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Aging Associations: Influence of Speed on Adult Age Differences in Associative Learning

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Two studies, involving a total of nearly 500 Ss, were conducted to determine the mechanisms by which processing speed contributes to the relations between adult age and associative learning. Results of both studies indicated that increased age was related to poorer associative learning largely because of a failure to retain information about previously correct responses. This in turn was related to the effectiveness of encoding briefly presented information in an associative memory task, which was related to measures of processing speed. It is therefore suggested that age-related decreases in speed of processing lead to less effective encoding or elaboration, which results in a fragile representation that is easily disrupted by subsequent processing.

At least two different perspectives have been adopted in attempts to explain an individual's performance in learning and memory tasks. The experimental approach typically focuses on specifying the components or processes, such as encoding or rehearsal, that are presumably required to perform the criterion task. The correlational approach concentrates on identifying relatively broad abilities, such as verbal comprehension or short-term acquisition and retrieval, that may be contributing to performance on the criterion task. Despite several appeals for an integration of the two perspectives (e.g., Cronbach, 1957; Underwood, 1975), experimental and correlational approaches to learning and memory have remained largely independent. (But see Geiselman, Woodward, & Beatty, 1982, and Underwood, Boruch, & Malmi, 1978, for notable exceptions.)

The current project represents one attempt at integrating the two approaches in the context of understanding the source of a particular type of individual differences—those related to increased age in adulthood—in a specific cognitive task—associative learning. Unlike traditional experimental approaches, the processes or components identified in task analyses are not considered in isolation, but instead their relations with measures from other tasks are examined. However, unlike traditional correlational approaches, the explanatory constructs are not broad abilities, but instead are measures derived from task decompositions.

Although only a single criterion task was examined in this project, associative learning is a moderately complex cognitive activity that occupies a central role in many cognitive theories. Furthermore, if relational or structural analyses at the level of task components or processes prove successful in the current project, then the procedures should also be applicable to other tasks and to other types of individual differences, including those based on talent or ability, developmental differences in childhood, specific brain damage, or disease category.

Pronounced adult age differences have been reported in the efficiency of many types of learning, including trial-by-trial improvement in learning to associate pairs of unrelated words (e.g., Kausler & Puckett, 1980; Monge, 1971; Winn, Elias, & Marshall, 1976). An example of this phenomenon is evident in a study reported by Salthouse, Kausler, and Saults (1988), in which 362 adults between 20 and 79 years of age were presented with pairs of unrelated words. Eight word pairs were presented, followed by the first word in each pair together with the instruction to recall the second word of the pair. A second study-test sequence with the same word pairs was administered immediately after the first recall attempt. Multiple regression analyses revealed that the age-related effects were larger in the second trial (i.e., R^2 for age of .144) than in the first trial (i.e., R^2 of .087). Furthermore, there was a significant increment in R^2 associated with age (i.e., .020) in the prediction of Trial 2 performance after Trial 1 performance was statistically controlled, indicating that there were independent age-related influences on Trial 2 performance.

A similar result was obtained in a recent unpublished study from my laboratory involving 50 young adults (ages 18 to 27) and 44 older adults (ages 56 to 83). In this study the R^2 associated with age in the prediction of Trial 1 performance was .381, and that for Trial 2 performance was .584. The increment in R^2 associated with age in Trial 2 performance after control of Trial 1 performance was statistically significant (i.e., .083). In each of these cases, therefore, there was a smaller benefit of repetition with increased age, which may reflect an age-related decrease in the retention of information across successive trials.

Previous research has also found a large influence of processing speed on the relations between age and measures of performance on tasks ranging from reasoning and spatial abilities, to free recall and paired-associate memory (e.g., Hertzog, 1989; Lindenberger, Mayr, & Kliegl, 1993; Nettelbeck & Rabbitt, 1992; Salthouse, 1991, 1992a, 1993a, 1994; Salthouse & Babcock, 1991; Schaie, 1989, 1990). Processing speed in these studies has typically been measured with paper-and-pencil tests involving comparisons, substitutions, or

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search, or with various reaction time tasks. In each of these studies, comparisons of the proportion of variance (i.e., R^2) associated with age before and after control of the speed measures indicated that between approximately 50% and 100% of the age-related variance in the cognitive measures is shared with speed. (See Table 1 in Salthouse, 1993a, for the actual values in many of these studies.)

Similar statistical control analyses have also been conducted to examine the influence of speed on the relations between age and measures of associative memory. In a study by Salthouse (1993a), two lists of six word pairs each were presented to 305 adults from a wide range of ages. Scores on paper-and-pencil Letter Comparison and Pattern Comparison tests (described here later) were combined to serve as the speed measure. The age-related variance (i.e., R^2) in the prediction of accuracy of remembering the second word in each pair was .162 when age was the only predictor in the equation, but it was only .024 after the speed measure had been controlled. The same speed and paired-associate tasks were also used in another unpublished study from my laboratory with an extreme-groups design (77 young adults and 69 older adults). In this study, the R^2 associated with age was .596 when age was considered alone but only .069 when age was examined after control of the speed measure. These studies therefore suggest that over 85% (i.e., 85.2% and 88.4%, respectively) of the age-related variance in performance in associative memory tasks is shared with measures of perceptual comparison speed.

The results just described strongly imply that processing speed contributes to the relations between age and various measures of cognitive performance, including associative learning and memory. What they fail to indicate, however, is the manner in which that influence is manifested. A primary goal of this research was to investigate a specific hypothesis about how processing speed might mediate age-related effects on associative learning.

