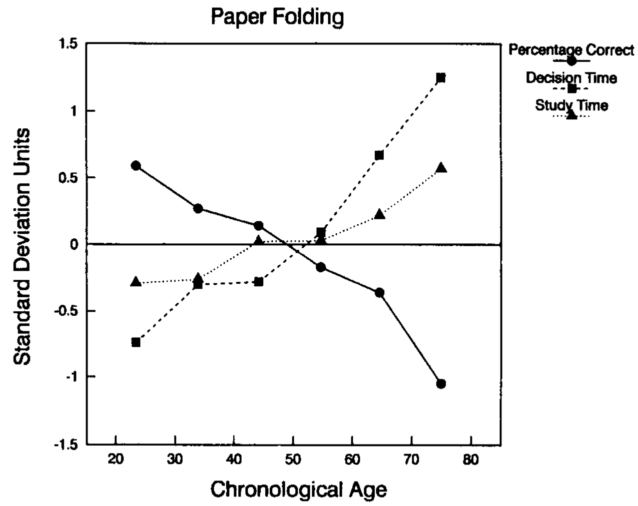

Figure 4. Mean standard deviation scores by decade for the study time, decision time, and decision accuracy measures in the Paper Folding test, Study 1.

sponse times: age decade, $F(5, 240) = 28.79$, $MS_e = 248{,}150$; number of symbols, $F(3, 720) = 1{,}799.20$, $MS_e = 14{,}100$; and Age Decade × Number of Symbols, $F(14, 720) = 9.02$, $MS_e = 14{,}100$. The pattern in Figure 3 suggests that the significant interaction in the response time variable is a consequence of larger age relations on trials with more symbols. The age correlations were consistent with this interpretation, as they were .51 for zero symbols, .59 for three symbols, .59 for six symbols, and .61 for nine symbols.

One manner in which the Digit Symbol test can be conceptualized is to assume that performance in the nine-symbol version of the test reflects processes of encoding, responding, and search of the code table, and that performance in the zero-symbol version of the test only requires processes of encoding and responding. According to this interpretation, the slope of the function relating the number of symbols to response time represents the time to decide to search the code table and to carry out the search. One or both of these processes should occur on one third, two thirds, or all of the trials when the code table contains three, six, or nine symbols, respectively. Regression equations relating number of symbols (between three and nine) to response time were therefore computed for each subject. The mean of the correlations was .95, indicating that the fit of the regression equations was generally good. The mean of the slope parameters was 51 ms per symbol. The intercept of these regression functions can be hypothesized to represent the time needed to respond when no search processes are required. The mean of the intercept parameters was 1,049 ms, which was substantially greater than the mean response time in the DigSym-0 condition (i.e., 760 ms). One possible interpretation of this discrepancy is that the additional time in the intercept parameter in relation to the actual time to respond with zero symbols represents uncertainty about when, and how, to search the code table.

Both the slope and the intercept parameters were larger with increased age (cf. Table 2), as was the difference between the intercept and the DigSym-0 time (i.e., age correlation = .22). These results suggest that increased age is associated with slower encoding and response processes (DigSym-0 and intercept), slower search of the code table (slope), and a longer time to decide to search the code table (difference between the intercept and DigSym-0).

Computer-administered cognitive tests. For each of the computer-administered cognitive tests, mean study time, mean decision time, and mean decision accuracy across all complexity levels were converted into *z* scores, and the means were plotted as a function of decade. Results from the Paper Folding test are illustrated in Figure 4, those from the Matrix Reasoning test in Figure 5, and those from the Associative Memory test in

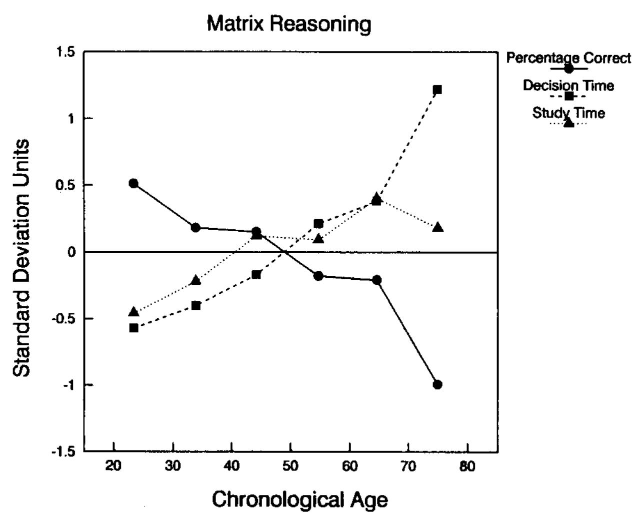

Figure 5. Mean standard deviation scores by decade for the study time, decision time, and decision accuracy measures in the Matrix Reasoning test, Study 1.

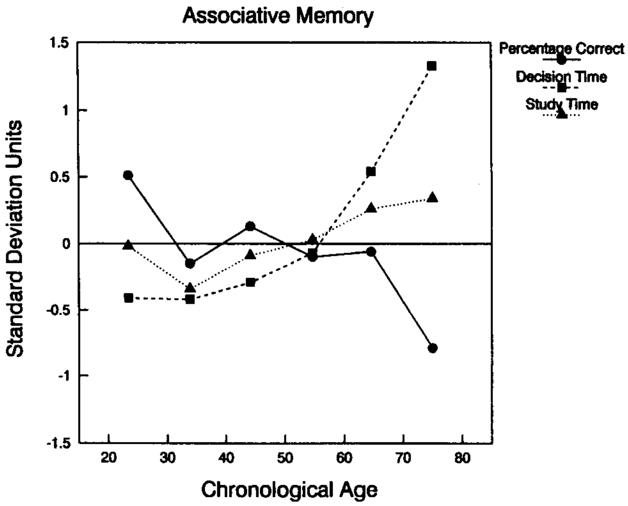

Figure 6. Mean standard deviation scores by decade for the study time, decision time, and decision accuracy measures in the Associative Memory test, Study 1.

Figure 6. It is apparent in each figure that the age trends are generally monotonic and that there are substantial age effects on the measure of decision accuracy as well as the measures of decision time and study time. These results therefore indicate that, in conditions in which accuracy is emphasized and subjects are allowed to proceed at their own pace, increased age is associated with less accurate decisions as well as with more time used to reach and communicate the decisions.

Regression analyses. A series of multiple regression analyses was conducted to evaluate the relative contribution of different factors to the age differences in the primary performance variables. To determine whether education and health could be adequately represented by composite variables, I conducted a confirmatory factor analysis specifying two factors on the two education variables (number of years of formal education and the classification of the highest grade or degree completed) and on four health variables (two ratings of the individual's own health, one rating reflecting degree of satisfaction with one's health, and one rating indicating degree of health-related limitations). The fit of the model was good, as revealed by the following indices: $\chi^2(8, N = 246) = 10.46$, adjusted goodness-of-fix index (GFI) = .964, and adjusted root-mean-square (RMS) = .036. The correlation between the education and health factors was −20. Because the standardized weights of the variables on their respective factors were similar (i.e., .94 and .98 for education and .81 to .90 for health, except .56 for health-related activity limitations), composite scores for the education and health constructs were created by averaging the relevant *z* scores.

Each of the variables in Table 2 was examined for the presence of main effects of gender, health, and education and for interactions of these variables with age. The predictor variables were all centered to means of zero to avoid problems of multicollinearity and to facilitate interpretations of any interactions. Significant main effects of education were evident in the following variables: Boxes, Digit Copy, Letter Comparison, Number Series, Matrix Reasoning decision accuracy, and Paper Folding accuracy. In all cases, the effects were in the direction of greater education associated with higher scores. More education was also associated with longer study times in the Matrix Reasoning test but with shorter decision times in the Paper Folding and Associative Memory tests and with shorter DigSym-0 times. Better self-reported health was associated with higher scores on Boxes and Matrix Reasoning decision accuracy and with faster DigSym-0 and Digit Symbol intercept scores. Women performed at significantly lower levels than men on Number Series, Cube Assembly, and Paper Folding decision accuracy, but they performed significantly better than men on Letter Comparison. Most important for subsequent analyses, none of the interactions between age and these predictors were significant, indicating that the age trends were not moderated by these factors.

