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Speed Mediation of Adult Age Differences in Cognition

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Previous research has established that a large proportion of the adult age-related variance in various measures of fluid or process cognition is reduced when statistical control procedures such as hierarchical regression are used to eliminate variation in measures of perceptual speed. This finding was confirmed in the present study and was extended to include paired-associate and free-recall measures of memory in addition to measures of reasoning and spatial abilities. Most of the speed mediation was associated with speed measures requiring cognitive operations such as comparison or substitution instead of merely motor responses such as copying symbols or drawing lines. These results suggest that the rate of performing elementary cognitive operations is an important proximal mediator of the adult age differences in several types of cognitive tasks.

Inspired largely by ideas of Birren (e.g., 1955, 1965, 1974), Salthouse (1985a) proposed that the adult age differences in certain measures of cognitive functioning might be partially mediated by age-related reductions in the speed of executing relevant mental operations. The evidence available at that time was rather weak, because no published studies had been explicitly designed to investigate this hypothesis. Most of the data relevant to the hypothesis were obtained by locating published articles reporting correlations among age, a measure of processing speed, and a measure of cognition (or studies by Salthouse containing the relevant data), and then computing partial correlations between age and the cognitive measure after partialing out the measure of speed. Only a few data sets with the necessary information could be identified, and the samples were often small and usually involved two extreme age groups rather than a continuous range of ages. Furthermore, in all cases the relevant constructs were assessed with a single measure rather than with potentially more reliable and valid multiple measures. Despite these limitations, the hypothesis received some support because statistical control of the measure of speed frequently resulted in an appreciable reduction in the magnitude of the relation between age and the measure of cognition.

In the last 5 years, several more extensive studies have been conducted in which data relevant to the hypothesis have been reported. The major ones involving at least 200 adults with an age range of at least 35 years and including several measures of both speed and cognition are summarized in Table 1. In all cases, the available speed measures have been combined to form a more reliable composite index. (This required a reanalysis of the data from Salthouse, Kausler, & Saults, 1988.) It can be seen that results from these more recent studies are clearly consistent with the speed-mediation hypothesis. That is, the average R^2 for age when it was considered alone was .158, but the value was reduced to only .035 after the variation in a composite measure of perceptual speed was controlled. These results therefore suggest that almost 80% (i.e., [.158 − .035]/.158 = .778) of the age-related variance in certain measures of fluid cognition is associated with variations in perceptual speed.

The research reported in this article was designed with two major goals in mind. One goal was to examine the generality of the speed-mediation phenomenon by including measures of memory in addition to measures of fluid or process aspects of cognition. Extending the research in this direction is of interest, because less convincing support for a mediational effect of speed was found with measures reflecting memory functioning in the partial correlation analyses reported in Salthouse (1985a). That is, partialing a measure of processing speed had a smaller effect on the correlations between age and measures of memory than it did on the correlations between age and measures of other types of cognitive functioning. Moreover, additional analyses on the data from the Salthouse et al. (1988) project similar to those summarized in Table 1 also revealed weaker attenuation of the age relations for measures representing memory functioning than for measures representing other types of cognitive functioning. For example, the attenuation was only 63.8% for a measure of the accuracy of reproducing the identities of items in a matrix, only 47.5% for a measure of the accuracy of reproducing the positions of items in a matrix, and only 16.7% for a measure of paired-associate memory.

The smaller attenuation of the age-related memory differences after control of measures of speed raises the possibility that quickness of mental operations may be a less important factor in the age differences in traditional memory tests than in cognitive tests assessing reasoning or spatial abilities. Although this speculation is plausible on the basis of the available results, stronger evidence of the differential influence of speed on cognitive and memory measures is desirable before one can conclude that speed factors have a minimal role in the relations between age and memory. One type of evidence that would be relevant in this regard would be a discovery that substantial age-related effects remained after statistical control of a measure of perceptual speed, or equivalently, a finding that the

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relations between age and measures of memory were attenuated only slightly after one removed the variance in the perceptual speed measures that was linearly related to the measures of memory. Several memory measures were therefore included in the present study to allow this implication to be investigated.

The second major goal of the present study was to examine a variety of different speed measures to identify the aspects of speed most responsible for mediating age–cognition relations. Two issues were of particular interest in this connection. One was the extent to which sensory or motor factors were involved in the influence of perceptual speed on age–cognition relations. Because most tests of perceptual speed involve visual presentation of materials and require a written response to communicate decisions, sensory and motor aspects may be contributing to many measures of perceptual speed. In an attempt to remove the influence of peripheral input and output speed when analyzing the influence of perceptual speed, participants in the present research project, in addition to performing more conventional perceptual speed tests, also performed several speeded tasks with minimal cognitive requirements.

Another issue related to the measurement of speed concerns the significance of the systematic relations often reported between the average times of young and old adults across different combinations of speeded tasks. Many researchers have found that there is frequently an orderly relation between the response times of young adults across a range of experimental conditions or tasks and the response times of older adults in those same conditions or tasks (e.g., Brinley, 1965; Cerella, 1985, 1991; Lima, Hale, & Myerson, 1991; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; Salthouse, 1985a, 1985b). It is possible to distinguish between strong and weak positions regarding the theoretical significance of these systematic relations. The strong position emphasizes the quantitative form of the relation between the times of young and old adults because of the assumption that the relation is informative about both the magnitude and the nature of the age-related slowing evident across many measures of speeded performance. A weaker position maintains that the existence of systematic relations suggests that the age-related influences on the various measures are not independent, but this perspective does not necessarily consider the form of the relation informative about either the rate or the precise nature of age-related slowing. That is, lack of independence can be inferred if knowledge of the age differences in one measure provides information about the age differences in other measures, but no special significance is attached to the parameters of the functions relating the times of young adults to the times of older adults.

The distinction between strong and weak positions regarding the systematic relations between the times of adults of different ages can be elaborated after one first considers how these relations were determined in the present study. The initial step involved the administration of a battery of speed tests—involving a range of operations and completion times—to 100 college students who served as the reference group. Scores on each of these tests were then converted into units of seconds per item, with the averages ranging from 0.4 s to almost 2 s per item. The next step in the procedure consisted of administering the same battery of speed tests to a sample of over 300 adults from a wide range of ages. Each of these participants' scores were then converted into the seconds-per-item metric and was analyzed in a linear regression equation relating those times to the average times of the reference group on the same tasks. It is important to emphasize that unlike most previous reports of systematic relations (but see Charness & Campbell, 1988, for an exception), these analyses are conducted at the level of individual subjects. That is, a regression equation was computed for each subject relating his or her times (as the dependent or criterion variables) to the mean times of the student reference group (as the independent or predictor variables).

Linear regression equations can be characterized in terms of three parameters corresponding to the correlation, the intercept, and the slope. The correlation is informative about the degree to which there is a systematic (linear) relation among the variables. The intercept indicates the magnitude of an influence that is constant across all variables, and the slope represents the amount by which the individual's time increases for every unit increase in the time of the reference group. Of these parameters, the slope is often considered the most interesting, because it has been interpreted as a reflection of the magnitude of age-related slowing (e.g., Cerella, 1985, 1991; Cerella, Poon, & Williams, 1980; Lima et al., 1991; Myerson et al., 1990).

A strong interpretation of the systematic relations among speed measures is that the slope is a direct index of a general speed factor. The slope is not measured in absolute units because it is always relative to some reference group, but it can still be meaningful in across-individual comparisons if everyone is evaluated against the same reference group. A weaker position regarding the systematic relations among speed measures is that the slope is merely an index of the relation among variables that are each determined by other influences in addition to the hypothesized speed factor. Because the contribution of the other influences can be expected to differ across variables, the weak position views the slope as a less direct index of the hypothesized speed factor than many of the observed speed measures. (See Salthouse, 1992a, for further discussion of this distinction.)

In summary, in both the strong and weak interpretations, a high correlation between the times of the individual and the times of the reference group implies that the measures are associated and not independent, but the meaning of the slope parameter is quite different in the two perspectives. The strong position maintains that the slope is an important index of a central speed construct because it has a special status as the most direct indicator of the hypothesized speed factor, whereas the weak position views the slope as much less interesting because it is assumed only indirectly to reflect the operation of any relatively general age-related speed factors that might exist.