The proposed interpretation of the speed influence is based on three related assumptions. First, it is postulated that speed of processing directly affects the encoding of information because the quality or availability of stimulus information is presumed to degrade over time; hence, more accurate and elaborate encoding is possible when the relevant processing operations can be performed quickly. Second, better encoding is hypothesized to result in a more durable representation that is less susceptible to disruption from subsequent processing. Third, it is assumed that more information is preserved (i.e., less is forgotten) when the internal representation is more durable and stable.

The investigative strategy in this project consisted of three steps. The first involved analyzing the associative learning task into distinct components. Next, components of a continuous associative memory task presumed to be related both to speed measures and to associative learning components were identified. Finally, empirical relations among the component measures were examined by means of hierarchical regression and path analyses.

Two studies were conducted, and each involved two phases. The initial phase consisted of an examination of the relations among the variables in a sample (i.e., college students) that was relatively homogeneous in terms of age and speed. In the second phase, those same relations were examined in a sample that had a much greater range of age and variation in processing speed. Comparison across the two phases was expected to be informative about how the pattern of relations among variables changes when the range of speed is increased. That is, some relations may only be salient when there is moderate-to-large variation in the speed measures.

Three sets of tasks were therefore administered in each study. The primary criterion task was associative learning. Associative memory tasks involving continuously changing pairs of items were administered to assess the efficiency of encoding, and the rate of forgetting, of associative information. Finally, a variety of paper-and-pencil and computer-administered tasks were used to assess processing speed.

Associative Learning Task

The associative learning task used in these studies required subjects to learn to associate pairs of symbols with one another. The criterion for learning was three successive sequences in which all pairs were correct, and the task was discontinued if a subject did not reach the criterion within 10 sequences. The left panel of Figure 1 contains a display of a single trial in this task. Notice that one symbol from the stimulus set is presented as the probe item, along with the entire set of response symbols. The subject is instructed to select which symbol from the response set is associated with the probe symbol by moving the pointer in front of his or her choice. If the subject had no prior exposure to the associations, then the first response is necessarily a guess. However, performance on subsequent trials can improve if the subject makes use of the feedback from earlier trials.

Detailed measures of performance in this task were derived by analyzing responses to the same probe symbol across successive trials. Only immediately successive trials were considered because the analyses become quite complicated if the response history is extended beyond the immediately preceding trial. The focus was also restricted to the first four

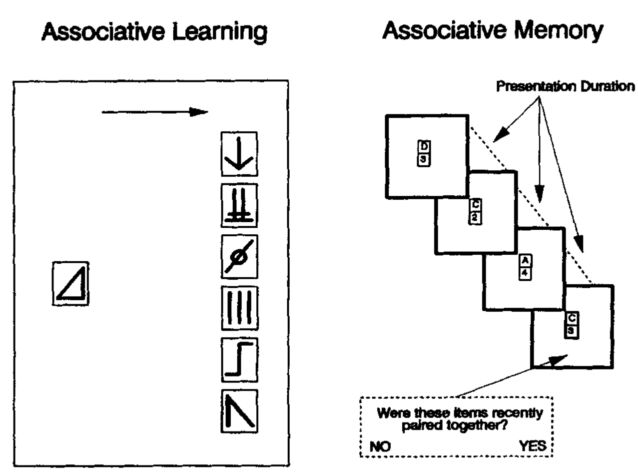

Figure 1. Illustration of a sample trial in the Associative Learning task (left) and of a sequence of displays in the Associative Memory task (right).

trials within each set because some subjects could have reached the criterion with this number of trials, and thus there was a possibility of missing data if a greater number of trials were used.

For the purposes of the analyses, the associative learning responses were classified into six mutually exclusive categories. A *successful response* was defined as a correct response preceded either by no previous exposure to this stimulus (i.e., it was the first trial) or by an incorrect response on the previous exposure to this stimulus. A *retain* was defined as a correct response to a given stimulus followed by a correct response the next time that stimulus was presented. The converse of the retain category was *forget*, defined as a correct response to a stimulus followed by an incorrect response to the same stimulus the next time it occurred. A *discrimination failure* was defined as an incorrect response in which the response had already been linked to a different stimulus since the last presentation of this stimulus. That is, the subject failed to discriminate that the selected response had already been confirmed as being paired with another stimulus. A *perseveration* was defined as an incorrect response in which the response was a repetition of a response already disconfirmed for this stimulus on the previous trial. That is, the subject continued with an inappropriate response despite the negative feedback received the last time the stimulus was presented. Finally, an *unsuccessful guess* was defined as an incorrect response from a subject who either had had no previous exposure to this stimulus or had made an incorrect response on the previous trial with the current response not having been previously confirmed with another stimulus (i.e., not a discrimination failure) or disconfirmed with this stimulus (i.e., not a perseveration).

Three of the error categories are particularly interesting because they each correspond to the loss of information. That is, forget responses represent a loss of positive (confirming) direct (to this stimulus) information; discrimination failures represent a loss of positive (confirming) indirect (to another stimulus) information; and perseverations represent a loss of negative (disconfirming) direct (to this stimulus) information. Because absolute frequencies are not very meaningful when there are large variations in the total number of errors, each response category was converted into a percentage. The discrimination failure and perseveration categories were examined in relation to the total number of incorrect responses (including unsuccessful guesses), and forgetting responses were examined in relation to the number of correct responses on the preceding trial because forgetting can only occur if the previous response was correct. A percentage correct measure was also formed by dividing the sum of successful responses and retains by the number of opportunities for a response (i.e., the product of trials and symbols).