A confirmatory factor analysis specifying two correlated factors was conducted on the four paper-and-pencil speed measures (i.e., Boxes and Digit Copy as measures of motor speed and Letter Comparison and Pattern Comparison as measures of perceptual speed) to verify the proposed distinction between motor speed and perceptual speed. The fit of the model was not impressive, $\chi^2(1, N = 246) = 5.02$, adjusted GFI = .900, adjusted RMS = .142, and the correlation between the motor speed and perceptual speed factors was quite high (i.e., .913). However, when the correlation between factors was fixed to 1.0 and the analysis was repeated, the fit of the model was significantly poorer, difference $\chi^2(1, N = 246) = 4.94$), implying that although the correlation between the two factors is very high, it is less than 1.0.

Although the results of the confirmatory factor analysis did not provide convincing support for the distinction between motor speed and perceptual speed in this study, the results of other analyses that were based on the same or very similar measures (e.g., Salthouse, 1993a, 1993b) and the results of an identical analysis conducted on the data of Study 2 were consistent with the hypothesized distinction. I therefore decided to treat the two sets of variables as representing distinct constructs despite the weak results from the confirmatory factor analysis. Because the standardized weights for the variables on their respective factors were similar (i.e., Boxes = .80, Digit Copy = .90, Letter Comparison = .74, and Pattern Comparison = .74), the average of the relevant *z* scores was used as a composite variable for each construct.

Two variables from the Digit Symbol test—DigSym-0 representing minimal cognitive demands and DigSym-9 representing greater cognitive involvement—were also used as speed measures in the regression analyses. Although I originally planned to use the slope and intercept of the functions relating response time to number of digit symbol pairs as additional speed measures, the low reliability of the slope parameter and its weak relation with age (cf. Table 2) diminished the value of these analyses, and consequently the intercept and slope variables were not included as predictors in the subsequent regression analyses.

Two separate sets of analyses were conducted to yield information about both the moderating and the mediating effects of speed. One type of analysis was designed to examine moderating effects, as revealed by significant interactions of age and speed. Interactions of this type would indicate that the age-related influences vary according to the level of speed, and hence that speed moderates the influence of age. The second type of analysis was intended to examine mediating effects, as revealed by contrasts of the magnitude of the age-related variance before and after control of the measure of speed. To the extent that statistical control of a speed measure results in a substantial attenuation of the age-related variance in a criterion variable, it can be inferred that the speed measure probably plays a mediating role in the relations between age and the criterion variable.

In the analyses of the interaction terms, both the age and the speed variables were centered to means of zero, and the cross-product interaction term was entered in the regression equation after both the age and speed variables. If the interaction was statistically significant, the R^2 associated with the interaction was then determined. All but two of the interactions were in the direction of smaller age-related influences at faster levels of speed (or equivalently, larger effects of speed at older ages). The two exceptions were with the Cube Assembly and Matrix Reasoning study time measures, in which the age-related effects were larger among subjects with faster DigSym-0 scores. The variables with significant interactions between age and the composite motor speed variable, with the increment in R^2 associated with the interaction presented in parentheses, were as follows: Associative Memory decision time (.056), DigSym-0 (.049), and DigSym-9 (.018). Variables with significant interactions involving age and the composite perceptual speed variable were as follows: Digit Copy (.016), Paper Folding decision accuracy (.023), Matrix Reasoning decision time (.028), Associative Memory decision time (.080), DigSym-0 (.068), DigSym-9 (.028), and Digit Symbol intercept (.038). Interactions involving age and DigSym-0 were significant with Cube Assembly (.035), Matrix Reasoning study time (.035), DigSym-9 (.010), and Digit Symbol intercept (.011). Finally, two variables had significant interactions between age and DigSym-9: Associative Memory decision time (.026) and DigSym-0 (.045). Note that all but two (i.e., Paper Folding decision accuracy and Cube Assembly correct-minus-incorrect) of these interactions involved time or speed measures as the criterion variable.

The assessment of mediational effects was based on a comparison of the proportion of variance (as reflected in increments in R^2 corresponding to squared semipartial correlations) associated with age before and after the variance associated with the measure of the hypothesized mediator was controlled. For example, the influence of variations in health and education on the age differences in the primary variables can be determined by comparing the proportion of variance associated with age before (column 4 in Table 2) and after (column 1 in Table 3) the composite measures of health and education were controlled. Examination of these values reveals that there was some attenuation of the age relations, particularly for the reasoning measures of Number Series (i.e., R^2 of .118 to .059) and Matrix Reasoning (i.e., R^2 of .149 to .080). However, it is also apparent

Table 3
R^2 for Age After Control of Demographic and Speed Variables, Study 1

	R^2 for age after control of:				
Criterion	Health, education	Health, education, motor speed	Health, education, perceptual speed	Health, education, Digit Symbol-0	Health, education, Digit Symbol-9
Boxes	.212*	.000	.030	.108*	.075*
Digit Copy	.197*	.000	.011	.075*	.035*
Letter Comparison	.191*	.034*	.005	.063*	.027*
Pattern Comparison	.321*	.093*	.005	.173*	.094*
Digit Symbol-0	.187*	.054*	.026*	—	.001
Digit Symbol-9	.299*	.105*	.049*	.058*	—
Intercept	.211*	.077*	.047*	.022*	.001
Slope	.105*	.032*	.008	.047*	.002
Correct − incorrect					
Number Series	.059*	.028*	.003	.033*	.009
Cube Assembly	.062*	.045*	.018	.036*	.009
Name Number	.048*	.025	.007	.014	.016
% correct					
Paper Folding	.161*	.078*	.041*	.073*	.033*
Matrix Reasoning	.080*	.028*	.010	.024*	.007
Associative Memory	.047*	.016	.004	.014	.009
Decision time					
Paper Folding	.268*	.136*	.080*	.112*	.070*
Matrix Reasoning	.196*	.078*	.043*	.088*	.055*
Associative Memory	.168*	.065*	.036*	.044*	.021*
Study time					
Paper Folding	.063*	.045*	.031*	.048*	.051*
Matrix Reasoning	.080*	.039*	.026*	.069*	.036*
Associative Memory	.020	.011	.010	.011	.007

Note. Dashes indicate no data.
* $p < .01$.

from the entries in the first column of Table 3 that the residual age relations are still significantly greater than zero for most of the variables.

Two types of comparisons are of interest in Table 3. One consists of contrasts of the values in the second through the fifth columns with the values in the first column, and the other consists of contrasts of the values in the columns representing the two types of speed. The overall pattern can be described quite simply by stating that the age-related variance is smaller after control of a speed variable in addition to the health and education variables (columns 2 through 5) than only after control of health and education (column 1), and that the residual age-related variance is smaller after control of speed measures with greater cognitive involvement than after control of speed measures with minimal cognitive involvement (columns 3 vs. 2 and columns 5 vs. 4). As an example, the average R^2 associated with age for the three paper-and-pencil cognitive measures was .056 after health and education were controlled, but it was .033 (41% attenuation) after motor speed was also controlled, and it was only .009 (83.9% attenuation) after perceptual speed was controlled in addition to health and education. The average value for the measure of decision accuracy in the computer-administered cognitive tests was .096, and this was reduced to .041 (57.3% attenuation) after control of motor speed and to .018 (81.3% attenuation) after control of perceptual speed. For every variable except the two used to create the composite motor speed index (i.e., Boxes and Digit Copy), the residual age-related variance was smaller after control of perceptual speed than after control of motor speed. Comparison of the values in the fourth and fifth columns reveals that a similar pattern existed with the Digit Symbol measures in that the attenuation of the age-related variance was larger with the measure presumed to have greater cognitive involvement (i.e., DigSym-9).

Note that the influence of perceptual speed actually appears to be larger on the accuracy measures than on the measures of study time or decision time. For example, the attenuation of the age-related variance in average decision accuracy after control of perceptual speed was 81.3%, but the corresponding value for the average study time measure was 61.3% and that for the average decision time measure was 74.4%. These results therefore suggest that, if anything, the relations between perceptual speed and decision accuracy may be stronger than those between perceptual speed and either study time or decision time.

The residual age-related variance in DigSym-9 after control of perceptual speed was significantly greater than zero, as was the age-related variance in the perceptual speed measures (Letter Comparison and Pattern Comparison) after control of DigSym-9. This is somewhat surprising because these measures were presumed to involve very similar types of comparison processes. Methodological differences associated with the format of administration (i.e., paper-and-pencil vs. computer-administered) may be responsible for the significant residual age variance in these measures.