One manner in which the validity of these alternative conceptualizations of the systematic relations among speed measures might be investigated involves examining the strength of linkages between various measures of speed and both age and cognition. The reasoning is as follows. If, as the results summarized in Table 1 suggest, speed of processing is an important mediating factor in the age differences in some measures of cognition, then comparisons of the degree to which age–cognition relations are attenuated after control of alternative speed measures may be informative about the status of those speed measures as reflections of a common or general speed factor. Specifically,

Table 1
Results of Studies Examining the Relations Between Age and Cognition Before and After Statistical Control of Perceptual Comparison Speed

					R^2 for age		
n	Age range (in years)	Speed	*r*(age − speed)	Cognition	Before	After	% attenuation
Schaie (1989)							
611	22–84	FindA's, IDPict	−.53	PMA Space	.168	.036	78.6
				PMA Reason	.281	.058	79.4
628	22–84	FindA's, IDPict	−.65	PMA Space	.221	.032	85.5
				PMA Reason	.360	.058	83.9
Hertzog (1989)							
592	43–78	FindA's, IDPict	?	PMA Space	.124	.011	91.1
		Number Compar.		PMA Reason	.237	.027	88.6
		Answer Speed		Spatial Relations	.209	.032	84.7
				Spatial Visualization	.128	.029	77.3
				Induction	.202	.021	89.6
Salthouse (1991a)							
221	20–80	Letter Compar.	−.61	Shipley # Cor.	.221	.024	89.1
		Pattern Compar.		Raven # Cor.	.322	.056	82.6
				Shipley % Cor.	.117	.021	82.1
				Raven % Cor.	.129	.012	90.7
				Working Memory	.292	.050	82.9
228	20–82	Letter Compar.	−.71	PapFld # Cor.	.037	.007	81.1
		Pattern Compar.		CubAsm # Cor.	.019	.002	89.5
				Analog # Cor.	.189	.001	99.5
				Reason # Cor.	.165	.022	86.7
				PapFld % Cor.	.069	.006	91.3
				CubAsm % Cor.	.056	.003	94.6
				Analog % Cor.	.123	.012	90.2
				Reason % Cor.	.121	.015	87.6
				Working Memory	.254	.014	94.5
223	20–84	Letter Compar.	−.60	PapFld # Cor.	.133	.029	78.2
		Pattern Compar.		CubAsm # Cor.	.097	.033	66.0
				Analog # Cor.	.227	.012	94.7
				Reason # Cor.	.186	.020	89.2
				PapFld % Cor.	.203	.065	68.0
				CubAsm % Cor.	.178	.070	60.7
				Analog % Cor.	.083	.009	89.2
				Reason % Cor.	.104	.037	64.4
				Working Memory	.208	.012	94.2
Salthouse and Babcock (1991)							
233	18–82	Letter Compar. Pattern Compar.	−.65	Working Memory	.211	.006	97.2
Salthouse, Kausler, and Saults (1988)							
233	20–78	Digit Symbol	.46	Analog Time	.328	.100	69.5
		Number Compar.		SeriesCompl. Time	.100	.019	81.0
				Analog % Cor.	.184	.092	50.0
				SeriesCompl. % Cor.	.074	.033	55.4
Salthouse and Mitchell (1990)							
383	18–84	FindA's	−.28	PapFld # Cor.	.172	.137	20.3
		Number Compar.		SurDev # Cor.	.179	.128	28.5
				LetSet # Cor.	.112	.046	58.9
				Shipley # Cor.	.108	.049	54.6
				PapFld % Cor.	.116	.082	29.3
				SurDev % Cor.	.047	.025	46.8
				LetSet % Cor.	.014	.001	92.9
				Shipley % Cor.	.018	.008	55.6

Note. FindA's = Finding A's Test from Ekstrom, French, Harman, and Dermen (1976); IDPict = Identical Pictures Test from Ekstrom et al. (1976); PMA Space = Space Test from Primary Mental Abilities Battery (Schaie, 1985); PMA Reason = Reasoning Test from Primary Mental Abilities

Table 1 (*continued*)

Battery (Schaie, 1985); Number Compar. = Number Comparison Test from Ekstrom et al. (1976); Shipley # Cor. = number of correct responses in Shipley Abstraction Test; Shipley % Cor. = percentage of responses correct in Shipley Abstraction Test; Raven # Cor. = number of correct responses in Raven's Advanced Progressive Matrices Test; Raven % Cor. = percentage of responses correct in Raven's Advanced Progressive Matrices Test; Working Memory = composite of Listening Span and Computation Span scores; PapFld # Cor. = number of correct responses in a paper folding test; PapFld % Cor. = percentage of correct responses in a paper folding test; CubAsm # Cor. = number of correct responses in a cube assembly test; CubAsm % Cor. = percentage of correct responses in a cube assembly test; Analog # Cor. = number of correct responses in a geometric analogies test; Analog % Cor. = percentage of correct responses in a geometric analogies test; Reason # Cor. = number of correct responses in an integrative reasoning test; Reason % Cor. = percentage of correct responses in an integrative reasoning test; Analog Time = median time per correct response in a geometric analogies test; SeriesCompl. Time = median time per correct response in a series completion test; SeriesCompl. % Cor. = percentage of correct responses in a series completion test; SurDev # Cor. = number of correct responses in the Surface Development Test (Ekstrom et al., 1976); SurDev % Cor. = percentage of correct responses in the Surface Development Test (Ekstrom et al., 1976); LetSet # Cor. = number of correct responses in the Letter Sets Test (Ekstrom et al., 1976); LetSet % Cor. = percentage of correct responses in the Letter Sets Test (Ekstrom et al., 1976).

the attenuation produced by statistical control of the slope parameter should be greater than that produced by statistical control of the observed measures if the slope is a direct reflection of the speed factor, but it should be less than that produced by at least some of the observed measures if the slope only indirectly represents the influence of a common speed factor. The proposed method focuses on relations with cognition to discriminate among the alternative interpretations of speed because of the assumption that speed is interesting primarily because of the implications it has for other aspects of cognitive functioning.

The present research project involved a battery of 17 tests, yielding 19 separate measures, that was administered to two samples of research participants. One sample consisted of 100 college students who served as the reference group for certain analyses, and the other sample consisted of 305 adults ranging from 19 to 84 years of age. Eleven of the tests were intended to measure speed, with 8 of them specially designed to vary systematically with respect to the amount of required processing. These 8 new tasks were composed of four pairs, with each member of the pair requiring similar activities but involving slightly different materials. The four pairs involved the following operations: Marking (i.e., crossing vertical or horizontal lines to make plus signs); Copying (i.e., copying letters or numbers); Completing (i.e., comparing two strings of letters or digits and then writing the item missing from one string); and Transforming (i.e., incrementing an initial value by one or two in the alphabetic or numeric sequence and then writing the new value). Three other speed measures were also included to facilitate comparisons with earlier research using those measures: the *Wechsler Adult Intelligence Scale—Revised* (WAIS–R) Digit Symbol Substitution Test (Wechsler, 1981) and the Letter Comparison and Pattern Comparison measures described by Salthouse (1991a) and Salthouse and Babcock (1991).

The criterion, or to-be-explained, variables were four cognitive measures and four memory measures. The cognitive measures were derived from tests similar to those used in earlier studies. These were the Primary Mental Abilities (PMA) Space and PMA Reasoning tests used by Hertzog (1989) and Schaie (1989) and the integrative reasoning and geometric analogies tests used by Salthouse (1991a). The four memory measures were derived from a paired-associates test and a free-recall test yielding measures of recall accuracy for the primacy, asymptote, and recency segments of the serial position function.

Method

Subjects

Demographic characteristics of the individuals who participated in this project are summarized in Table 2. College students received credit toward a course requirement for their participation, and members of the adult sample, who were recruited from newspaper advertisements, received $10 for their participation. Because of the relatively high mean levels of education, the adult sample can be considered to be a positively biased sample composed largely of people from middle and high socioeconomic levels. Health status was evaluated by responses to three questions: (a) How would you rate your overall health on a scale from 1 = *excellent* to 5 = *poor* with 3 = *average?*; (b) How many prescription medications do you take each week?; and (c) How many times in the past 5 years have you been hospitalized or received other treatment for cardiovascular or neurological problems (e.g., heart attack, stroke, or high blood pressure)? As can be seen in Table 2, the number of medications and medical treatments was greater with increased age, but the overall health ratings remained relatively constant. (See Salthouse, Kausler, & Saults, 1990, for similar findings.)

Procedure

All testing was conducted in small groups, and every participant received the tests in the same fixed order. Materials for the tests were assembled in folders, which also contained the informed-consent form and a brief questionnaire requesting information about age, gender, health, and years of education completed. The order of the tests was as follows: Digit Symbol, Line Marking (in the order vertical, horizontal, vertical, and horizontal), Copying (in the order numbers, letters, numbers, and letters), Completion (in the order numbers, letters, numbers, and letters), Transformation (in the order numbers, letters, numbers, and letters), Pattern Comparison (in the order three-item pairs, six-item pairs, and nine-item pairs), Letter Comparison (in the order three-item pairs, six-item pairs, and nine-item pairs), PMA Reasoning (Schaie, 1985), PMA Space (Schaie, 1985), integrative reasoning, geometric analogies, paired-associate memory, and free-recall memory. In all but the memory tests, the participants were encouraged to perform as rapidly and as accurately as possible. Instructions in the two memory tests emphasized trying to remember as many words as possible, with guessing encouraged when in doubt about a response.