A recent study by Salthouse and Kersten (1993) required subjects to perform a version of this associative learning task after having performed two other tasks involving the same stimulus pairs. Reanalyses of the data according to the classification scheme described above revealed that the 53 older adults were significantly less accurate than the 53 young adults in the first four trials (74.5% vs. 93.1%) and had a significantly higher rate of forgetting from one trial to the next (24.2% vs. 8.1%). The percentage of errors that were perseverations was also significantly higher among older adults (4.8% vs. 1.3%), but there was no significant difference in the percentage of discrimination failure errors (14.4% vs. 11.8%). The results of the Salthouse and Kersten study are thus consistent with the hypothesis that age differences occur in the trial-to-trial retention of associative information. Furthermore, the age differences are apparently most pronounced for direct information about the stimulus (i.e., forgetting and perseverations).

Associative Memory

The associative memory task was included to investigate two possible factors that might contribute to the hypothesized poorer retention of associative information with increased age. The two possibilities were less effective initial encoding and more rapid forgetting. Pairs of letters and digits were presented sequentially, interspersed with probes in which the subject was to decide whether the displayed items had been paired together when either member of the pair was last presented. The task is loosely based on the continuous paired-associates procedure described by Atkinson and Shiffrin (1968). A series of displays in this task is illustrated in the right panel of Figure 1. The number of displays intervening between the initial presentation and test (i.e., lag) was manipulated, as well as the duration of each stimulus presentation. The example contains one pair intervening between the presentation of the target and its test, and therefore the lag in this case is 1.

Presentation–test lag was manipulated by varying the number of intervening pairs between 0 and 3. If older adults forget more rapidly than young adults, then they would be expected to have greater losses of accuracy with increased lag. Stimulus presentation time was manipulated by varying the duration of each stimulus pair. If there are age differences in the time to register or encode the stimulus, then young adults would be expected to be more accurate than older adults even when the stimulus pairs are displayed for very short durations.

Processing Speed

Results from earlier studies have indicated that the influence of speed varies with the nature of the speed measure; it is generally greatest with measures that have a cognitive component (e.g., substitution or comparison) and least with measures that primarily involve sensory and motor aspects (Salthouse, 1993a). In an attempt to replicate and extend the previous results, several different speed measures were included in these studies. On the basis of results from earlier studies (e.g., Salthouse, 1993b; 1994), two paper-and-pencil tests requiring simply copying or drawing lines were included to assess motor speed, and two paper-and-pencil tests requiring same–different comparisons were included to assess perceptual speed. Two computer-administered reaction-time speed measures used in other studies (Salthouse, 1992b; Salthouse & Kersten, 1993) were also included. These measures were derived from similar tasks that differed only with respect to whether the decisions were based on physical identity or associational equivalence according to a displayed code table.

The difference between the two reaction time measures served as a measure of the speed of the association or substitution process.

Analytical Procedures

Two statistical procedures were used to examine the hypothesized relations among variables in this project. Hierarchical multiple regression or semipartial correlation (e.g., Cohen & Cohen, 1983; Pedhazur, 1982) analyses were used to determine the amount of age-related variance in each variable both before and after the variance in measures reflecting speed of processing were controlled. The difference between the two estimates of age-related variance provides an indication of the relative contribution of the speed measure to the age-related differences in the criterion variable. (See Salthouse, 1992a, for further discussion of this reasoning.)

Path analysis (e.g., Asher, 1983; James, Mulaik, & Brett, 1982; Kenny, 1979) was the other analytical procedure used in this project. The purpose of the path analyses was to examine the plausibility of a particular pattern of relations among the variables. Although causal direction is ambiguous with simultaneous correlational data, path analyses are nevertheless useful in determining whether specific relations among variables exist and in providing an estimate of the relative strength of those relations.

Because both statistical methods are based on the partitioning of variance in the variables, it is essential that the variables used in these analyses have sufficient systematic variance to allow associations with other variables. Reliability estimates were therefore derived for all variables, and variables with low reliabilities were not used in the primary analyses.

Another method of minimizing measurement error involves conducting the path or structural analyses on latent constructs rather than on observed manifest variables. Unfortunately, identification of latent constructs typically requires three or more indicators of each construct, and that was not feasible with the task decomposition approach adopted in this project.

Study 1

Method

Subjects

Two groups of subjects participated in this study—64 college students and 240 adults from a wide range of ages. The nonstudent adults were recruited from a variety of sources, such as churches, newspaper advertisements, and acquaintances of the research assistants. Demographic characteristics of all participants are summarized in Table 1. The correlation between age and health in the adult sample was .24, and that between age and education was −.11. Analyses examining interactions of these variables with age are reported here later.

Procedure

All subjects performed the tasks in the same order, with the paper-and-pencil speed tasks first (in the order of Boxes, Pattern Comparison, Letter Comparison, and Digit Copying), followed by the computer-administered speed tasks (Digit Digit and Digit Symbol), the Associative Memory task, and then the Associative Learning task.

Table 1
Demographic Characteristics of Research Participants

Group	*n*	Age		Female	Education (years)		Health	
		M	*SD*	(%)	*M*	*SD*	*M*	*SD*
Study 1								
Students	64	19.6	1.6	47	13.2	1.9	2.0	1.8
Adults (ages)								
19–39	83	30.0	5.4	64	14.1	2.7	1.8	0.9
40–59	85	49.8	6.0	64	14.0	2.4	2.4	1.1
60–82	72	67.0	5.6	64	13.3	2.4	2.4	1.1
All	240	48.1	15.9	64	13.9	2.5	2.2	1.1
Study 2								
Students	67	19.4	1.2	46	13.4	1.2	1.9	0.8
Adults (ages)								
20–39	35	30.5	5.1	54	15.2	2.0	2.0	1.0
40–59	46	50.3	5.7	61	15.9	2.3	2.1	1.0
60–89	44	69.3	6.6	41	15.2	2.5	2.3	1.0
All	125	51.5	16.5	52	15.5	2.3	2.1	1.0

Note. Education is self-reported number of years for formal education completed, and health is a self-rating on a scale ranging from 1 for *excellent* to 5 for *poor.*

Paper-and-pencil speed tasks. The paper-and-pencil speed tasks each consisted of an instruction page with examples, followed by two test pages. Subjects were allowed 30 s to complete as many problems as possible in each test page, and the average score across the two administrations served as the measure of performance in the test.