The R^2 in the cognitive variables associated with the composite perceptual speed variable and with the DigSym-9 variable was also examined before and after control of age, health, and education to evaluate the magnitude of the speed influence when other sources of individual differences were controlled. The top portion of Table 4 summarizes the results for the correct-minus-incorrect measure in three paper-and-pencil cognitive tests and for the decision accuracy measure in the three computer-administered cognitive tests. The results indicate that a significant relation exists between perceptual speed and some measures of cognitive performance, even among individuals for whom the variation associated with age, health, and education is controlled. However, the magnitude of the relation is much

Table 4
R^2 Associated With Perceptual Speed and Digit Symbol Before and After Control of Other Variables

Criterion	Perceptual speed: Alone	Perceptual speed: After age, health, and education	Digit symbol: Alone	Digit symbol: After age, health, and education
Study 1				
Correct − incorrect				
Number Series	.207*	.053*	.157*	.031*
Cube Assembly	.088*	.011	.125*	.036*
Name Number	.085*	.023	.063*	.008
% correct				
Paper Folding	.224*	.038*	.257*	.065*
Matrix Reasoning	.214*	.044*	.238*	.068*
Associative Memory	.105*	.035*	.088*	.021
Study 2				
% correct				
Spatial Rotation	.141*	.048*	.139*	.054*
Matrix Reasoning	.166*	.100*	.202*	.168*
Associative Memory	.134*	.040*	.196*	.100*

* $p < .01$.

Table 5
Results of Commonality Analyses Conducted on Decision Accuracy Measures in Study 1

Variable	Predictor variable Age	MSpd	PSpd
Paper Folding accuracy as criterion			
Unique to age	.038		
Unique to MSpd		.002	
Unique to PSpd			.030
Common to Age and MSpd	.007	.007	
Common to Age and PSpd	.044		.044
Common to MSpd and PSpd		.024	.024
Common to Age, MSpd, and PSpd	.126	.126	.126
Total effects	.215	.159	.224
Matrix Reasoning accuracy as criterion			
Unique to age	.009		
Unique to MSpd		.009	
Unique to PSpd			.035
Common to age and MSpd	.006	.006	
Common to age and PSpd	.024		.024
Common to MSpd and PSpd		.045	.045
Common to Age, MSpd, and PSpd	.110	.110	.110
Total effects	.149	.170	.214
Associative Memory accuracy as criterion			
Unique to age	.005		
Unique to MSpd		.002	
Unique to PSpd			.022
Common to age and MSpd	.001	.001	
Common to age and PSpd	.013		.013
Common to MSpd and PSpd		.018	.018
Common to Age, MSpd, and PSpd	.052	.052	.052
Total effects	.071	.073	.105

Note. MSpd = motor speed; PSpd = perceptual speed.

smaller than that evident when the age-related variance is included, suggesting that the age-related variation in speed is a major contributor to the overall relations between perceptual speed and cognition observed in this study.

Commonality analyses. Another analytical procedure applied to the decision accuracy measures was commonality analysis (Pedhazur, 1982). The method described by Salthouse (1993b) was used, in which the total effects of age on a criterion variable were decomposed into a unique influence of age and into common influences shared with either motor speed, perceptual speed, or both. Measures of speed in these analyses were the composite speed measures that were based on the paper-and-pencil speed tests.

Summary information for the commonality analyses conducted on the decision accuracy measures in the three computer-administered cognitive tests is presented in Table 5. Because the entries in the first column represent the partitioning of the age-related variance, they are of greatest interest in this context. Three points should be noted about the information in this table. First, the variance uniquely associated with age is only a small proportion of the total age-related variance in the criterion variable. This is consistent with the results of the hierarchical regression analyses because it indicates that much of the age-related variance is shared with one or more measures of speed. Second, the proportion of age-related variance shared with perceptual speed is substantially greater than the proportion of age-related variance shared with motor speed. This is also consistent with the hierarchical regression results because it indicates that perceptual speed has a greater influence on the age–cognition relations than does motor speed. And finally, one of the largest proportions of variance is that common to age, motor speed, and perceptual speed. This finding extends the earlier analyses by revealing that a considerable amount of the age-related variance is not uniquely associated with one type of speed.

Path analyses. The initial step in the path analyses was a confirmatory factor analysis on nine cognitive variables: study time, decision time, and decision accuracy for each of the three computer-administered cognitive tests. Three factors (study time, decision time, and decision accuracy) were specified, with correlations allowed between factors. The fit of the model was rather poor: $\chi^2(24, N = 246) = 117.43$, adjusted GFI = .828 and adjusted RMS = .123. Examination of the residuals revealed that the poor fit was attributable to relatively high correlations among the variables from the same test. Because this pattern implies that the relations among the variables might differ across tests, separate analyses were conducted on the data from each test.

Two sets of analyses were conducted on the data from each test, one with the composite motor speed and perceptual speed variables, and the other with the DigSym-0 and DigSym-9 variables. The model determination procedure began by postulating paths from age to all variables: from motor speed to perceptual speed, from perceptual speed to study time, decision time, and decision accuracy, and from both study time and decision time to decision accuracy, with a bidirectional path (correlation) between study time and decision time (see Figure 7). Paths with coefficients different from zero by less than two standard errors were deleted. Paths between motor speed and study time and between motor speed and decision time were then added if the resulting path coefficient differed from zero by more than two standard errors. Coefficients for those paths in Figure 7 that were significant and three measures of the fit of the final path model for each test are reported in Table 6.

Four points should be noted with respect to the results of the path analyses summarized in Table 6. First, the models with the two sets of speed measures (based on paper-and-pencil procedures and computer-administered versions of the Digit Symbol test) were quite similar and did not differ in any substantial respect. (Note that the difference in signs is due to high scores representing better performance in the paper-and-pencil speed measures but poorer performance in the Digit Symbol speed measures.) Second, there were little or no relations between motor speed and any of the cognitive variables (see Paths 7, 8, and 9 in Table 6). This is consistent with the inference that motor speed is not a very important mediator of the age–cognition relations. Third, perceptual speed had a consistent influence on both decision accuracy and decision time but no effect on study time. These results imply that the variation in study time is attributable to different factors than those responsible for the

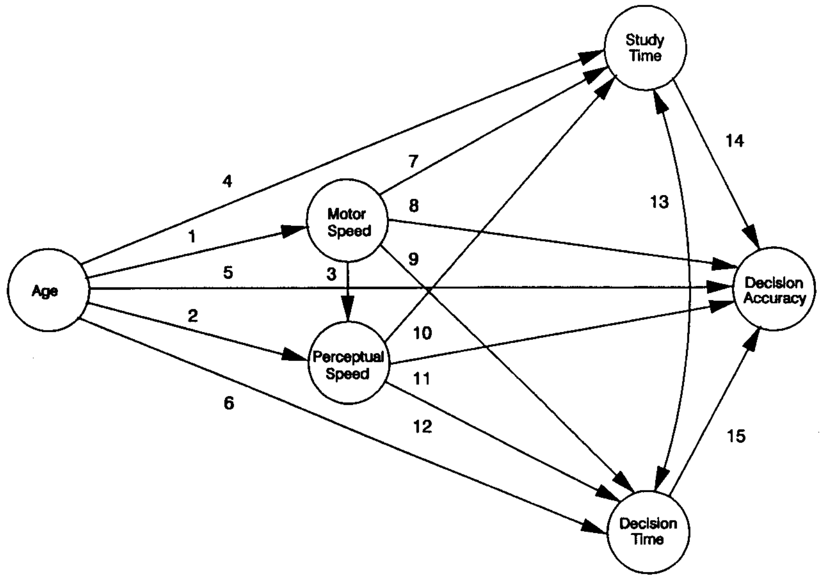

Figure 7. Structural diagram illustrating possible paths among variables in the computer-administered cognitive tests.

variation in perceptual speed. And finally, negative relations between decision time and decision accuracy were evident in each test, indicating that people who are less accurate also tend to take longer to make their decisions (or that more accurate people are faster in their decisions).

Because Study 2 was very similar, further discussion of the results of this study will be deferred to the General Discussion, where the results of both studies can be integrated and interpreted together.

Study 2

The primary purpose of Study 2 was to replicate and extend the results of Study 1. Computer-administered cognitive tests with lower levels of difficulty than those of Study 1 were examined to avoid a possible measurement floor in older adults, and new computer-administered tests were included to provide additional measures of speed.