The Digit Symbol, PMA Reasoning, and PMA Space tests were administered according to the published instructions except that answers were to be written directly on the test form in the two PMA tests rather than on separate answer sheets as specified in the standard administrations of these tests. This modification was introduced to avoid possible

Table 2
Means and Standard Deviations of Demographic Characteristics of the Research Samples by Age Decade

Age decade	n	Age M	Age SD	Education M	Education SD	Health M	Health SD	Medication M	Medication SD	Medical treatment M	Medical treatment SD
Men											
Students	59	20.9	1.3	13.3	1.3	1.7	0.8	0.27	0.78	0.08	0.53
20s	20	23.9	3.0	14.1	1.9	2.3	1.4	0.20	0.52	0.00	0.00
30s	19	34.4	2.9	15.1	2.9	2.0	1.3	0.11	0.32	0.00	0.00
40s	17	43.9	2.9	15.1	2.5	2.7	1.6	0.53	1.23	0.18	0.53
50s	21	54.2	3.5	15.8	3.4	2.5	1.2	0.62	1.16	0.10	0.30
60s	33	65.0	2.2	16.4	1.9	2.6	1.3	1.52	1.82	0.52	1.06
70s	14	74.2	3.7	16.1	2.9	2.4	1.4	1.00	1.41	0.93	2.64
Women											
Students	41	20.8	1.7	13.7	1.5	2.0	1.0	0.29	0.51	0.00	0.00
20s	22	24.2	2.6	15.0	1.4	2.3	1.3	0.55	0.86	0.18	0.39
30s	22	34.5	3.0	15.7	1.7	2.5	1.4	0.32	0.78	0.86	3.23
40s	36	44.9	2.8	15.4	2.4	2.3	1.3	0.50	1.13	0.17	0.56
50s	32	53.9	3.0	15.8	2.6	2.1	1.3	1.22	1.21	0.09	0.39
60s	39	64.6	2.7	14.7	2.7	2.3	1.2	1.44	2.12	0.13	0.41
70s	30	74.0	3.7	14.0	2.3	2.4	1.2	1.63	1.27	0.97	2.77

Note. Education refers to years of formal education completed, and health represents a self-assessment on a 5-point scale ranging from 1 = *excellent* to 5 = *poor.* Medication refers to number of prescription medications taken each week, and medical treatment refers to number of treatments for cardiovascular or neurological problems in the past 5 years.

confusion or delays associated with the use of a separate form for recording one's answers, which may be greater with increased age (e.g., Bellucci & Hoyer, 1975; Hertzog, 1989; Hoyer, Hoyer, Treat, & Baltes, 1978–1979).

Two versions of the Line Marking test were administered, one with 28 rows of 16 horizontal lines and the other with 23 rows of 20 vertical lines. Research participants were instructed to work from left to right placing short vertical lines through each horizontal line and to work from top to bottom placing short horizontal lines through each vertical line. The pages were arranged such that vertical marks were made first, then horizontal marks, then vertical marks, and finally horizontal marks. The time allowed to work on each page was 30 s.

The Copying test was administered in two versions, one containing numbers and the other letters. In both cases, the test pages contained 10 rows of 15 pairs of boxes, with a letter or number in the top box and nothing in the bottom box. The participant's task was to copy the item in the top box in the empty box immediately below it. There were four separately timed sections in the task, involving numbers, letters, numbers, and letters, with 30 s allowed for each section.

The Completion tests were also administered with both number and letter versions. The materials in these tests consisted of pages of 50 pairs of numbers or letters, with one element missing from one member of the pair. The complete member of the pair contained nine elements and appeared randomly on either the left or the right. The participant's task was to examine the complete member of the pair to determine the identity of the missing element and then to write that element in a box corresponding to the number or letter missing from the other member of the pair. There were four separately timed sections in the task, involving numbers, letters, numbers, and letters, with 30 s allowed for each section.

The Transformation test was similar to the Copying test except that each item consisted of three boxes, with a letter or a number in the top box, nothing in the bottom box, and either one or two +'s (pluses) in the middle box. The plus signs in the middle box indicated how the letter or number in the top box was to be transformed; one plus meant that the value should be incremented by one in the alphabetic or numeric sequence, and two pluses meant that the value should be incremented by two. For example, an F with two pluses would yield H, and a 5 with 1 plus would yield 6. After carrying out the transformation specified in the middle box, the participant must write the identity of the new letter or number in the bottom box. Each page contained seven rows of 15 sets of boxes, and the separately timed (30 s) pages were presented in the order numbers, letters, numbers, and letters.

The Pattern Comparison and Letter Comparison tests were very similar to the earlier versions of these tests described by Salthouse and Babcock (1991). The patterns were constructed by connecting dots within an imaginary 4 × 4 matrix, and the letter sequences were constructed by random selection (without replacement) of consonants. Within each test, there were three separately timed (30 s) sections, with successive sections containing pairs of items with three, six, and nine elements per item. The task for the participant was to examine the two members of the pair and to write an "S" on the line between them if they were the same and a "D" on the line if they were different. One half of the pairs on each page were the same, and the other half were different because of an alteration in the identity or the position of one of the elements. Each section of the test consisted of 32 pairs of line patterns or 64 pairs of letter strings.[1]

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[1] Analyses were also conducted on the Letter Comparison and Pattern Comparison scores according to the number of items (letters or line segments) being compared. Correlations between age and the average of the Letter Comparison and Pattern Comparison scores were −.58 for three items, −.54 for six items, and −.52 for nine items. The percentage attenuation of the age–cognition relations, analogous to the

The integrative reasoning test consisted of 72 problems, each containing premises describing the relation between two terms (e.g., R and S, do the OPPOSITE), and a question about the consequences on one term of a specified change in another term (e.g., If R DECREASES, will S INCREASE?). (See Salthouse, Mitchell, Skovronek, & Babcock, 1989; and Salthouse, Legg, Palmon, & Mitchell, 1990, for further description of this task.) One problem within each set of three problems had a single premise before the question, one problem had two premises, and one problem had three premises presented before the question. The correct answer for half of the problems was *yes* and that for the remaining problems was *no*. In all cases, the task for the research participant was to place a mark either in a column labeled yes or in a column labeled no. Participants were allowed 4 min to complete as many problems as possible.

The geometric analogies test was arranged in a fashion similar to the integrative reasoning test in that there were 72 problems, with 1 of each of 3 problem types in every set of 3 problems. Problems in this test consisted of four boxes, with each box containing between one and three letters in various configurations. For example, one problem consisted of the following arrangement of letters: first box—a solid letter C in the upper left corner and a solid letter A rotated clockwise 90° in the bottom right corner; second box—an outline letter C in the upper left corner and a solid letter A rotated clockwise 90° in the bottom right corner; third box—a solid letter D in the upper left corner and a solid letter C rotated clockwise 90° in the bottom right corner; fourth box—a solid letter D in the upper left corner and a solid letter C rotated clockwise 90° in the bottom corner. The participant's task was to determine if the pattern of relationships between the letters in the first two boxes was identical to that in the second two boxes. The answer to the problem just described would therefore be *no*, because the shift of solid to outline form for the letter in the upper left corner was not represented in the second pair of boxes. An equal number of problems had one, two, or three letters in each box in the problem, and one half of the problems had corresponding relationships, and the other half did not. As in the integrative reasoning test, decisions were communicated by placing a mark either in a column labeled YES or in a column labeled NO. Participants were allowed a time limit of 4 min to complete as many problems as possible.

The words used in the two memory tests were four-letter nouns selected from the most frequent 1,000 words listed in the Thorndike and Lorge (1944) word count. The rate of presentation in both tasks was approximately 1 word every 2 s. Two separate trials with different words were presented in each task. Trials in the paired-associates task consisted of the oral presentation of 6 word pairs, followed immediately by instructions to turn to a page containing the first members of each pair. Participants were instructed to write the second member of each pair adjacent to the first term, and they were encouraged to guess even if they were not sure of the correct response. Approximately 60 s was allowed for the response phase of the trial. Trials in the free-recall task involved the oral presentation of a list of 12 words followed immediately by the word RECALL, at which time the participant turned the page and wrote as many words as he or she could remember. Approximately 60 s was allowed for the response phase of each trial.

Measurement Reliability

Estimates of the reliabilities for the dependent measures in the two samples are reported in Table 3. All estimates were derived by using the Spearman-Brown formula to adjust the correlation between the values from the two administrations of each test to predict the reliability of the average value. Because there was only one administration for some tests in this study, reliability could not be computed for all measures. However, reliabilities of standardized tests have been reported in other sources, with values of .82 for the Digit Symbol test (Wechsler, 1981), .72 to .81 for the PMA Space test (Schaie, 1985), and .82 to .86 for the PMA Reasoning test (Schaie, 1985).

Most of the values in Table 3 appear satisfactory because the reliability estimates are generally in the moderate to high range of .80 or greater. The three measures from the free-recall task are notable exceptions, perhaps because these components of free-recall memory performance are not very stable when assessed with only two trials. Estimated reliability of a measure of total recall across all serial positions was somewhat greater (i.e., .68), but the component measures were retained because they are of greater theoretical interest than the undifferentiated measure of total recall.

The complete correlation matrix with all measures, including age, is presented in Table 4. All of the correlations involving age in the main sample of adults (above the diagonal) are negative, and most of the remaining correlations in this sample are moderate in magnitude. Correlations in the sample of students (below the diagonal) are somewhat smaller and, as expected, because of the restricted age range, none of those involving age were significantly different from zero.