The Boxes test consisted of a page of squares, with each square having one missing side. The task for the subject was to draw a line to make a square, or box, out of each three-sided figure. The Digit Copying test consisted of a page of double boxes, with a digit in each top box and nothing in the bottom box. In this task, the subject was to copy the digit from the top box in the empty box below it. The Pattern Comparison test consisted of a page containing pairs of line patterns each composed of three, six, or nine line segments. The task for the subject was to write an *S* (for Same) between the pair if the two patterns were identical and to write a *D* (for Different) if they were not. The Letter Comparison test consisted of a page containing pairs of three, six, or nine letters. The task for the subject was to write an *S* (for Same) between the pair if the two patterns were identical and to write a *D* (for Different) if they were not. In both the Pattern Comparison and Letter Comparison tests, one half of the pairs were different because of a change in the position or identity of one of the elements (i.e., line segments or letters) in one member of the pair. To adjust for guessing, scores in these latter two tests consisted of the number of correct responses minus the number of incorrect responses.

Computer-administered speed tests. The two computer-administered speed tests were based on the Wechsler Digit Symbol Substitution Test (see Salthouse, 1992b). The display for a trial in each test consisted of a code table at the top of the screen and a pair of probe items in the middle of the screen. In the Digit Symbol version of the test, the code table contained digits in its top row and symbols in its bottom row, and the probe items consisted of a single digit-symbol pair. If the digit and symbol matched according to the code table at the top of the screen, the subject was to press the / (slash) key as rapidly as possible; if they did not match, the Z key was to be pressed as rapidly as possible. In the Digit Digit version of the test, the code table was redundant because the bottom row contained the same digits as those in the top row. Subjects in this version of the test simply had to decide whether the two probe digits were the same or different. If they were the same, the / key was to be pressed as rapidly as possible; if they were different, the Z key was to be pressed as rapidly as possible.

A practice block of 18 trials was administered in each task, followed by two experimental blocks of 90 trials each. The order of the blocks was Digit Digit practice, Digit Digit experimental, Digit Symbol practice, Digit Symbol experimental, Digit Symbol experimental, and Digit Digit experimental. The mean of the median reaction time (RT) and the percentage of correct responses across the two experimental blocks served as the performance measures in each task.

Associative memory. The stimuli in this task consisted of a letter between A and F as the stimulus term and a digit between 1 and 6 as the response term. Pairings of letters and digits changed continuously from presentation to presentation throughout the task. Each letter–digit pair was displayed for a specified presentation duration, but subjects had an unlimited time to respond to the test probe. Test probes consisted of a letter and a digit, along with the instruction to decide whether the items had been paired with one another the last time either had been presented. A positive decision was communicated by pressing the / key, and a negative decision was communicated by pressing the Z key. Subjects could take as long as they wanted to make their decision.

After a block of practice trials, seven experimental trial blocks were presented. The first and last block of trials consisted of 12 tests at each lag from 0 to 3, with a stimulus presentation duration of 1,000 ms. The middle five trial blocks consisted of 18 tests each at Lags 0 and 1, with stimulus presentation durations of 750, 150, 450, 300, and 600 ms, respectively. The sequence of stimulus presentations and tests with each lag was randomly determined for each subject. The first and last trial blocks had an average of about 240 stimulus presentations each, with 48 tests, and the middle five blocks had an average of about 140 stimulus presentations each, with 36 tests.

Associative learning. Stimuli in this task consisted of symbols created from a 5 × 7 matrix. The symbols were designed to be similar in complexity to letters and digits but without familiar labels. (See Figure 1 for examples.) Three different sets of six symbols each were created, and they were paired in different combinations across the three sets of trials. Within a given set, presentation of the stimulus symbols was blocked such that all symbols were presented once before any symbol was presented again.

The arrangement of response symbols was different on each trial to prevent the use of position as a cue. A pointer could be moved in a vertical column adjacent to the response symbols with the up- and down-arrow keys on the keyboard. When the pointer was in front of the selected response symbol, the selection could be registered by pressing the ENTER key on the keyboard. The pointer could be moved as frequently as desired, and there was no limit on the time to choose and register a response. Feedback, consisting of a brief tone and visual highlighting of the correct response for 1.5 s, was presented after the selection was registered.

Each set of trials continued until the subject achieved a criterion of three successive sequences with all six pairs correct or a maximum of 10 trials with each stimulus symbol. The first set was considered practice, and hence these data were not analyzed. Responses in the first four trials of the second and third sets were categorized according to the classification scheme described earlier.

Miscellaneous. In addition to the tasks described earlier, all subjects also performed three tasks not reported here. Two were paper-and-pencil tasks designed to measure transformation speed, but the data were not meaningful because the absolute level of performance was very low and the reliabilities were near zero. The results from the other task, a computer-administered arithmetic task, are described along with results from a separate study in another report (Salthouse & Coon, 1994).