Method

Subjects. The characteristics of the 258 adults, age 20 to 87, who participated in this study are summarized in Table 1. Subjects in this study were recruited from advertisements in a major metropolitan newspaper and were paid for participating in a single session of approximately 2 to 3 hr. Background questions asked of all participants were identical to those described in Study 1. Correlations among the alternative measures of the background variables were .89 for education and .48 to .78 for health. The correlations between age and the measures reported in Table 1 were −.08 for education and .10 for health (both *ps* > .10).

Note that the sample in this study had a higher average level of education than the sample in Study 1, particularly for adults in the older decades in which the average is nearly 1 year greater than the average for those age ranges in Study 1.

Procedure. Subjects were tested in groups of 1 to 6 each, and separate personal computers were provided for each subject for the computer-administered tests. The tests were performed in the following order by all subjects: Boxes, Pattern Comparison, Letter Comparison, Digit Copying, Digit Symbol with zero symbols, Digit Symbol with nine symbols, Associative Memory, Spatial Rotation, Matrix Reasoning, Memory Search With Digits, and Memory Search With Letters. The Boxes and Digit Copying tests were again postulated to assess motor speed, and the Pattern Comparison and Letter Comparison tests were postulated to assess perceptual speed. The Digit Symbol test with zero symbols was used as an additional measure of motor speed, with the Digit Symbol test with nine symbols representing perceptual and motor speed. The Associative Memory, Spatial Rotation, and Matrix Reasoning tests were intended to assess memory, spatial visualization, and reasoning abilities, respectively. The two memory search tests were designed to yield measures corresponding to encoding and response (intercept) and search (slope) processes.

The paper-and-pencil speed tests (Boxes, Digit Copying, Letter Comparison, and Pattern Comparison) were identical to those used in Study 1, as were the two versions of the computer-administered Digit Symbol test. Unlike Study 1, however, each version of the Digit Symbol test in this study was presented for only one 90-trial block after an 18-trial practice block.

Two new computer-administered speed tests were memory search tasks with digits and with letters. For both types of stimulus material, 8 practice trials were followed by two blocks of 48 trials each, with 6 positive and 6 negative trials at each set size between one and four. The memory set items were displayed for 2 s in the top middle of the computer screen, and after a 0.5-s delay, the target stimulus appeared in the middle of the screen. Responses were communicated by pressing the slash key for yes and the Z key for no. Both speed and accuracy were emphasized.

The Associative Memory test was identical to the test used in Study 1 except that the lags between presentation and test of the stimulus items were 0, 1, and 2 pairs instead of 0, 2, and 4 pairs. This change was implemented because accuracy was rather low, and nearly equivalent, with lags of 2 and 4 pairs in Study 1. A practice block of 9 items was followed by 90 items consisting of eight tests at each of three lags.

Table 6
Significant Path Coefficients for Paths Illustrated in Figure 7, Study 1

	Paper Folding		Matrix Reasoning		Associative Memory	
Path	P&P	DigSym	P&P	DigSym	P&P	DigSym
1 (Age–MSpd)	−.58	.51	−.58	.51	−.58	.51
2 (Age–PSpd)	−.34	.29	−.34	.29	−.34	.29
3 (MSpd–PSpd)	.51	.64	.51	.64	.51	.64
4 (Age–Study Time)	.24	.24	.26	.26	—	—
5 (Age–DecAcc)	−.25	−.26	−.19	−.18	—	−.16
6 (Age–DecTime)	.39	.34	.30	.30	.23	.17
7 (MSpd–Study Time)	—	—	—	—	—	—
8 (MSpd–DecAcc)	—	—	—	—	—	—
9 (MSpd–DecTime)	—	—	—	.19	—	—
10 (PSpd–Study Time)	—	—	—	—	—	—
11 (PSpd–DecAcc)	.23	−.25	.33	−.37	.28	−.17
12 (PSpd–DecTime)	−.31	.39	−.31	.15	−.33	.44
13 (Study Time–DecTime)	.26	.29	.29	.31	.33	.33
14 (Study Time–DecAcc)	.36	.34	.39	.39	.52	.52
15 (DecTime–DecAcc)	−.27	−.24	−.18	−.17	−.21	−.18
Model fit indices						
χ^2/df	2.10/4	7.95/4	6.08/4	4.79/3	12.91/6	20.38/5
Adjusted GFI	.985	.945	.957	.955	.941	.889
Adjusted RMS	.000	.068	.051	.057	.071	.114

Note. P&P = composite measures of motor speed (MSpd) and perceptual speed (PSpd) from the paper-and-pencil tests; DigSym = Digit Symbol-0 (for motor speed) and Digit Symbol-9 (for perceptual speed) variables; DecAcc = decision accuracy; DecTime = decision time; GFI = goodness-of-fit index; RMS = root-mean-square. Dashes indicate the coefficients were not significant.

The Matrix Reasoning test differed from that used in Study 1 by replacing the contents of the matrix cells with sets of letters and digits instead of geometric patterns and by presenting only four answer alternatives instead of eight. The cell contents were changed to try to make it easier for subjects to identify the relations among the elements. Three types of trials were distinguished by containing one, two, or three elements (digits or letters) per cell. Relations among the elements were determined by addition or subtraction in either the numeric or alphabetic sequence in steps of one, two, or three. For example, one of the two-element problems consisted of 22R, 18T, and 14V in the first row, 20O, 16Q, and 12S in the second row, and 18L and 14N in the third row, with answer alternatives of 16K, 18L, 10P, and 6Q. Six practice trials were presented, followed by two blocks of 30 trials each, 10 with each number of elements per cell.

The Spatial Rotation test was based on a task used by Salthouse, Babcock, Mitchell, et al., (1990) and consisted of same–different recognition judgments of six-segment line patterns after rotations of 0°, 90°, or 180°. The initial stimulus pattern could be inspected for as long as desired, and then two flags representing the orientation of the second stimulus in relation to the first stimulus were presented. The left flag was always vertical, and if the right flag was also vertical then the orientation discrepancy between the initial and test stimulus was 0°. If the right flag was horizontal, then the orientation discrepancy was 90°, and if the right flag was inverted, then the orientation discrepancy was 180°. The duration that the subject viewed the initial pattern and the duration that he or she viewed the display of the flags indicating the relative orientations of the initial and test stimuli were combined to represent study time, and the time to respond to the test pattern was used as the measure of decision time. Responses were communicated by pressing the slash key for same trials and by pressing the Z key for different trials. A practice block of six trials was followed by two blocks of 30 trials each. Within each block, there were five same and five different trials at each orientation, presented in a random arrangement.

Results and Discussion

Means, standard deviations, estimated reliabilities, and R^2 for linear and quadratic age relations for the primary dependent measures are reported in Table 7. As in Study 1, the age (linear) and age-squared (quadratic) terms were centered to minimize collinearity. The correlation between the number correct score and the number correct minus the number incorrect score was .95 in both Pattern Comparison and Letter Comparison tests, and thus the number correct minus the number incorrect measure was used in subsequent analyses to adjust for guessing.

Scores on the four paper-and-pencil speed tests and the DigSym-0 and DigSym-9 measures were converted to z scores, and the means were plotted as a function of decade in Figure 8. It is apparent that the general pattern is similar to Figure 1, although the age relations in this study are somewhat smaller than those of the previous study, perhaps because the older adults in this sample were more select with respect to amount of education (cf. Table 1).

Memory search. Mean response time and mean percentage of errors as a function of number of items in the memory set are plotted for each decade in Figure 9. Both variables with each type of stimulus material were analyzed by separate repeated measures ANOVAs in which age was categorized by decade and set size was a within-subjects variable. Only the age decade

Table 7
Summary Statistics for Primary Dependent Variables, Study 2

Variable	M	SD	Est. Rel.	R^2 Linear age	R^2 Quadratic age
Boxes	47.1	14.0	.78[a]	.074*	.004
Digit Copy	50.7	10.8	.84[a]	.116*	.054*
Letter Comparison	10.5	3.1	.38[a]	.129*	.027*
Pattern Comparison	16.0	4.5	.52[a]	.265*	.004
Digit Symbol-0 (s)	0.75	0.21	.94[b]	.131*	.015
Digit Symbol-9 (s)	1.51	0.42	.95[b]	.291*	.018*
Memory Search					
Digits, intercept	0.92	0.48	.92[c]	.164*	.016
Digits, slope	0.06	0.06	.59[c]	.002	.000
Letters, intercept	0.85	0.41	.88[c]	.132*	.010
Letters, slope	0.06	0.06	.23[c]	.004	.000
% correct					
Spatial Rotation	79.0	12.4	.81[d]	.079*	.008
Matrix Reasoning	88.8	16.8	.94[d]	.009	.079*
Associative Memory	80.0	13.9	.66[d]	.071*	.007
Decision time					
Spatial Rotation	2.66	1.51	.94[d]	.325*	.014
Matrix Reasoning	3.30	1.97	.94[d]	.231*	.055*
Associative Memory	2.57	1.77	.97[d]	.201*	.038*
Study time					
Spatial Rotation	7.95	4.57	.97[d]	.120*	.005
Matrix Reasoning	23.55	11.73	.89[d]	.244*	.001
Associative Memory	2.19	1.38	.96[d]	.028*	.000

Note. Est. Rel. = estimated reliabilities.
[a] Alternate-forms correlation from a sample of 212 college students. [b] Value from Study 1. [c] Correlation between scores from first and second administrations boosted the by Spearman-Brown formula. [d] Computed from correlations across three levels of complexity with formula in Kenney (1979, p. 132): Reliability = n(average r)/[1 + (n − 1)(average r)].
* $p < .01$.