Measurement Model

Relations among the variables for the main sample of adults in Table 4 were examined by means of a confirmatory factor analysis specifying four factors of motor speed, perceptual speed, memory, and cognition. The hypothesized factor structure, with the estimated coefficients, is portrayed in Figure 1. Notice that a correlation was postulated between the residuals of each of the measures derived from parallel methods, with the exception of the two copy measures. Because the initial estimate of the correlation between the residuals of the letter copy and number copy measures was negative, no relation was specified between the residuals of those measures. The chi-square for the model illustrated in Figure 1 was $\chi^2(142, N = 305) = 319.25, p < .01$, indicating that there was a significant discrepancy between the model and the data. However, other measures suggested that the model provided at least an adequate fit to the data. According to Steiger (1989, p. 91), values above .90 of the adjusted population gamma index, which is a coefficient of model determination adjusted for model complexity, and values below .10 of the adjusted root-mean-square, which is a root-mean-square standardized residual adjusted for model complexity, can be considered as representing a good fit. Values with this model were .928 for the adjusted population gamma index and .062 for the adjusted root-mean-square. The Joreskog-Sorbom goodness-of-fit index was .905.

A surprising feature of the coefficients in Figure 1 is the high correlation (.881) between the latent variables of perceptual speed and cognition. As a means of testing whether this correlation was significantly different from 1.0, the path between these two variables was fixed at 1.0 and the fit of the model redetermined. The chi-square for the adjusted model was $\chi^2(143, N = 305) = 362.22, p < .01$, which yields a significant difference chi-square of 42.97 ($df = 1, p < .01$), indicating that the altered model fit the data significantly worse than the original model. Because the model constraining the correlation to 1.0 provides a significantly poorer fit to the data than the model with the correlation as a freely estimated parameter, it can be inferred that, given the assumptions represented by the structure of the model, the true correlation between the perceptual speed and cognition constructs in these data is not equal to 1.0. In other words, although the two constructs are highly related, they are not completely identical.

The correlation between the motor speed and perceptual speed constructs was .812. The nested model procedure was used to test whether

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values reported in Table 8, were 94.6% for three items, 88.6% for six items, and 85.1% for nine items.

Table 3
Reliabilities of the Performance Measures

Measure	Estimated reliability	
	Students	Adults
Horizontal mark: No. of horizontal marks made on vertical lines (30 s)	.82	.88
Vertical mark: No. of vertical marks made on horizontal lines (30 s)	.89	.92
Copying, letters: No. of letters correctly copied (30 s)	.88	.97
Copying, numbers: No. of digits correctly copied (30 s)	.88	.95
Letter completion: No. of correct completions of letter strings (30 s)	.88	.86
Number completion: No. of correct completions of number strings (30 s)	.71	.92
Letter transformation: No. of correct transformations of letters (30 s)	.89	.92
Number transformation: No. of correct transformations of numbers (30 s)	.92	.91
Letter comparison: No. of correct same/different judgments about letter strings (30 s)	.83	.83
Pattern comparison: No. of correct same/different judgments about line patterns (30 s)	.85	.90
Digit symbol: No. of items correct in WAIS–R Digit Symbol Substitution Test (90 s)	—	(.82)[a]
PMA Reasoning: No. of items correct in PMA Series Completion Reasoning Test (6 min)	—	(.84)[b]
PMA Space: No. of items correct in PMA Figure Rotation Test (5 min)	—	(.77)[b]
Integrative reasoning: No. of items correct in integrative reasoning test (4 min)	—	—
Analogy: No. of items correct in geometric analogies test (4 min)	—	—
Paired associates: No. of words correct in paired associates	.80	.82
Primacy: No. of words recalled from serial positions 1 to 4	.39	.39
Asymptote: No. of words recalled from serial positions 5 to 8	.44	.50
Recency: No. of words recalled from serial positions 9 to 12	.57	.46

Note. WAIS–R = Wechsler Adult Intelligence Scale—Revised; PMA = Primary Mental Abilities.
[a] Value from Wechsler (1981). [b] Average values from Schaie (1985).

this correlation was significantly different from 1.0 by constraining the correlation to 1.0 and examining the chi-square difference between the original and altered models. The difference chi-square was 199.75 ($df = 1$, $p < .01$), implying that the correlation was significantly less than 1.0.

All standard errors for the coefficients illustrated in Figure 1 were less than .06, and those for the coefficients between perceptual speed and cognition and between motor speed and perceptual speed were both .024. Because these values indicate that the relations between the observed variables and the latent constructs are significantly greater than zero and that the correlations between constructs are all significantly less than 1.0, the constructs can be considered to have both convergent and discriminant validity, respectively (cf. Anderson & Gerbing, 1988).

Results

Composite Variables

Composite variables were created for each of the four constructs by averaging the unit-weighted z scores for the measures hypothesized to represent each construct (according to the relations portrayed in Figure 1). Correlations among these composites and estimates of their reliabilities are presented in Table 5. Notice that the correlations among the composite variables have the same pattern but are generally smaller in magnitude than those among the latent constructs portrayed in Figure 1.

Mean composite scores at each decade, expressed in standard deviations of the scores of the reference student sample, are illustrated in Figure 2. There are two particularly salient features of these data. The first is the very pronounced age trends evident in each measure: The average performance of adults in their 60s and 70s is between one and two standard deviations below that of adults in their 20s and 30s for each of the composite variables.

The second noteworthy feature of the data in Figure 2 is that even the performance of the adults in their 20s is appreciably lower than that of the reference group of students, particularly for the cognition composite variable. This difference may be attributable to the fact that the students were recruited from a relatively select university and consequently may have had higher levels of cognitive ability than the average young adult recruited from newspaper advertisements to participate in projects of this type. Some support for this interpretation is available in the observation that the students in this study performed between 0.6 and 0.9 standard deviations above the means of the 22- to 28-year-olds in the normative sample for the 1985 version of the PMA Space and Reasoning tests (Schaie, 1985). The fact that the nonstudent research participants in their 20s had a slightly lower average number of years of education than adults in subsequent decades (see Table 2) could also be interpreted as indicating that the 20- to 30-year-old adults in this sample were not as positively biased as the adults from other age ranges.

Whether it is because the sample in the decade of the 20s is less select than the samples from other age groups or because there are little age-related effects in these measures until middle age, the data in Figure 2 suggest that performance in some tests may remain relatively stable until the 30s or 40s. The nature of the age relations in the composite variables was investi-

Table 4

Correlation Matrix for All Performance Measures

Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1. Age	—	−.38	−.40	−.49	−.41	−.53	−.55	−.24	−.23	−.51	−.59	−.51	−.41	−.39	−.37	−.26	−.40	−.39	−.37	−.08
2. Horizontal mark	−.02	—	.89	.69	.71	.45	.47	.32	.45	.41	.49	.54	.30	.23	.24	.24	.22	.25	.16	.09
3. Vertical mark	−.01	.77	—	.69	.69	.47	.51	.39	.49	.44	.53	.55	.35	.22	.26	.26	.28	.30	.22	.12
4. Copy, letters	.10	.63	.63	—	.89	.65	.63	.51	.56	.61	.66	.72	.53	.32	.36	.34	.38	.39	.30	.19
5. Copy, numbers	.08	.68	.70	.85	—	.53	.56	.42	.56	.55	.60	.63	.43	.24	.31	.30	.34	.35	.26	.17
6. Letter completion	.08	.50	.51	.62	.59	—	.88	.53	.56	.65	.68	.72	.60	.51	.46	.49	.40	.38	.34	.13
7. Number completion	.08	.44	.44	.50	.51	.83	—	.53	.59	.67	.73	.74	.68	.50	.49	.53	.41	.39	.33	.19
8. Letter transformation	.01	.09	.20	.29	.19	.44	.43	—	.64	.49	.47	.51	.61	.35	.41	.44	.37	.29	.23	.21
9. Number transformation	.10	.39	.51	.52	.55	.58	.52	.57	—	.58	.53	.60	.53	.31	.37	.42	.27	.24	.20	.24
10. Letter comparison	−.02	.38	.44	.56	.50	.55	.51	.42	.56	—	.74	.64	.57	.40	.40	.40	.33	.33	.25	.24
11. Pattern comparison	.02	.36	.47	.49	.43	.40	.45	.25	.35	.59	—	.63	.60	.48	.45	.49	.45	.35	.33	.24
12. Digit symbol	.12	.53	.51	.64	.61	.73	.65	.33	.54	.52	.33	—	.64	.40	.44	.51	.44	.35	.32	.24
13. PMA Reasoning	.01	.04	.03	.17	.10	.28	.37	.47	.19	.30	.32	.31	—	.53	.54	.57	.57	.43	.38	.36
14. PMA Space	−.05	.15	.19	.16	.16	.09	.21	.15	.20	.22	.29	.12	.23	—	.43	.50	.33	.27	.23	.14
15. Integrative reasoning	.10	.06	.00	.10	.10	.26	.40	.39	.21	.34	.29	.21	.48	.26	—	.45	.34	.23	.23	.14
16. Analogy	−.09	.35	.23	.36	.30	.43	.48	.28	.30	.32	.45	.40	.35	.11	.44	—	.41	.22	.27	.25
17. Paired associates	.00	.01	.10	.07	.05	.14	.23	.16	.01	.12	.21	.08	.16	−.10	.27	.13	—	.47	.56	.37
18. Primacy	−.10	.16	.19	.14	.24	.12	.23	.10	.06	.09	.13	.07	.12	.14	.19	.12	.36	—	.41	.12
19. Asymptote	.08	.05	.03	.04	.03	.08	.19	.11	−.01	.04	.05	.00	.16	.11	.32	.03	.37	.30	—	.19
20. Recency	.14	.15	.15	.06	−.01	.16	.16	.15	.09	.19	.09	.20	.23	.03	.21	.17	.29	.02	.12	—
Adults (*n* = 305)																				
M	51.1	67.9	65.0	44.3	52.5	12.5	12.9	16.1	30.9	12.9	17.7	56.4	16.8	27.1	11.7	35.0	2.6	2.5	1.7	2.6
SD	16.6	12.1	11.2	8.5	9.4	3.9	3.7	5.5	6.5	2.8	3.4	13.5	7.2	11.4	6.4	14.4	1.6	0.9	0.9	0.8
Students (*n* = 100)																				
M	20.9	75.7	70.6	51.4	60.6	16.6	16.4	17.7	35.4	15.9	21.8	72.1	24.6	38.0	19.5	48.6	3.9	2.7	2.0	2.9
SD	1.5	10.0	8.9	6.8	7.6	2.9	2.8	5.3	5.6	2.7	3.2	10.0	4.0	10.9	8.2	10.9	1.6	0.9	0.9	0.7