Table 2
Descriptive Statistics of Major Variables for 64 Students, Study 1

Variable	*M*	*SD*	Estimated reliability
Paper and pencil speed tests			
Boxes	58.3	14.5	.95
Digit Copy	59.1	8.1	.91
Letter Comparison	12.6	2.5	.62
Pattern Comparison	20.6	3.7	.76
Computer speed tests			
Digit Digit RT	586	70	.90
Digit Symbol RT	1063	189	.94
Digit Digit % correct	95.6	2.8	.52
Digit Symbol % correct	94.6	3.6	.81
Substitution (Digit Symbol RT–Digit Digit RT)	477	162	.90
Associative Memory			
Lag 0 (1,000)	87.1	13.1	.64
Lag 1 (1,000)	73.6	12.8	.60
Lag 2 (1,000)	65.7	9.4	0
Lag 3 (1,000)	60.2	10.1	0
Lag 0 (150,300)	71.7	11.0	.47
Lag 1 (150,300)	57.8	6.8	0
Lag 0 (600,750)	84.4	13.1	.78
Lag 1 (600,750)	71.5	11.4	.50
Associative Learning			
Trials-to-criterion	7.8	1.8	.58
First four trials			
% correct	58.7	15.3	.66
% forget	20.7	17.4	.56
Other error %			
Unsuccessful guesses	66.0	15.4	.32
Discrimination failures	12.3	7.8	0
Perseverations	4.9	4.8	0

Note. Estimated reliability computed from Spearman-Brown formula. Negative reliability estimates replaced by value of 0.

Results and Discussion

Student Data

Means, standard deviations, and estimates of the reliabilities of the performance measures are displayed in Table 2.[1] Reliabilities were computed by boosting the correlation between the measures obtained from the two administrations of the task by the Spearman-Brown formula. It can be seen that the reliabilities for the speed measures were in the moderate-to-high range but that the reliabilities were very low for some measures in the Associative Memory and Associative Learning tasks.

Correlations among the speed measures are presented in Table 3. Because the correlations between the measures postulated to represent the same construct (i.e., motor speed, perceptual speed, RT speed) were in the moderate range, composite indexes of each speed construct were created by averaging the relevant z scores. Correlations among these composites are contained in the bottom of Table 3. Note that because lower scores represent faster performance in the RT speed measures but slower performance in the paper-and-pencil tests, correlations between the two types of speed

[1] Unless specifically noted, a significance level of .01 was used in all statistical comparisons.

Table 3
Correlations Among Speed Measures

Subjects	Observed variables		
	Boxes–Digit copy (Motor speed)	Letter comparison–Pattern comparison (Perceptual speed)	Digit digit–Digit symbol (RT speed)
Study 1			
Students	.58*	.54*	.54*
Adults	.67*	.62*	.76*
Study 2			
Students	.44*	.28	.50*
Adults	.64*	.59*	.76*
	Composite indexes		
	Motor speed–Perceptual speed	Motor speed–RT speed	Perceptual speed–RT speed
Study 1			
Students	.37*	−.26	−.33*
Adults	.59*	−.53*	−.65*
Study 2			
Students	.53*	−.20	−.31
Adults	.53*	−.30*	−.70*

Note. RT = response time.
*$p < .01$.

measures would be expected to be negative rather than positive. The values are all in the low-to-moderate range, suggesting that the different types of speed in the student sample were related but not identical.

There was little evidence of a between-subject speed–accuracy trade-off in the RT speed tasks because the correlations between RT and percentage correct were low (i.e., .05 for Digit Digit and .17 for Digit Symbol).

Associative memory. Because there were relatively few data from each presentation time condition in the Associative Memory task, the data from the two fastest (i.e., 150 and 300 ms) and the two slowest (i.e., 600 and 750 ms) times in the varied time versions of the task were combined with one another to increase reliability. It is apparent in Table 2 that, as expected, accuracy was higher with shorter lags and with longer times. However, the reliability was very low for Lags 2 and 3; thus these measures were dropped from subsequent analyses.

The correlation between accuracy at Lag 0 averaged across the 600 and 750 ms presentation times, and accuracy at Lag 0 with the 1,000 ms presentation time was .76. Because this correlation is actually larger than the theoretical maximum based on the estimated reliability of the latter measure (i.e., .64), these two measures can be inferred to be assessing the same construct of encoding effectiveness with adequate presentation time. Only the Lag 0 measure at the 1,000 ms presentation time was therefore used as the measure of accuracy at the slow presentation time in the subsequent analyses.

Associative learning. Correlations among the three types of associative learning errors were .35 between forget and perseveration, .06 between forget and discrimination failure, and .12 between perseveration and discrimination failure. A likely reason for these low correlations is the low reliabilities of all but the forget measure (cf. Table 2). Only the measure of percentage forgetting was therefore used in subsequent analyses.

Path analysis. The relations among the variables from the different tasks were examined with path analysis procedures. Seven variables selected on the basis of theoretical relevance and reliability were included in these analyses. The measures from the Associative Learning task were trials-to-criterion as the primary dependent variable, percentage correct in the first four trials as a reflection of initial learning, and percentage forgetting in the first four trials as an indication of the failure to retain information. Measures from the Associative Memory task were accuracy at Lag 0 with fast (average across 150 and 300 ms) presentation times to reflect efficiency of encoding with limited time, accuracy at Lag 0 with slow (1,000 ms) presentation time to represent effectiveness of encoding with a longer presentation duration, and accuracy at Lag 1 with slow (1,000 ms) presentation time to represent short-term retention in the presence of intervening information. The composite RT speed measure was used as the primary speed index because the Associative Learning and Memory tasks were also presented on computers.