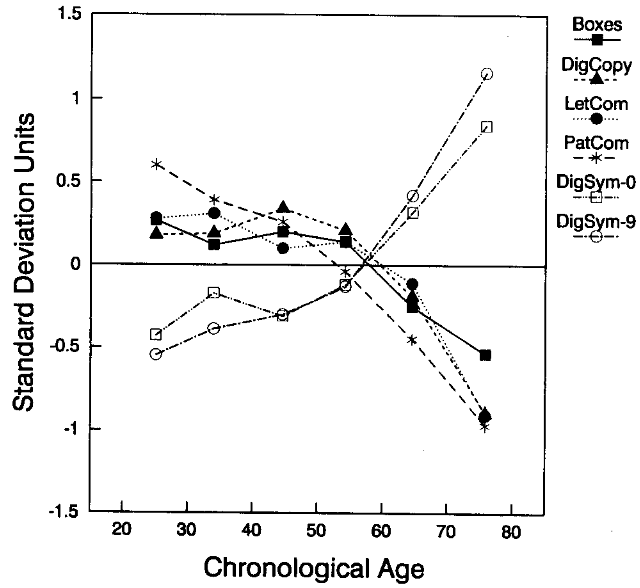

Figure 8. Mean standard deviation scores by decade for the speed measures, Study 2. DigCopy = Digit Copy; LetCom = Letter Comparison; PatCom = Pattern Comparison; DigSym-0 = Digit Symbol with zero symbols; DigSym-9 = Digit Symbol with nine symbols.

effect with the letter stimuli, $F(5, 252) = 5.53$, $MS_e = 123.99$, was significant in the analyses of the error data. In the reaction time analyses, the effect of age decade was significant for both digits, $F(5, 252) = 14.25$, $MS_e = 592{,}253$, and letters, $F(5, 252) = 12.75$, $MS_e = 470{,}545$, as was the effect of set size: digits, $F(3, 756) = 126.91$, $MS_e = 12{,}864$, and letters, $F(3, 756) = 130.44$, $MS_e = 12{,}621$. The Age Decade × Set Size interaction was not significant with either digits or letters (both Fs < 1.20).

The absence of a significant Age × Set Size interaction with either stimulus material was unexpected, but it is consistent with the lack of a significant age relation on the slopes of the Set Size × Response Time functions reported in Table 7. This failure to detect significant age-related effects on the slopes does not appear to be caused by unsystematic relations between the number of items in the memory set and response time, because the mean correlations between set size and reaction time were .73 for both letters and digits. Moreover, the slope parameters were not completely lacking in reliability, because the correlation between them was .46, a value significantly greater than zero.

One possible explanation for the failure to find significant Age × Set Size interactions may be that some of the slowest and, likely among the oldest, subjects might have responded in the same manner to all trials regardless of set size. The analyses were therefore repeated after eliminating the data from subjects with mean response times greater than 1.5 s, which is approximately one standard deviation above the mean response time of the entire sample. The correlations between age and the slope measures in this restricted sample of 228 adults were still very low (i.e., .05 for digits and .12 for letters), despite a moderate correlation (.47) between the two slopes. Finally, the Age Decade × Set Size interactions were still not significant with either the digit or letter stimuli in this restricted sample (i.e., both Fs < 1.4).

Computer-administered cognitive tests. Only means across the three complexity levels (i.e., angular disparity in Spatial Rotation, number of elements per cell in Matrix Reasoning, and presentation-test lag in Associative Memory) are reported for the computer-administered cognitive tests, because only one Age (by decade) × Complexity interaction was significant in either the entire sample or in subsamples of subjects with means in the simplest condition above the sample mean. The single exception was an interaction for the decision accuracy measure in the Spatial Rotation test, $F(10, 504) = 2.44$, $MS_e = .009$, but this was difficult to interpret because it was not monotonic as the age correlations were −.18 for 0° rotations, −.29 for 90° rotations, and −.24 for 180° rotations.

The mean z scores for study time, decision time, and decision accuracy are plotted by decade for the Spatial Rotation test in Figure 10, for the Matrix Reasoning test in Figure 11, and for the Associative Memory test in Figure 12. The age effects were significant in every variable in the Spatial Rotation and Associative Memory tests. The linear age trend was not significant in the decision accuracy measure in the Matrix Reasoning test, but the quadratic age trend was significant (cf. Table 7).

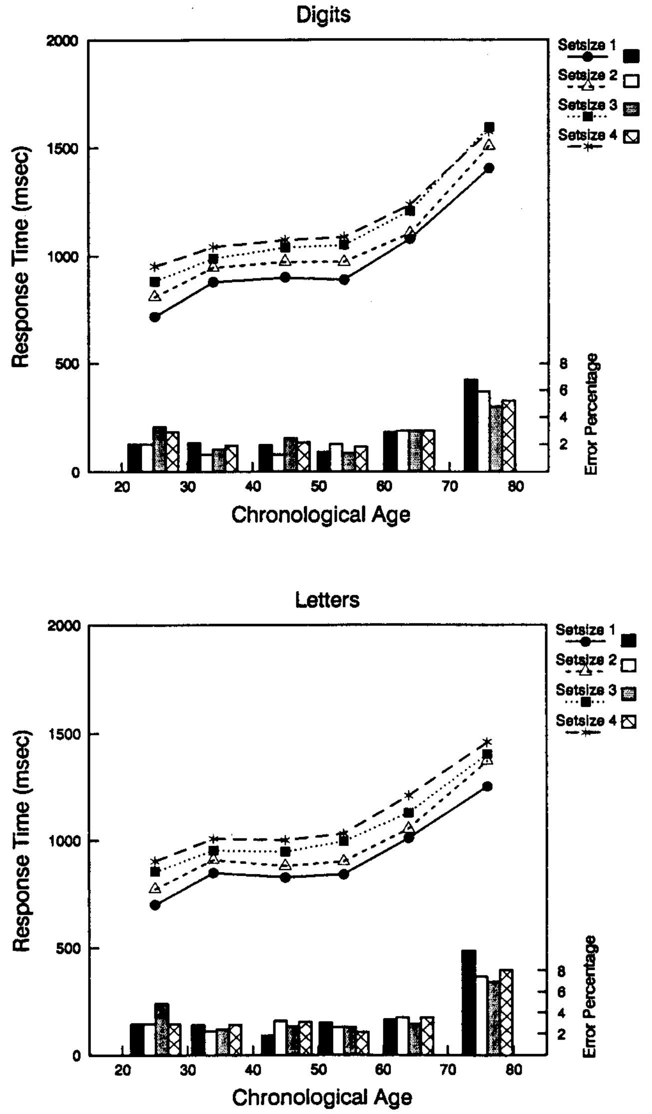

Figure 9. Mean reaction time and mean percentage of errors as a function of memory set size by decade for digits (top) and letters (bottom) in the Memory Search test, Study 2.

Regression analyses. A confirmatory factor analysis conducted on the four health and two education variables revealed a good fit: $\chi^2(8, N = 258) = 12.83$, adjusted GFI = .959, and adjusted RMS = .049. The correlation between the education and health factors was −.23. Because the standardized factor weights were similar (i.e., .92 and .97 for the education variables and .79 to .92 for the health variables, except .56 for the health-related activity limitation variable), the constructs were represented by the average of the relevant z scores.