Note. Values above the diagonal are correlations from the adult sample, and those below the diagonal are correlations from the student sample. PMA = Primary Mental Abilities.

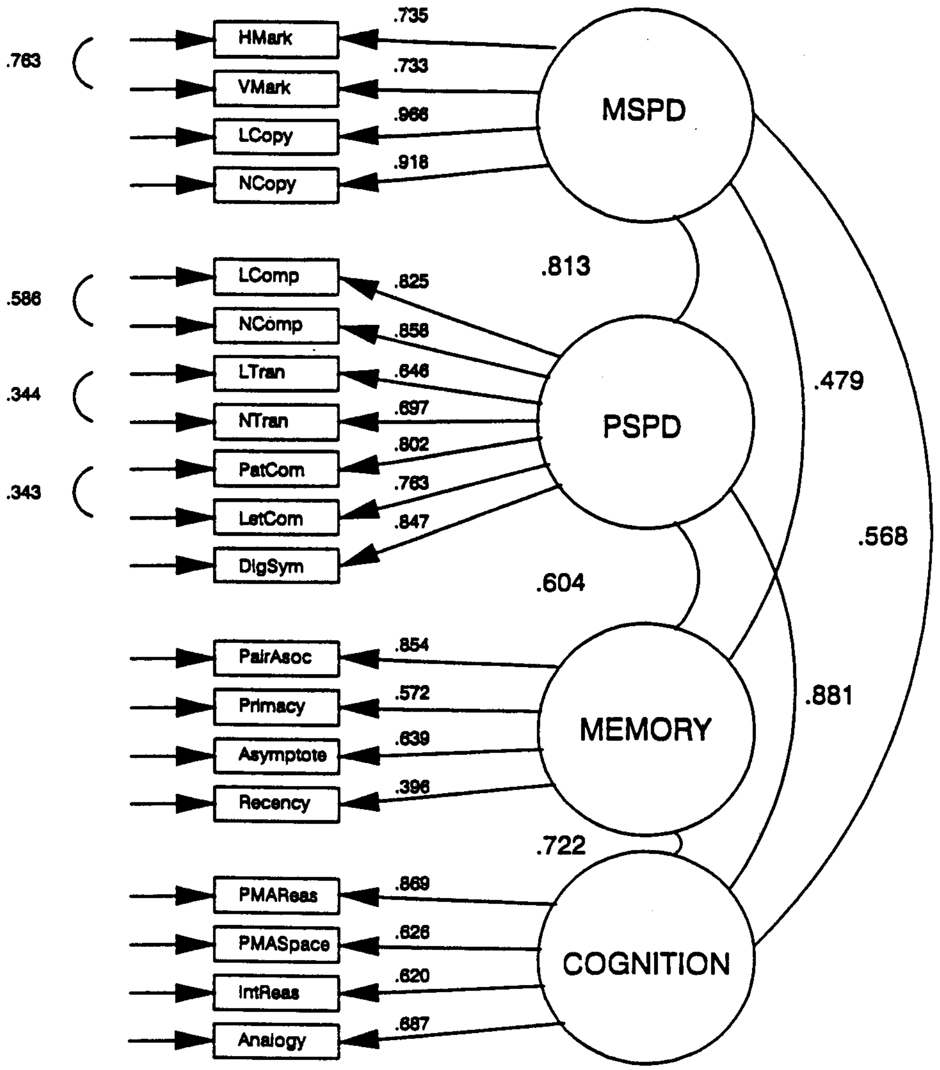

Figure 1. Hypothesized measurement model and coefficients obtained from confirmatory factor analysis. (MSPD = motor speed; PSPD = perceptual speed. Variables in the boxes are as follows: HMark = no. of horizontal marks made on vertical lines; VMark = no. of vertical marks made on horizontal lines; LCopy = no. of letters correctly copied; NCopy = no. of digits correctly copied; LComp = no. of correct letter-strings completion; NComp = no. of correct number-strings completion; LTran = no. of correct transformation of letters; NTran = no. of correct transformation of numbers; PatCom = no. of correct same/different pattern comparison judgments; LetCom = no. of correct same/different letter comparisons; DigSym = digit symbol; PairAsoc = paired associates; PMAReas = Primary Mental Abilities Inductive Reasoning Test; IntReas = integrative reasoning.)

gated more systematically by examining the significance of quadratic (age-squared) terms in the regression equation. The quadratic term was associated with a significant increment in R^2 for the motor speed and memory variables, but in both cases it was relatively small (i.e., .029 and .037, respectively). Because the variance associated with the linear age trend was much larger (i.e., R^2 values ranging from .184 to .297), only the linear relations were considered in all subsequent analyses.

Main effects and interactions of gender, self-assessed health status, number of medications, number of medical treatments, and years of education were also examined in regression equations on the four composite variables. The only significant effect other than age was the main effect of education on the memory composite variable, $F(1, 301) = 10.79$, $p < .01$, $MS_e = 0.367$, indicating that people with more education performed better on the memory tests than people with less education. The absence of any interactions involving age suggests that the age trends in the composite variables were not moderated by gender, available indexes of health, or education, and consequently these factors were ignored in all remaining analyses.

Hierarchical Regression Analyses

Results of the hierarchical multiple regression analyses conducted on the composite variables are summarized in Table 6.

Table 5
Correlations Among Composite Scores

Variable	1	2	3	4	5
1. Age	—	−.46	−.55	−.43	−.45
2. Motor speed	.04	(.95)	.70	.38	.43
3. Perceptual speed	.08	.59	(.97)	.51	.74
4. Memory	.05	.16	.23	(.77)	.52
5. Cognition	−.01	.25	.52	.31	(.86)

Note. Values above the diagonal of numbers in parentheses are correlations from the adult sample (n = 305), and those below the diagonal are correlations from the student sample (n = 100). Values in parentheses are reliabilities of the composite scores for the adult sample estimated by the formula described by Kenney (1979, p. 132): reliability = n(average r)/[1 + (n − 1)(average r)].

Entries in the first column of this table indicate the cumulative R^2 in the prediction of the criterion variable after the variable on that row and the variables on immediately preceding rows had been entered into the regression equation. Entries in the second column indicate the increment in R^2 associated with the addition of the variable on that row into the regression equation. Finally, values in the third column indicate the F values for the significance either of the initial R^2 or of the increment in R^2.

Several points should be noted regarding the results summarized in Table 6. First, it is clear that earlier findings were replicated concerning the attenuation of the relations between age and cognition after statistical control of a composite measure of perceptual speed. This is evident in the reduction of the age-associated variance in the cognition measure from .202 when age was the only variable in the equation to .003 when the variance associated with perceptual speed was controlled by entering age in the regression equation after perceptual speed.

Second, the earlier results are extended by the finding that the relations between age and perceptual speed are still statistically significant after controlling the influence of motor speed (i.e., R^2 of .062) and by the finding that there was a larger attenuation of the age-related effects in cognition after control of perceptual speed than after control of motor speed (i.e., reductions in R^2 to .003 for perceptual speed vs. .080 for motor speed). This combination of results suggests that only a portion of the age-related slowing that affects cognitive functioning is motoric in nature.

Third, another new finding is that the age-related variance in measures of memory is also substantially attenuated after statistical control of perceptual speed. The percentage attenuation, 82.6%, is not as large as the 98.5% evident in the cognitive measure, but it is still quite substantial.

And fourth, age was associated with a very small proportion of the total variance in the cognitive measure after the influences of motor speed, perceptual speed, and memory were taken into consideration. Furthermore, the direction of the standardized regression coefficient for age in the complete regression analysis was actually positive rather than negative, indicating that if anything, increased age was associated with higher levels of cognitive performance when the contributions of motor speed, perceptual speed, and memory were controlled.