Strong relations were expected among the measures from the same task. That is, in the Associative Learning task, percentage forgetting was predicted to be negatively related to percentage correct, and percentage correct was predicted to be negatively related to trials to criterion. In the Associative Memory task, accuracy at Lag 0 with fast presentation times was predicted to be related to accuracy at Lag 0 with slow presentation times, which in turn was predicted to be related to accuracy at Lag 1 with slow presentation times. The Associative Memory and Associative Learning tasks were postulated to be related to one another by a linkage between accuracy at Lag 1 and percentage forgetting because the ability to briefly retain information in the presence of intervening information was expected to be negatively related to the inability to retain information from one trial to the next. In the interests of parsimony, the only linkage postulated from speed was to accuracy at Lag 0 with the fast presentation times. All relations were postulated to be directional from simple to more complex (i.e., from processing speed to measures of associative memory to measures of associative learning).

The model specification sequence for the path analysis on the student data is summarized in Table 4.[2] Relations with large standardized residuals were selected for inclusion as new paths, and a model was modified when the difference in chi-square from the preceding model was significant. Models were also considered in which paths were specified between speed and Lag 0 (slow), and between speed and percentage correct because those paths were added in the best-fitting

[2] The measures of fit in Table 4 reflect the statistical comparison of the actual and observed covariances (χ^2), an index of the residual standardized error (Adj. RMS), and two coefficients (Adj. Pop. Γ, Adj. GFI) representing the relative amount of the variances and covariances accounted for by the model. Values of residual standardized error below 0.1 and values of model determination above 0.9 are considered to represent good fits (e.g., Steiger, 1989).

Table 4
Fits of Path Analysis Models

Model	Description	n	X^2	df	Adjusted RMS	Adjusted Pop. Γ	Adjusted GFI
		Study 1					
Student data		64					
1	Initial		35.46	15	.1327	.8690	.7703
2	Add Lag 0 (slow): % forget		29.06	14	.1267	.8792	.7782
3	Delete lag 1 (slow): % forget		30.06	15	.1284	.8767	.7770
Adult data		240					
4	Add age: Speed to Model 3		121.63	21	.1333	.8537	.8241
5	Add age: % forget		101.94	20	.1278	.8642	.8340
6	Add speed: Lag 0 (slow)		48.58	19	.0802	.9439	.9105
7	Add speed: % correct		37.65	18	.0706	.9561	.9221
		Study 2					
Student data		67					
8	Model 3		25.09	15	.0969	.9279	.8261
Adult data		125					
9	Model 7		48.09	18	.0961	.9202	.8579

Note. RMS = root-mean-square error; Pop. Γ = Population Gamma; GFI = goodness-of-fit index.

model for the adult data. Neither model differed significantly in fit from Model 3, and the coefficients for the added paths differed from zero by less than two standard errors. It was therefore concluded that although Model 3 only provides an adequate fit to the data, it cannot be improved with the addition of the paths needed to fit the adult data. This model, with the significant path coefficients, is illustrated in Figure 2. Parallel analyses with the other speed measures yielded generally similar results (i.e., the chi-square values for Model 3 were 21.11 for the perceptual speed composite, 30.42 for the motor speed composite, and 32.72 for the substitution speed measure).

Inspection of Figure 2 reveals that there is support for the expected relations among measures from the same tasks. The relation between faster speed (lower times) and higher accuracy at Lag 0 with short presentation times is consistent with the assumption that faster processing speed allows more extensive or elaborate encoding when the stimulus duration is limited. However, there was no relation between accuracy at Lag 1 in Associative Memory and percentage forgetting in Associative Learning. This was surprising, and consequently it was examined further in hierarchical regression with accuracy at both Lag 0 and Lag 1 as predictors of percentage forgetting in opposite orders. The increment in R^2 in the prediction of percentage forgetting was .013 (not significant) for Lag 1 after control of Lag 0, but .086 ($p < .02$) for Lag 0 after control of Lag 1. Because there is a relation between forgetting and the residual variance in Lag 0 independent of Lag 1, but not between percentage forgetting and the residual variance in Lag 1, these analyses confirm that it is accuracy at Lag 0 and not accuracy at Lag 1 that is most closely related to percentage forgetting. It can therefore be concluded that forgetting in Associative Learning is more likely when the initial representation is weak, as reflected by low accuracy in Associative Memory at Lag 0.

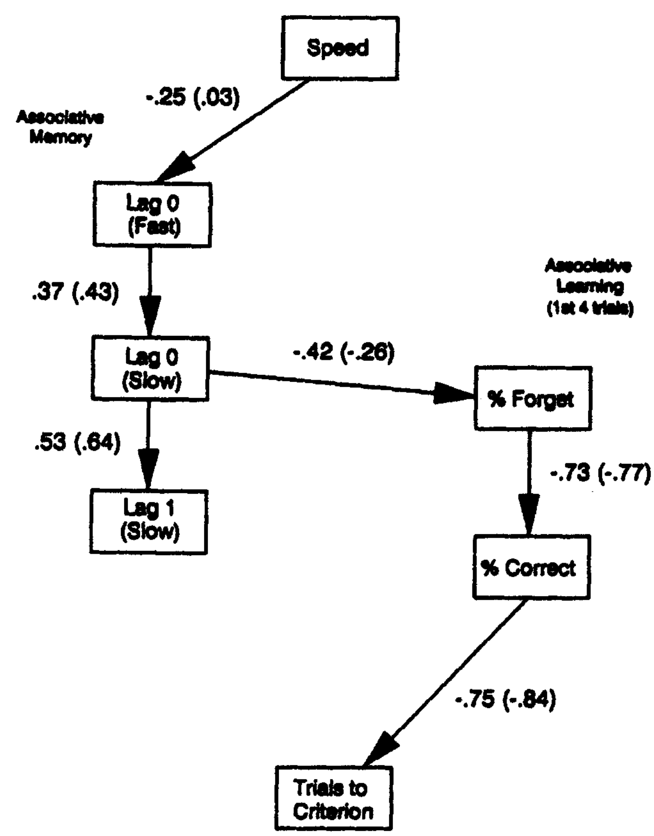

Figure 2. Path model indicating relations among variables in the student data. Values outside of the parentheses are the coefficients from Study 1; those inside parentheses are the coefficients from Study 2. All coefficients except that between speed and Lag 0 (fast) in Study 2 were significantly different from 0.