A confirmatory factor analysis was also conducted on the measures from the four paper-and-pencil speed measures. In contrast to the results of Study 1, the fit was fairly good: $\chi^2(1, N = 258) = 1.44$, adjusted GFI = .972, and adjusted RMS = .063. The correlation between the motor speed and perceptual speed factors was .75, but when this correlation was fixed at 1.0, the

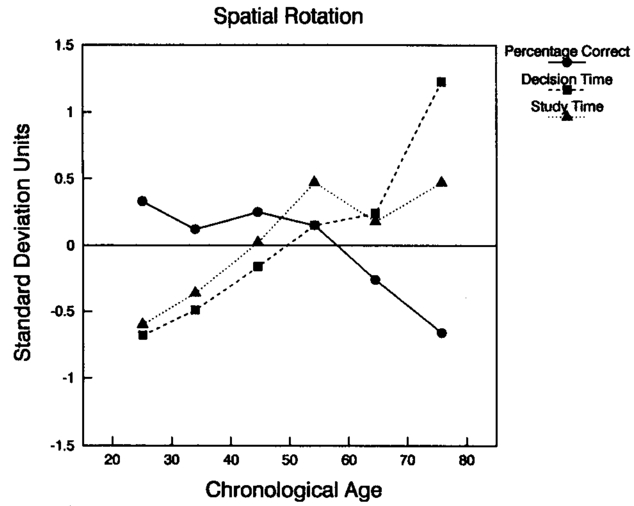

Figure 10. Mean standard deviation scores by decade for the study time, decision time, and decision accuracy measures in the Spatial Rotation test, Study 2.

fit of the model was significantly worse, difference $\chi^2(1, N = 258) = 31.13$. Because the standardized factor weightings were similar (i.e., .73 for Boxes, .84 for Digit Copy, .72 for Letter Comparison, and .86 for Pattern Comparison), the average *z* score for the Boxes and Digit Copy measures was used to represent motor speed, and the average *z* score for the Pattern Comparison and Letter Comparison measures was used to represent perceptual speed.

Each of the 19 variables in Table 7 was examined for the presence of main effects of gender, health, and education, and for interactions of these predictors with age. The significant effects in the regression analyses and the direction of the effects were as follows: for health, better self-reported health was associated

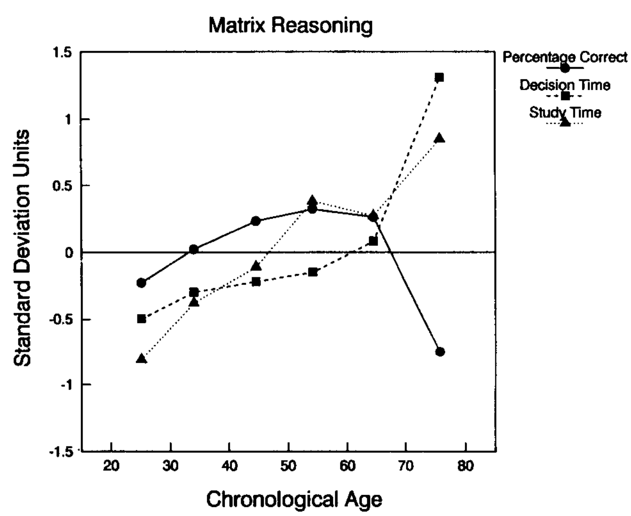

Figure 11. Mean standard deviation scores by decade for the study time, decision time, and decision accuracy measures in the Matrix Reasoning test, Study 2.

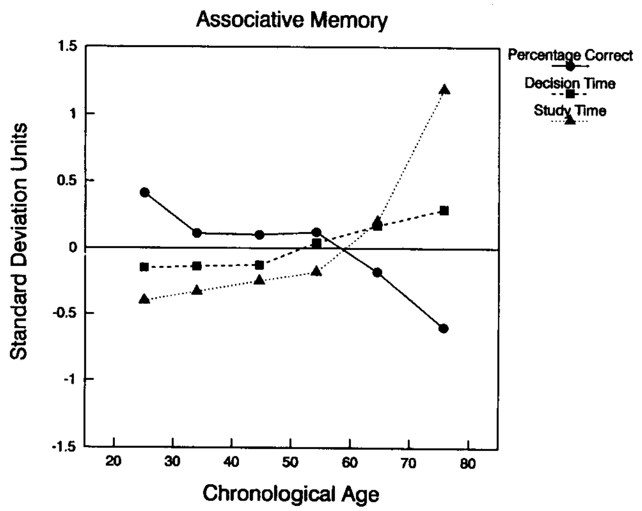

Figure 12. Mean standard deviation scores by decade for the study time, decision time, and decision accuracy measures in the Associative Memory test, Study 2.

with higher scores in Digit Copy and Spatial Rotation decision accuracy; for education, greater amounts of education were associated with higher scores on Boxes, Digit Copy, Letter Comparison, Pattern Comparison, Spatial Rotation decision accuracy, Matrix Reasoning decision accuracy, Associative Memory decision accuracy, and longer Spatial Rotation study time, but with shorter Matrix Reasoning decision time and shorter DigSym-0 time. The only significant interaction was between age and the composite education variable on Matrix Reasoning decision time, in the direction of larger effects of education at older ages.

Women were significantly slower than men in Spatial Rotation decision time and Matrix Reasoning study time. Age and gender interacted on Matrix Reasoning decision accuracy and on Matrix Reasoning decision time (in both cases, the advantage for men was larger among older adults than among younger adults).

Moderating effects of speed were investigated by examining interactions of age and speed after the predictors had been centered to a mean of zero and the main effects were partialed out. All interactions were in the direction of smaller age-related influences at faster levels of speed (or greater influences of speed at older ages). Significant interactions involving age and the composite motor speed variable, with the increment in R^2 associated with the interaction presented in parentheses, were evident in Letter Memory Search intercept (.026), Letter Memory Search slope (.043), Matrix Reasoning decision accuracy (.038), Matrix Reasoning decision time (.079), and Associative Memory decision time (.049). Significant interactions between age and the composite perceptual speed variable were evident in Digit Copy (.021), Digit Memory Search intercept (.020), Letter Memory Search intercept (.024), Matrix Reasoning decision accuracy (.049), Matrix Reasoning decision time (.077), and Associative Memory decision time (.023). Variables with significant interactions involving age and DigSym-0 were Digit Memory Search intercept (.026), Letter Memory Search intercept (.028), Matrix Reasoning decision time (.023), and Associative Memory decision time (.094). Finally, interactions of age and DigSym-9 were evident in Pattern Comparison (.024), Digit Memory Search intercept (.015), Matrix Reasoning decision time (.048), and Associative Memory decision time (.026). As in Study 1, most of the Age × Speed interactions were on measures of time rather than measures of accuracy.

The proportions of variance associated with age after control of health, education, and the four speed variables are summarized in Table 8. It is apparent that the general pattern is very similar to that of Study 1 in that the attenuation of the age-related variance was greater when speed measures were controlled in addition to health and education, and the attenuation was greatest after control of the speed measures with the most cognitive involvement.

The R^2 values associated with the perceptual speed measures in the prediction of decision accuracy before and after control of age, health, and education are reported in the bottom of Table 4. The results are generally consistent with those from Study 1 in that the amount of variance associated with the speed measures is reduced but not eliminated when the other sources of variance are controlled.

Commonality analyses. Results from the same type of commonality analyses that were performed in Study 1 are summarized in Table 9. Note that the earlier results are replicated with respect to (a) a small portion of variance uniquely associated with age in relation to the total age-related variance, (b) a larger proportion of variance shared between age and perceptual speed than between age and motor speed, and (c) a relatively large proportion of variance shared among age, motor speed, and perceptual speed. The only exceptions to these patterns are in the Matrix Reasoning test in which there was very little age-related variance in the measure of decision accuracy.

Path analyses. As in Study 1, the initial step in the path analyses was a confirmatory factor analysis on the nine cognitive variables specifying factors of study time, decision time, and decision accuracy. Consistent with the results of the previous study, the fit of the model was poor: $\chi^2(24, N = 258)$, = 213.99, adjusted GFI = .724, and adjusted RMS = .169, and correlations among the residuals for measures from the same test were high. The tests were therefore examined separately, following the same procedural steps described in Study 1. The significant path coefficients and the goodness-of-fit indices for the final path models are summarized in Table 10.

In general, the results in Table 10 are quite similar to those from Study 1 (summarized in Table 5). That is, as in the previous study, there were small or inconsistent influences of motor speed on the cognitive variables and little or no influence of perceptual speed on study time, but there was a consistent relation between perceptual speed and both decision time and decision accuracy.