The results just described are relevant to both of the major

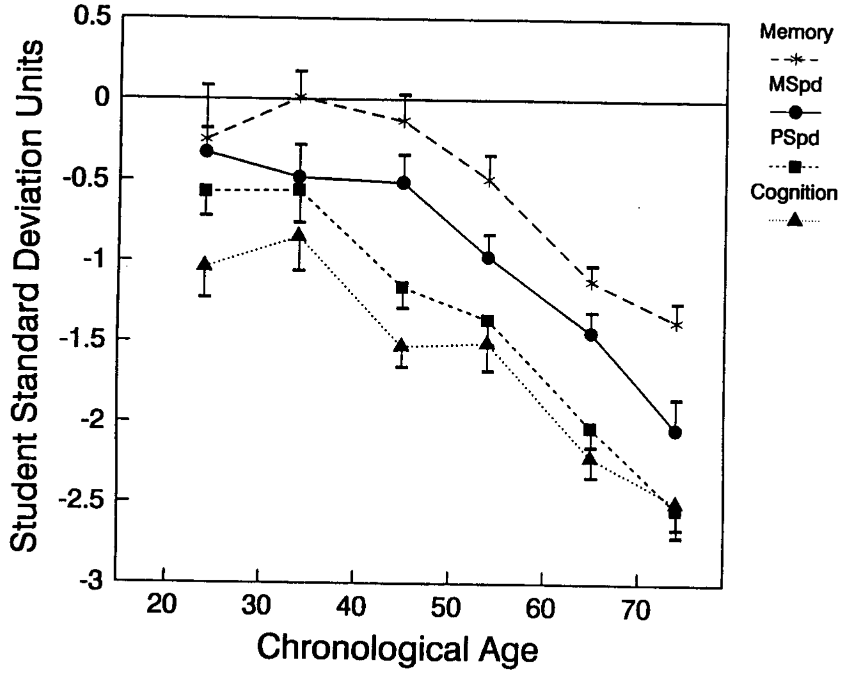

Figure 2. Mean performance at each decade for the four composite variables expressed in standard deviations of the 100 college students serving as the reference group. (Bars above or below the symbols represent one standard error. MSpd = motor speed; PSpd = perceptual speed.)

Table 6
Hierarchical Regression Results Based on Composite Scores in Adult Sample

Criterion/predictor	R^2	Incr. R^2	F
Motor speed			
Age	.214		82.45*
Perceptual speed			
Age	.297		128.12*
Motor speed	.495		337.30*
Age	.557	.062	41.80*
Memory			
Age	.184		68.12*
Motor speed	.147		57.58*
Age	.227	.080	31.31*
Perceptual speed	.261		112.24*
Age	.293	.032	13.70*
Motor speed	.147		62.69*
Perceptual speed	.262	.115	48.71*
Age	.293	.031	13.20*
Cognition			
Age	.202		76.68*
Motor speed	.185		75.98*
Age	.265	.080	32.78*
Perceptual speed	.546		365.20*
Age	.549	.003	2.08
Memory	.275		125.35*
Age	.337	.062	28.15*
Motor speed	.185		128.57*
Perceptual speed	.562	.377	261.80*
Age	.567	.005	3.71
Motor speed	.185		136.78*
Perceptual speed	.562	.377	278.51*
Memory	.593	.031	23.11*
Age	.594	.001	1.05

Note. Incr. R^2 = increment in R^2 association with addition of second, third, or fourth variable.
* $p < .01$.

goals of the project. They address the issue of speed mediation of age differences in memory, because statistical control of the composite measure of perceptual speed greatly attenuates the age-related variance in the composite measure of memory. The results are also relevant to the issue of the type of speed involved in the mediation, because the attenuation of the age-related variance was greater after control of measures of perceptual speed than after control of measures of motor speed.

Structural Model

A structural model illustrating the hypothesized relations among the primary constructs is represented in Figure 3. The causal linkages are hypothesized to be from motor speed to perceptual speed and from memory to cognition rather than vice versa, because motor speed and memory are assumed to be more elementary than, and perhaps even constituents of, perceptual speed and cognition, respectively. Coefficients in the top panel of Figure 3 are based on the standardized regression coefficients from multiple regression analyses on the composite scores. Coefficients in the bottom panel were derived from the EZPATH (Steiger, 1989) structural equation program with the latent constructs defined in the measurement model illustrated in Figure 1. (That is, this figure illustrates the structural coefficients from a structural equation model superimposed on the measurement model represented in Figure 1.) The chi-square for this model was $\chi^2(165, N = 305) = 414.92$, $p < .01$, but the goodness-of-fit measures indicated an adequate fit of the model to the data (i.e., adjusted population gamma index = .907, adjusted root-mean-square = .069, and Joreskog-Sorbom goodness-of-fit index = .883). Exploration of several variations of the model portrayed in Figure 3 revealed that the fit could be improved by minor alterations of the structure represented in Figures 1 and 3 (e.g., specifying direct as well as indirect paths between age and the letter transformation, number transformation, and recency variables), but none of the modifications resulted in an appreciable change in the structural parameters depicted in the bottom of Figure 3.

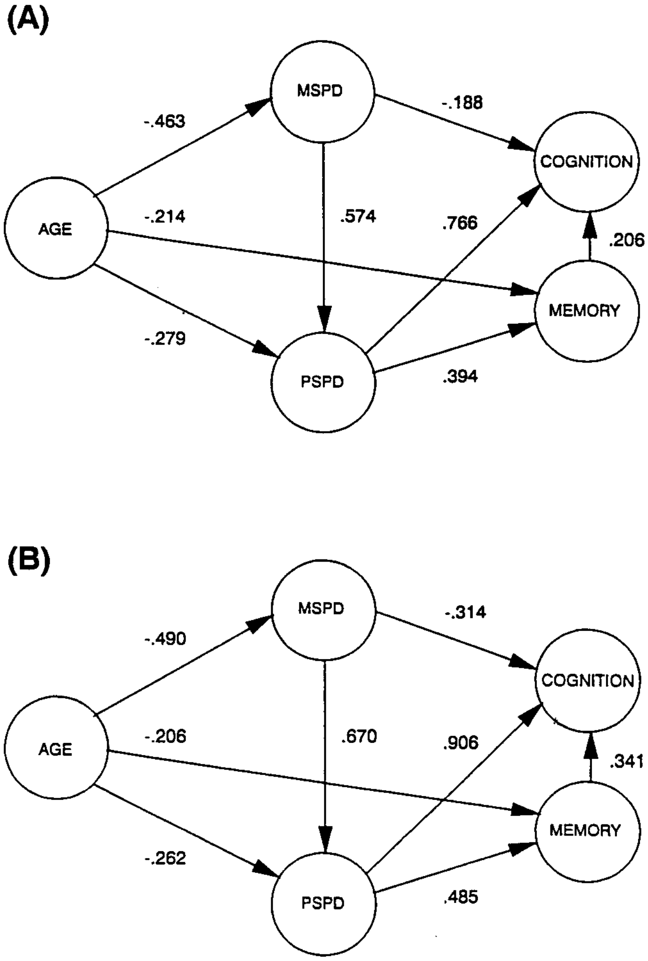

Figure 3. Hypothesized structural relations and path coefficients based on the composite variables (A) and on the latent variables (B). (MSPD = motor speed; PSPD = perceptual speed.)

It is apparent in Figure 3 is that although the relation between perceptual speed and cognition is highly positive, there is a negative relation between motor speed and cognition. This was unexpected, because it indicates that when perceptual speed is controlled, faster motor speed is associated with lower levels of cognitive performance. Interpretation of this finding should probably be deferred until it has been confirmed in another sample, but it may reflect the operation of some type of impulsiveness. In most other respects, however, the relations portrayed in Figure 3 are similar to the conclusions inferred from the regression analyses. Specifically, there are negative relations between age and motor speed, perceptual speed, and memory; no significant relation between age and cognition; and large positive relations between motor speed and perceptual speed and between perceptual speed and cognition. Moreover, it is reassuring to note that the same patterns are evident when the analyses are based on unit-weighted composite scores (Figure 3A) and on latent constructs defined by a confirmatory factor analysis (Figure 3B).

The results from the structural analyses are related to the primary goals of the project in the following manner. First, examination of the paths leading to the memory variable reveals that some, but not all, of the age-related variance in memory is mediated through slower perceptual speed. That is, unlike the cognitive variable, a direct path exists between age and memory in addition to the indirect path through perceptual speed. And, second, at least when motor speed is assumed to influence perceptual speed, the relations between motor speed and cognition are very small and are actually negative rather than positive, whereas the relations between perceptual speed and cognition are large and positive.

Table 7

Results of Commonality Analyses Conducted on the Cognition and Memory Composite Variables in Adult Sample

	Predictor variable		
Criterion	Age	Motor speed	Perceptual speed
Cognition			
Unique to age	.005		
Unique to motor speed		.018	
Unique to perceptual speed			.302
Common to age and motor speed	−.002	−.002	
Common to age and perceptual speed	.074		.074
Common to motor speed and perceptual speed		.045	.045
Common to age, motor speed, and perceptual speed	.124	.124	.124
Total effects	.202	.185	.545
Memory			
Unique to age	.031		
Unique to motor speed		.000	
Unique to perceptual speed			.065
Common to age and motor speed	.001	.001	
Common to age and perceptual speed	.049		.049
Common to motor speed and perceptual speed		.044	.044
Common to age, motor speed, and perceptual speed	.103	.103	.103
Total effects	.184	.148	.261

Commonality Analysis

Another method of partitioning the variance in a criterion variable is commonality analysis (Pedhazur, 1982). As applied in the present context, the goal of this technique is to decompose the total effects of age on either the cognition or memory composite variable into a unique contribution of age and into contributions in common with motor speed, perceptual speed, or both. The unique influence corresponds to the age-related variance that is independent of both motor speed and perceptual speed, and the common influence represents the age-related variance that is shared with either motor speed or perceptual speed or both.