Adult Data

Means, standard deviations, estimated reliabilities, and correlations with age for all performance variables are summarized in Table 5. As with the student data, the reliabilities were moderate to high for the speed measures and in the low-to-moderate range for measures from the Associative Memory and Associative Learning tasks. The age correlations were significantly different from 0 for most variables, particularly when the estimated reliability of the measure was at least moderate. The correlation between the reliability estimate and the absolute value of the age correlation was .85, indicating that the age relations were larger for the measures with the highest proportions of systematic variance.

Nonlinear age trends were examined for all variables in Table 5. A significant quadratic age trend was evident only in the measure of accuracy in the Digit Symbol task. Interactions of age with gender, health, and education were also examined for all variables. The only significant interactions were with gender on accuracy in the Digit Digit and Digit Symbol tasks (i.e., negative age effects for male subjects, positive age effects for female subjects) and with health on accuracy at Lag 3 (i.e., larger age effects for those in poorer health).

Table 5
Descriptive Statistics of Major Variables for 240 Adults, Study 1

Variable	*M*	*SD*	Estimated reliability	Age correlation
Paper and pencil speed tests				
Boxes	51.4	12.8	.92	−.47*
Digit Copy	53.0	10.8	.92	−.50*
Letter Comparison	9.7	3.1	.73	−.44*
Pattern Comparison	15.5	3.9	.84	−.58*
Computer speed tests				
Digit Digit RT	839	211	.76	.52*
Digit Symbol RT	1627	404	.96	.59*
Digit Digit % correct	96.9	3.2	.37	.03
Digit Symbol % correct	96.3	3.5	.59	−.01
Substitution (Digit Symbol RT–Digit Digit RT)	788	279	.79	.46*
Associative Memory				
Lag 0 (1,000)	81.1	14.6	.74	−.35*
Lag 1 (1,000)	69.9	14.2	.58	−.23*
Lag 2 (1,000)	63.4	12.4	.47	−.16
Lag 3 (1,000)	57.2	10.2	0	−.03
Lag 0 (150,300)	61.0	13.0	.54	−.21*
Lag 1 (150,300)	55.9	9.3	.20	−.06
Lag 0 (600,750)	78.2	15.2	.77	−.35*
Lag 1 (600,750)	67.2	13.4	.67	−.28*
Associative Learning				
Trials-to-criterion	9.2	1.5	.78	.28*
First four trials				
% correct	41.7	19.1	.83	−.41*
% forget	42.8	27.4	.65	.36*
Other error %				
Unsuccessful guesses	59.4	13.4	.36	−.08
Discrimination failures	14.7	9.0	.28	−.03
Perseverations	9.4	7.3	.40	.36*

Note. Estimated reliability computed from Spearman-Brown formula. Negative reliability estimates replaced by value of 0. RT = response time.
*$p < .01$.

There was little evidence of a between-subjects speed–accuracy tradeoff in the RT tasks because the correlations between the time and percentage correct values were small (i.e., −.13 for Digit Digit and .01 for Digit Symbol). Correlations among the speed measures and speed composites are presented in Table 3, where it can be seen that all of the correlations are larger than those in the student sample.

Associative memory. It is apparent in Table 5 that accuracy was lower with increased lag and that the magnitude of the age correlations also decreased with increased lag. This pattern was confirmed in an Age (19–39, 40–59, 60–82) × Lag (0, 1, 2, 3) analysis of variance (ANOVA) on the data from the 1,000 ms presentation duration condition. The Age, $F(2, 237) = 9.06$, $MS_e = 340.02$; Lag, $F(3, 711) = 244.48$, $MS_e = 98.73$, and Age × Lag, $F(6, 711) = 6.34$, $MS_e = 98.73$, effects were all significant, and Age ANOVAs on each lag revealed significant age effects on Lags 0 and 1 but not on Lags 2 or 3. The absence of significant age effects with longer lags is probably not very meaningful, however, because the reliabilities of the measures at long lags are quite low. Large age relations cannot be expected if the variables have little systematic variance that can be related to other variables. The Age × Lag interaction was not significant in an ANOVA with only Lags 0 and 1.

Mean levels of accuracy at each presentation time for subjects in four (including students) age groups are displayed in Figure 3. As expected, accuracy was lower with increased age and with shorter presentation time. Furthermore, accuracy at Lag 1 was consistently lower than accuracy at Lag 0. An Age (19–39, 40–59, 60–82) × Lag (0, 1) × Time (150, 300, 450, 600, 750 ms) ANOVA revealed that all main effects and interactions were significant except for the triple interaction of Age × Lag × Time. Age × Lag ANOVAs at each time revealed that the lag effects were significant at all times, the age effects were significant at the 450, 600, and 750 ms times, but the Age × Lag interaction was significant only at the 750 ms time. This latter interaction was attributable to larger age differences at Lag 0 than at Lag 1.