General Discussion

The initial section of the General Discussion focuses on the three goals of primary interest in this project: (a) Is there evidence of speed mediation of the age-related effects on cognitive measures without time limits? (b) What is the nature of the speed primarily responsible for mediating age–cognition re-

Table 8
R^2 for Age After Control of Demographic and Speed Variables, Study 2

Criterion	Health, education	Health, education, motor speed	Health, education, perceptual speed	Health, education, Digit Symbol-0	Health, education, Digit Symbol-9
	R^2 for age after control of:				
Boxes	.063*	.001	.003	.038*	.005
Digit Copy	.096*	.001	.007	.047*	.011
Letter Comparison	.114*	.048*	.007*	.064*	.005
Pattern Comparison	.239*	.117*	.008*	.141*	.063*
Digit Symbol-0	.125*	.076*	.037*	—	.000
Digit Symbol-9	.275*	.164*	.076*	.093*	—
Memory search					
Digits, intercept	.154*	.076*	.039*	.039*	.000
Digits, slope	.002	.000	.000	.001	.000
Letters, intercept	.120*	.049*	.022*	.024*	.000
Letters, slope	.004	.007	.006	.002	.004
M reaction time	.174*	.086*	.042*	.041*	.000
% correct					
Spatial Rotation	.062*	.034*	.013	.029*	.008
Matrix Reasoning	.003	.002	.011	.005	.030*
Associative Memory	.056*	.041*	.011	.011	.001
Decision time					
Spatial Rotation	.325*	.263*	.166*	.223*	.115*
Matrix Reasoning	.205*	.132*	.086*	.125*	.053*
Associative Memory	.188*	.118*	.073*	.057*	.019*
Study time					
Spatial Rotation	.136*	.125*	.086*	.122*	.088*
Matrix Reasoning	.233*	.224*	.114*	.218*	.159*
Associative Memory	.031*	.023	.008	.019	.006

Note. Dashes indicate no data.
* $p < .01$.

lations? and (c) How are measures of speed, study time, decision time, and decision accuracy related to one another and to age?

Speed Mediation on Measures Without Time Limits

Before describing the evidence relevant to the influence of speed on the age differences in cognitive measures obtained without time limits, it is first desirable to review the evidence indicating that age-related differences do exist in measures of decision accuracy under conditions of little or no time pressure. This evidence is provided in Tables 2 and 6, in which the R^2 associated with age was significantly greater than zero for all of the percentage correct measures except that for the Matrix Reasoning test in Study 2. The significant age trends for these measures, together with the nearly monotonic patterns evident in Figures 4 through 6 and Figures 10 through 12, indicate that age-related effects are definitely apparent in measures of decision accuracy, in addition to other measures of performance such as decision time.

The results of both Studies 1 and 2 indicate that these age differences in decision accuracy are substantially reduced when measures of perceptual speed are statistically controlled. In Study 1 the mean R^2 associated with age was .096 after health and education were controlled and .018 after perceptual speed was controlled, values which are equivalent to an attenuation of 81.3%. Corresponding values in Study 2 were .040 and .012, representing an attenuation of 70.0%. This magnitude of attenuation is about the same as that observed in paper-and-pencil cognitive tests, as the attenuation of the age-related variance for the Number Series, Cube Assembly, and Name-Number tests in Study 1 was 83.9%. Moreover, the proportional reduction of the age-related variance in decision accuracy was actually larger than that observed with measures of decision time. That is, the average percentage reductions in the age-related variance in decision time after control of perceptual speed were 74.5% in Study 1 and 54.8% in Study 2.

The answer to the first question addressed in these studies therefore seems quite clear in that the results indicate that there is apparently as much speed mediation of the age-related differences in decision accuracy as of the age-related differences in decision time or of the age-related differences in performance measures obtained from timed paper-and-pencil tests. It can thus be concluded that the involvement of speed in the relations between age and cognition is not restricted to timed or speeded measures of cognitive functioning.

Type of Speed Mediation

The key distinction between measures of speed investigated in these studies was based on the relative cognitive requirements

Table 9
Results of Commonality Analyses Conducted on Decision Accuracy Measures in Study 2

Variable	Age	MSpd	PSpd
	Predictor variable		
Spatial Rotation accuracy as criterion			
Unique to age	.010		
Unique to MSpd		.011	
Unique to PSpd			.034
Common to age and MSpd	.003	.003	
Common to age and PSpd	.025		.025
Common to MSpd and PSpd		.041	.041
Common to age, MSpd, and PSpd	.041	.041	.041
Total effects	.079	.096	.141
Matrix Reasoning accuracy as criterion			
Unique to age	.019		
Unique to MSpd		.039	
Unique to PSpd			.070
Common to age and MSpd	−.005	−.005	
Common to age and PSpd	−.017		−.017
Common to MSpd and PSpd		.101	.101
Common to age, MSpd, & PSpd	.012	.012	.012
Total effects	.009	.147	.166
Associative Memory accuracy as criterion			
Unique to age	.010		
Unique to MSpd		.000	
Unique to PSpd			.054
Common to age and MSpd	.000	.000	
Common to age and PSpd	.032		.032
Common to MSpd and PSpd		.019	.019
Common to age, MSpd, and PSpd	.029	.029	.029
Total effects	.071	.048	.134

Note. MSpd = motor speed; PSpd = perceptual speed.

in the tasks used to measure processing speed. Cognitive demands were presumed to be low when the subject only needed to draw lines, copy digits, or decide whether two digits were physically identical, but the demands were hypothesized to be much greater when the subject was required to compare sets of letters or patterns or to associate digits with symbols. I originally intended to use the slope and intercept parameters from the functions relating reaction time to the hypothesized number of cognitive operations in the visual search (Digit Symbol in Study 1) and memory search (in Study 2) tasks as additional speed measures. However, I abandoned this plan after discovering that the slope parameters had weak relations with age and low reliability, because it would have been unreasonable to expect these variables to mediate age relations with other variables when they had very small relations with age and when only a small proportion of their total variance was systematic.

The distinction between motor speed and perceptual speed in the paper-and-pencil tests was somewhat equivocal because composite measures of these constructs were highly correlated with one another, particularly in Study 1. Although this indicates that conclusions regarding types of speed must be considered tentative, the pattern of results was nevertheless consistent across numerous comparisons in the two studies. Furthermore, it seems likely that even larger differences between the influence of motor speed and perceptual speed would be expected if measures of these constructs could be identified that were not as highly correlated as those in the present studies.

Three types of analyses were conducted to evaluate the relative importance of motor speed and perceptual speed in the age–cognition relations. One analysis consisted of the examination of the residual age-related variance when the speed measure was statistically controlled. The reasoning was that the smaller the residual age-related variance, the larger the presumed influence of speed in the age–cognition relations. The results in Tables 3 and 7 indicate that the residual age-related variance was nearly always larger when motor speed measures were controlled than when perceptual speed measures were controlled, thus suggesting that the influence of perceptual speed was greater than that of motor speed.

Commonality analysis conducted on the decision accuracy measures from the computer-administered cognitive tests was the second type of analysis relevant to the comparison of motor speed and perceptual speed. The results summarized in Tables 5 and 9 indicate that the variance common to age and perceptual speed was nearly always larger than that common to age and motor speed. The only exception was with the Matrix Reasoning measure in Study 2, in which the total age effects were very small.

Path analyses were the third type of analysis used to evaluate the relative importance of motor speed and perceptual speed in the age–cognition relations. The results in Tables 6 and 10 indicate that there were no significant paths between motor speed and decision accuracy but that the paths between perceptual speed and decision accuracy were significant in the final models for all tests.

When considered together, the results of these three different types of analyses seem to provide a compelling case that perceptual speed is more important than motor speed as a mediator of age–cognition relations. Because the primary difference between the two types of speed measures appears to be in the amount of cognitive involvement, it seems reasonable to infer that it is the speed of cognitive operations that primarily contributes to the relations between age and measures of cognitive functioning.

Relations Among Measures

Tables 2 and 6 and Figures 4 through 6 and 10 through 12 indicate that, with only two exceptions, significant age relations were evident in the study time, decision time, and decision accuracy measures in every test. Relations among these measures and among age and the two types of speed were examined by means of path analyses.