Table 7 contains the summary information from the commonality analyses conducted on the cognition and memory composite variables. Entries in the first column (Age) are of greatest interest because they indicate the partitioning of the age-related effects. Two important points should be emphasized about these data. First, notice that only a small proportion of the total age-related effects is uniquely associated with age (i.e., .005 vs. .202 for the cognition variable and .031 vs. .184 for the memory variable). And second, notice that the variance common to age and perceptual speed is much larger than that common to age and motor speed (i.e., .074 vs. −.002 for the cognition variable and .049 vs. .001 for the memory variable). In both respects, these results reinforce the conclusions from the hierarchical regression and path analysis procedures. However, this analysis extends the earlier analyses by indicating that the largest proportion of variance in the cognition and memory composite variables was shared among age, motor speed, and perceptual speed.

Relations Among Speed Measures

As described in the introduction, regression equations were computed relating the times of each adult participant to the average times of the 100 students across the same measures of speed. That is, the predictor or X values in the regression equations were the mean times of the 100 students, and the criterion or Y values were the times of the individual subject in those same tasks. Intercept, slope, and correlation coefficients indicating the goodness of fit of the linear equation were therefore obtained for each subject to represent the relation of his or her times to the mean times of the reference group.

Means of the regression parameters were .93 (*SD* = .07) for the correlation, 1.40 (*SD* = 0.91) for the slope, and −0.13 (*SD* = 0.54) for the intercept. The high average correlation, together with the fact that the magnitude of the correlation coefficient was not significantly related to age (i.e., $r = -.14$), indicates that the linear equations provided a reasonable characterization of the data of most participants. The intercept parameter was significantly related to age (i.e., $r = -.19$), but the absolute magnitude of the effect was quite small, because each year of age was associated with a reduction in the intercept of only .006. The slope parameter had a significant positive age relation (i.e., r = .30) corresponding to an annual increase of .017.

Comparable analyses were also conducted on only the 7 perceptual speed measures, excluding the 4 motor speed measures. Results of these analyses were similar to those based on all speed measures except that the correlation coefficient was smaller (i.e., $r = .82$; intercept = −.13; slope = 1.45), suggesting a somewhat poorer fit of the linear equation to the data. The correlation between the slope based on all 11 speed measures and that based only on the 7 perceptual speed measures was .98.

To estimate the reliability of the slope parameter based on all 11 speed measures, the speed measures were rank-ordered in terms of average time and then separate slopes computed for the six odd-ranked measures (i.e., horizontal marking, number copying, number transformation, pattern comparison, number completion, and letter comparison) and for the five even-ranked measures (i.e., vertical markings, letter copying, digit symbol, letter completion, and letter transformation). The means for the two slopes were 1.42 and 1.38, respectively, and the correlation was .48. Application of the Spearman-Brown formula to this correlation resulted in an estimated reliability of the slope based on all 11 speed measures of .65.

Table 8 contains a comparison of the magnitude of the attenuation of the age relations across different speed measures and across different cognitive and memory measures. Values in the table were determined by computing the R^2 associated with age when it was the only variable in the equation and again when it was entered after the variables listed in the top row of the table. The difference between the two variance estimates was then divided by the total age-related variance, and this value was multiplied by 100. To illustrate, Table 6 reveals that the R^2 for age on the cognition variable was .202 when age was the only predictor in the regression equation but that the increment in R^2 associated with age after controlling the influence of motor speed was .080. Dividing the difference of .122 (i.e., .202 − .080) by .202 yields .604, which when multiplied by 100 results in the first entry in Table 8.

The recency memory measure is excluded from Table 8 because comparisons of the magnitudes of attenuation with this measure would not be meaningful given the very small relation between age and this measure (i.e., $r = -.08$). Entries labeled Average in the last row and in the last column are included to facilitate comparisons across measures, but it should be emphasized that these are not true averages, because the values in the columns and rows are not independent (e.g., the composite cognition variable is derived from the variables labeled PMA Reasoning, PMA Space, integrative reasoning, and analogy).

It can be seen in Table 8 that statistical control of the composite perceptual speed measure generally resulted in the greatest attenuation of the age-related effects, followed by a composite based on the Letter Comparison and Pattern Comparison measures, and then by the Digit Symbol measure. The composite motor speed measure was relatively ineffective in attenuating the age relations on any of the cognitive or memory measures, and the two slope measures fared the worst in terms of their inferred mediational influence on the age–cognition or age–memory relations.

These results are relevant to the second major goal of the project in that they are informative about the relative importance of different measures of speed as mediators of the relations between age and cognition or memory. Based on the data contained in Table 8, one can infer that perceptual speed is much more important than motor speed and that although there is a systematic relation between the speeds of adults of different ages, the slope of this relation does not appear to be very important as a mediator of age–cognition or age–memory relations.

Table 8
Attenuation of Age–Cognition Relations as a Function of the Measures of Speed and Cognition in the Adult Sample

	% attenuation of R^2 for age						
Criterion	Motor speed	Perceptual speed	Letter/pattern	Digit symbol	Slope	PSlope	Average
Cognition	60.4	98.5	95.5	89.1	46.0	31.7	70.2
Memory	56.5	82.6	80.4	73.4	34.2	22.8	58.3
PMA Reasoning	68.3	100	98.8	94.6	54.5	38.3	75.8
PMA Space	43.9	89.2	87.8	70.3	39.2	27.7	59.7
Integrative reasoning	55.6	93.3	88.9	79.3	34.1	21.5	62.1
Analogy	75.4	94.2	98.6	100	59.4	39.1	77.8
Paired associates	51.2	80.2	75.9	73.5	31.5	21.0	55.6
Primacy	57.5	73.2	68.6	59.5	32.7	24.2	52.6
Asymptote	42.5	66.4	60.4	57.5	18.7	11.9	42.9
Average	56.8	86.4	83.9	77.5	38.9	26.5	61.7

Note. Motor speed is a composite of horizontal and vertical line marking and letter and number copying; perceptual speed is a composite of letter and number completion, letter and number transformation, letter and pattern comparison, and digit symbol; letter/pattern is a composite of letter and pattern comparison; slope is the linear regression slope relating times of 11 speed measures to the average times of 100 college students; PSlope is the linear regression slope relating times of 7 perceptual speed measures to the average times of 100 college students. PMA = Primary Mental Abilities.

General Discussion

Theoretical Constructs

Although the four constructs of primary interest in this project—motor speed, perceptual speed, memory, and cognition—were found to have moderate to large correlations with one another, they are nevertheless distinguishable. That is, the measurement model illustrated in Figure 1 was found to provide an acceptable fit to the data, and the correlations between the composites in Table 5 were appreciably lower than the estimated reliabilities of the composites.

The discovery of high correlations (i.e., .74 for composites and .88 for factor scores) between the perceptual speed and cognition variables was somewhat surprising, because these are generally assumed to represent separate and distinct constructs, but correlations of similar magnitude have been reported in other studies. For example, in studies involving samples of older adults, the correlations reported between perceptual speed and inductive reasoning composites were .78 (Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980), .80 (Cornelius, Willis, Nesselroade, & Baltes, 1983), and .78 (Schaie, Willis, Hertzog, & Schulenberg, 1987). Schaie, Willis, Jay, and Chipuer (1989) have also reported a correlation of .86 between perceptual speed and inductive reasoning (and .77 between perceptual speed and spatial visualization) in a sample of 1,621 adults between 22 and 95 years of age. A later analysis of these data with a total of 1,628 adults resulted in correlations with perceptual speed of .88 for inductive reasoning and .78 with a spatial factor (Schaie, Dutta, & Willis, 1991). The results of all these studies therefore suggest that there is considerable overlap in what is measured by perceptual speed tests and timed tests of inductive reasoning and spatial visualization, particularly in samples containing a large proportion of older adults.

The motor speed and perceptual speed constructs also appear to be distinct despite fairly high correlations between the factors (.812) and the composite variables (.70). Schaie et al. (1991) have reported similar results with a more complex measure of motor speed based on the speed of copying paragraphs printed in uppercase and lowercase letters and on the speed of writing synonyms and antonyms of familiar words. The correlation between this motor speed factor and a perceptual speed factor in their study was .913, and, as in the present study, analyses revealed that this value was significantly less than 1.0.

Age Relations

The results summarized in Figure 2 and in Tables 4 and 5 clearly indicate that increased age is associated with slower performance on many speeded tasks and with lower levels of performance on certain memory and cognitive tasks. The age correlations with the composite measures (see Table 5) ranged from −.43 to −.55, indicating that between 18% and 30% of the total variance in these measures was systematically related to age. These values are in the same range as those summarized in Table 1 and are consistent with much research in the area of aging and cognition (see Salthouse, 1991b, for a recent review).

The correlation between age and the memory composite was −.43, but the age correlation was only −.08 for the recency measure. The lack of a significant age relation with the recency measure could be interpreted as suggesting that the factors responsible for the recency effect (e.g., primary memory) may be relatively unaffected by increased age (e.g., Craik, 1977). However, results from another similar project are inconsistent with this interpretation. Ronnberg (1990) also administered 12-word lists to adults from a wide range of ages and analyzed performance in terms of recall of words from successive thirds of the list. Correlations with age in that study were −.12, −.35, and −.27 for the primacy, asymptote, and recency segments, respectively, compared with the values of −.39, −.37, and −.08 in this study. The Ronnberg study therefore found smaller age-related influences on recall of primacy items compared with recency items, whereas the reverse was true in this study. Because participants in the Ronnberg study received eight lists of words and participants in the present study received only two lists, the discrepancy in the two sets of results may be related either to the reliability of the measures (which would be greater with more observations) or to some type of age-differential strategy shift across successive lists.

Speed Mediation

Consistent with the results of the studies summarized in Table 1, the age-related variance in the measures of cognitive functioning was found to be greatly reduced after statistical control of an index of perceptual speed. In fact, the results with the composite variables indicate that between 80% and 100% of the age-related influences on memory and cognition were eliminated by using statistical procedures to equate participants on an index of perceptual speed. Expressed somewhat differently, 18.4% of the total variance in the memory composite and 20.2% of the total variance in the cognition composite were associated with age before statistical control of the perceptual speed variable, but after statistical control of perceptual speed, the age-associated variance was only 3.2% for the memory composite and 0.3% for the cognition composite.

Although the results of this study do not by themselves indicate how speed mediates the influence of age-related effects on memory and cognition, it is nevertheless possible to speculate about the mechanisms that might be involved. An initial assumption is that perceptual speed measures such as those included in this study reflect the rate at which the individual can carry out many elementary mental operations. Given this assumption, one can speculate that at least some of the age differences in simple cognitive measures may be a direct consequence of a slower speed of mental processing because the required operations are relatively undemanding. Much of the age-related influences on the cognitive measures in the present study may be attributable to this type of influence, because most of the items in these tests would probably be answered correctly by individuals of moderate to high ability working without time constraints. In other words, with tests of low difficulty, a large proportion of the variance in performance can be hypothesized to be caused by variations in the number of items attempted rather than to variations in the percentage of attempted items answered correctly.

With more complex cognitive measures, the speed influence may be largely indirect and perhaps mediated by an impairment in the functioning of working memory. The precise nature of the working memory impairment is still not clear, but it may be related to a diminished ability to maintain the products of early processing during the execution of later processing. Much higher order thinking involving integration and abstraction can be postulated to require the simultaneous availability of relevant information, and the amount of simultaneously available information is likely to be a direct function of the effectiveness of working memory. Three observations are consistent with this working-memory mediation interpretation. First, the influence of working memory has been found to be greater than that of perceptual speed for difficult cognitive tests such as the Shipley Abstraction Test and the Raven's Advanced Progressive Matrices Test (Study 1 in Salthouse, 1991a), whereas the reverse was true for easier cognitive tests such as the integrative reasoning and geometric analogies tests included in this study (Studies 2 and 3 in Salthouse, 1991a). Second, a similar pattern of greater working-memory involvement and reduced influence of perceptual speed in more difficult or complex conditions has been found in within-task comparisons. That is, more detailed analyses of the results from Studies 2 and 3 in Salthouse (1991a) revealed that the influence of working memory was greater than that of perceptual speed for the more complex items in each of the tests (Salthouse, 1992c). And third, the results of several independent studies indicate that the age-related variance in measures of working memory is greatly attenuated by using statistical control procedures to remove the variance associated with perceptual speed (Salthouse, 1991a, 1992d; Salthouse & Babcock, 1991). This suggests that speed may be an important mediator of the age differences in at least some measures of working memory.

It is not yet obvious what factors besides perceptual speed contribute to the age differences in memory functioning. One possibility is that working memory plays an important role, much like that hypothesized with complex or difficult reasoning or spatial problems. Another possibility is that some of the age differences are attributable to variations in the effectiveness of particular mnemonic strategies or in the efficiency of specific processes concerned with encoding, retrieval, and so on. Systematic investigation of the effects of perceptual speed on adult age differences in specific memory components and on the efficiency of selected strategies is obviously needed to distinguish between these possibilities.

Comparability With Previous Studies

Because some of the same perceptual speed and cognitive tasks have been used before, the present results can be compared with those from the previous studies. The attenuation of the age differences in integrative reasoning with statistical control of the Letter Comparison/Pattern Comparison composite in this study was 88.9%, and the corresponding values in the two relevant studies reported in Salthouse (1991a) were 86.7% and 89.2%. Values for the analogies task were 98.6% in this study, and 99.5% and 94.7% in the two earlier studies. Hertzog (1989) and Schaie (1989) used different measures of perceptual speed in their studies, and thus the values with the PMA Space and PMA Reasoning tests cannot be compared directly, but inspection of the values in Tables 1 and 8 reveals that the patterns with these measures in this study were generally similar to those of the earlier studies.

Because it was recently reported (Salthouse, 1992b) that a very large proportion of the age-related variance in the Digit Symbol measure was shared with a perceptual speed composite created from the Letter Comparison and Pattern Comparison measures, the present data were examined to determine whether this phenomenon was also evident in this study. The earlier results were replicated because the R^2 for age in the prediction of Digit Symbol performance was .261 when it was considered alone but was only .019 when considered after statistical control of the Letter Comparison/Pattern Comparison composite. Although the residual age relation was still significantly greater than zero, it was only 7% of the original value, indicating that approximately 93% of the age-related variance in the Digit Symbol measure was shared with a composite of the two perceptual comparison speed measures.

Comparison of Speed Measures

The discovery that there was more attenuation of the relations between age and cognition after statistical control of perceptual speed measures involving comparison or transformation operations than after motor speed measures requiring little or no cognitive operations suggests that the speed of primary interest in the mediation of relations between age and cognition is perceptual or cognitive in nature rather than motoric. Also consistent with this interpretation is the finding that, at least for the sample of adults involving a wide range of ages, the relations between the composite measures were, if anything, slightly stronger between perceptual speed and cognition (r = .74) than between perceptual speed and motor speed (r = .70). It therefore appears that the aspect of processing speed responsible for the mediation of age differences in cognition is not that associated with sensory or motor processes but rather is related to the speed with which simple cognitive or mental operations can be executed.

Statistical control of the slope parameter led to only a small attenuation of the age–cognition relations, particularly in comparison with other speed measures. As discussed in the introduction, an outcome of this type is more consistent with the weak interpretation of the slope parameter in which it is considered to be an indirect reflection of the speed factor involved in age–cognition relations. The existence of the systematic relations among the speeded variables implies that the various speed measures are not independent with respect to age-related influences, but the present data offer little support for the view that the slope is a direct indicator of the speed factor postulated to be involved in mediating some of the age differences in cognition. The fact that the estimated reliability of the slope (i.e., .65) was lower than that for the other speed measures reported in Tables 3 and 5 raises the possibility that the weaker attenuation of the age relations with the slope measure might be attributable to the lower reliability of this measure relative to that of the directly observed measures. To investigate the extent to which differential measurement reliability contributed to the results summarized in Table 8, corrections for attenuation were applied to the correlations between age and speed and between speed and the composite measure of cognition. These disattenuated correlations were then used in the computation of partial correlations between age and cognition after controlling the relevant measure of speed. Finally, to express the results in a form comparable with that of Table 8, the square of the partial correlation was subtracted from the square of the age–cognition correlation, the difference divided by the square of the age–cognition correlation, and the quotient multiplied by 100 to yield a measure of percentage attenuation of the age-related variance. Values computed in this manner were 93% for the Digit Symbol measure, 85% for the Letter Comparison measure, 98% for the Pattern Comparison measure, and only 46% for the slope measure. These results therefore suggest that the discrepancies in the magnitude of the attenuation of age relations with the slope measure compared with other measures are not simply attributable to lower measurement reliability, and they hence serve to weaken confidence in the interpretation of the slope as an index of the magnitude of an age-related reduction in rate of cognitive or mental processing.

Conclusions

One conclusion from this study is based on the discovery that the age-related influences on several measures of memory functioning were greatly attenuated after statistical control of measures of perceptual speed. It therefore seems reasonable to infer that a substantial proportion of the adult age differences in at least some measures of memory appear to be mediated by the same speed factors that have been found to mediate age differences in reasoning and spatial abilities.

A second major conclusion is that the speed involved in the mediation of age–cognition relations does not merely reflect sensory and motor processes but instead is related to how quickly simple mental or cognitive operations can be executed. It is not yet apparent whether cognitive operation speed is a fundamental construct or whether it is a consequence of something even more basic, such as a reduction in certain attentional processes. What does appear clear, however, is that there is a strong association between measures of mental or cognitive speed and the negative relations between age and cognitive performance.

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