The path analysis results, based on an integration of the findings reported in Tables 6 and 10, are first considered with respect to the significant paths leading to decision accuracy. The negative path from decision time to decision accuracy indicates that longer time to make a decision was associated with less accurate decisions. This is opposite to the pattern expected from a speed–accuracy trade-off because this finding indicates that

Table 10
Significant Path Coefficients for Paths Illustrated in Figure 7, Study 2

	Spatial Rotation		Matrix Reasoning		Associative Memory	
Path	P&P	DigSym	P&P	DigSym	P&P	DigSym
1 (Age–MSpd)	−.34	.36	−.34	.36	−.34	.36
2 (Age–PSpd)	−.33	.33	−.33	.33	−.33	.33
3 (MSpd–PSpd)	.46	.57	.46	.57	.46	.57
4 (Age–Study Time)	.35	.35	.49	.49	.17	—
5 (Age–DecAcc)	−.18	−.19	.16	.20	—	—
6 (Age–DecTime)	.47	.41	.31	.28	.33	.17
7 (MSpd–Study Time)	—	—	—	—	—	—
8 (MSpd–DecAcc)	—	—	—	—	—	—
9 (MSpd–DecTime)	—	—	−.17	—	—	.36
10 (PSpd–Study Time)	—	—	—	—	—	.19
11 (PSpd–DecAcc)	.26	−.24	.34	−.37	.27	−.35
12 (PSpd–DecTime)	−.20	.31	−.23	.38	−.24	.25
13 (Study Time–DecTime)	.58	.60	—	—	.24	.24
14 (Study Time–DecAcc)	.48	.47	.33	.30	.38	.37
15 (DecTime–DecAcc)	−.25	−.22	−.53	−.51	−.37	−.27
Model fit indices						
χ^2/df	4.49/4	1.02/4	11.56/4	5.80/5	8.92/5	3.99/4
Adjusted GFI	.970	.993	.924	.970	.952	.973
Adjusted RMS	.025	.000	.089	.026	.060	.000

Note. P&P = composite measures of motor speed (MSpd) and perceptual speed (PSpd) from the paper-and-pencil tests; DigSym = Digit Symbol-0 (for motor speed) and the Digit Symbol-9 (for perceptual speed) variables; DecAcc = decision accuracy; DecTime = decision time; GFI = goodness-of-fit index; RMS = root-mean-square. Dashes indicate that coefficients were not significant.

people who are less accurate in their decisions also take longer to make those decisions. The positive path from study time to decision accuracy indicates that a longer time working on the problems was associated with a higher level of accuracy. The path from perceptual speed to decision accuracy was in the direction of faster perceptual speed associated with higher accuracy. This relation is independent of that between perceptual speed and decision time, which was in the direction of faster perceptual speed associated with faster decisions.

In light of the preceding information, several inferences can be made regarding the age-related influences on decision accuracy. First, there appears to be some direct[1] age-related effect on decision accuracy, although this effect was inconsistent across the two sets of speed measures in the Associative Memory test in Study 1, and the relevant path coefficients were not significant in the model for the Matrix Reasoning test in Study 2. Second, very little of the age-related effect was apparently mediated through the study time variable because although increased age was associated with longer study time, longer study time was associated with higher accuracy, and yet increased age was associated with lower accuracy. This pattern raises the possibility that the age differences might have been larger if study time had not been positively associated with age, but unfortunately no independent evidence relevant to this issue is available in these data. Third, it is possible that some of the age-related influences are mediated through slower decision time, but it seems more likely that both slower decisions and less accurate decisions are a consequence of a common third factor rather than that slower decisions cause lower accuracy. Finally, it seems probable that there is some mediation of the age-related effects on decision accuracy through slower cognitive operation speed because of the negative relation between age and perceptual speed and the positive relation between perceptual speed and decision accuracy. The net result of these two relations could be that older adults are less accurate in their cognitive decisions because they are slower in executing relevant cognitive operations. The speed influence is presumed to be largely a result of cognitive operations because there was no significant relation between motor speed and decision accuracy.

Miscellaneous

There are a number of additional results from Studies 1 and 2 that warrant some discussion. First, significant interactions between age and speed were evident with several of the performance measures in both studies. Interactions of this type are theoretically interesting because they indicate that faster speed is associated with smaller age-related influences. However, the fact that interactions of age and perceptual speed were not significant in four previous studies reported in Salthouse (1991, 1993) suggests that the results of these studies should be consid-

[1] Note that *direct* in this context does not mean unmediated by any factors, but merely not mediated by other measures included in this analysis.

ered tentative. It is also important to note that most of the interactions in the present study were evident with other speed measures or with the study time or decision time measures, as the only interactions with accuracy measures were with the Paper Folding test in Study 1 and the Matrix Reasoning test in Study 2. One possible interpretation of these results is that moderating effects of speed, in the form of Age × Speed interactions, are simply another consequence of age-related slowing in which people who are slow in some measures are also slow in other measures.

A second interesting result from the present studies is that the age-related effects in the Matrix Reasoning tests were much smaller in the version of the test with letters and digits in the matrix cells than in the version with geometric patterns in the cells (i.e., the R^2 for age was .009 in the version with letters and digits but .149 in the version with geometric patterns). It is tempting in view of this pattern to suggest that there may be a special age-related difficulty in identifying relations involving geometric patterns. However, such a conclusion would be premature because there were numerous other differences between the two versions of the test that could have contributed to the different pattern of results (e.g., only two types of relatively simple relations were used with letters and digits, whereas a variety of relations were used with geometric patterns, the letter-digit problems varied in terms of the number of elements and not necessarily with respect to the number of different relations, and choices were made among four alternatives in the letter-digit version of the test but among eight alternatives in the geometric pattern version).

Another noteworthy finding in these studies concerns the results in Table 4, which indicated that the relations between perceptual speed and cognition were significant even after the age variation had been controlled. This is consistent with the results of other researchers such as Jensen (e.g., 1987) and Vernon (e.g., 1983). However, it is important to note that the influence of perceptual speed was much larger when age was not controlled because of the substantial relation between age and perceptual speed. The role of age variation in the relations between speed and cognition is also evident in the commonality analyses because entries in the third column of Tables 5 and 9 indicate that a substantial proportion of the variance in decision accuracy associated with perceptual speed is also shared with age.

Finally, the effects of presentation-test lag in the Associative Memory tests in the two studies deserve some comment. Of particular interest is the existence of significant age-related effects in decision accuracy at Lags 1, 2, and 4 when the analyses were restricted to subjects with 100% accuracy At Lag 0.[2] The existence of a significant main effect of age in these analyses implies that increased age may be associated with a faster loss of information over very short intervals, even as short as one intervening item. However, the fact that the interactions between age and lag were not significant suggests that most of the loss of information occurs almost immediately, because there is apparently little additional loss between one and two or between two and four intervening items.

Conclusion

The results of this study confirm earlier findings that a large proportion of the age-related variance in cognitive performance is shared with measures of the speed with which simple operations can be executed. Moreover, previous results are extended by the discovery that the influence of speed was as great on measures of decision accuracy obtained under conditions of no time pressure as on measures of decision time or of the number of correct responses produced within a specified time. And, as in earlier studies (e.g., Salthouse, 1993b), the relevant speed appears to be related to the rate at which cognitive operations can be executed, and not merely to the time required for sensory and motor processes.

The results of these studies are consistent with the interpretation that a slower speed of processing affects the quality of cognitive performance by reducing the amount of simultaneously available information (cf. Salthouse, 1988, 1992a; Salthouse & Babcock, 1991). That is, the evidence now seems fairly compelling that slower processing speed may function as a proximal mediator of the relations between various measures of cognitive functioning and age during adulthood. However, further research is necessary to distinguish this interpretation from alternative explanations of the speed–cognition relation (e.g., on the basis of constructs such as inhibitory control or attentional selectivity). Additional research is also required to identify the causes of the relations between age and speed documented in these and in numerous other studies. Although many questions remain, there now seems little doubt that processing speed is a major factor in the age-related differences in several types of cognitive functioning.

[2] Results from the analysis of variance on the data from 154 subjects in Study 1 were as follows: age decade, $F(5, 148) = 5.31$, $MS_e = 474.87$, $p < .01$; lag, $F(1, 148) = 3.60$; and Age Decade × Lag, $F(5, 148) = 1.67$, $MS_e = 271.76$. Results from the analysis on the data from 176 subjects in Study 2 were as follows: age decade, $F(5, 170) = 5.51$, $MS_e = 522.63$, $p < .01$; lag, $F(1, 170) = 31.98$, $p < .01$; and Age Decade × Lag, $F(5, 170) = 0.13$, $MS_e = 228.81$.

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