A series of hierarchical regression analyses was conducted to examine relations among the accuracy measures at Lags 0 and 1 across all presentation times. Separate regression equations were created for each of the variables in Figure 4 with predictors in the following order: variable to the left, variable above, speed (composite RT measure), and age. For example, predictors for accuracy at Lag 1 with 450 ms presentation time were accuracy at Lag 0 with 450 ms, accuracy at Lag 1 with 300 ms, speed, and age. Nonsignificant predictors were then dropped from the equation, and standardized regression coefficients were determined for the significant predictors of each variable. The significant coefficients are displayed in Figure 4. The fit of the complete model was not very good: χ^2 (69, $N = 240$) = 292.93, adjusted root-mean-square error (RMS) = .1118; adjusted population $\Gamma = .8331$; adjusted goodness-of-fit index (GFI) = .7857). However, the standardized residuals for all relations involving both age and speed were quite small, suggesting that these variables were probably not responsible for the unimpressive fit.

As expected, there were significant relations between accuracy at Lag 0 and accuracy at Lag 1 for every presentation time

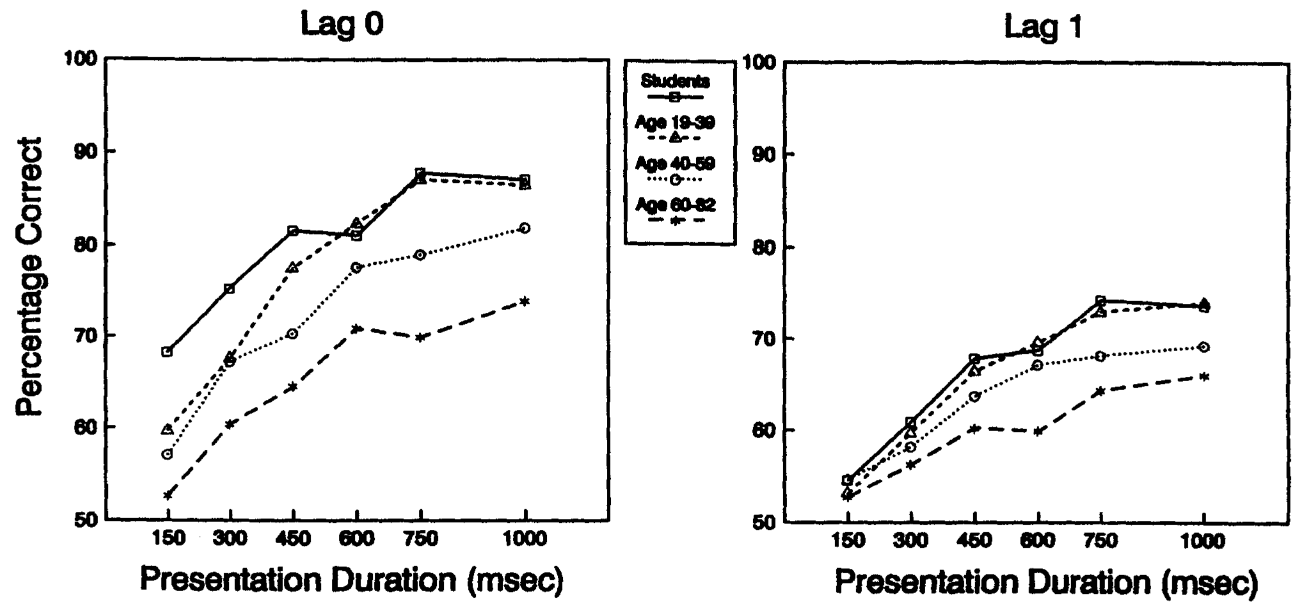

Figure 3. Percentage correct in associative memory as a function of stimulus presentation time for students and adults, Study 1.

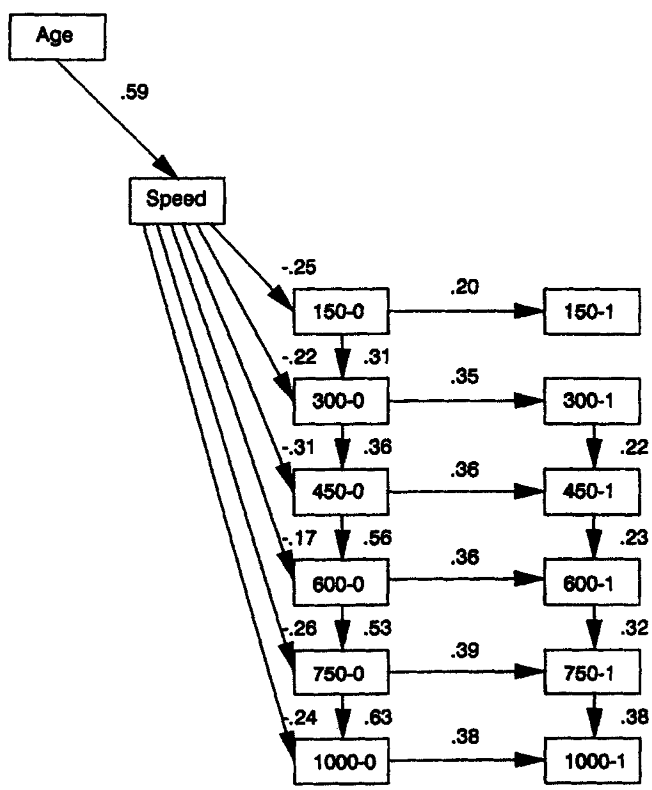

Figure 4. Relations among age, speed, and accuracy at Lags 0 and 1 for each presentation time in the adult sample, Study 1. Variables are labeled by presentation time and lag so that, for example, 750-1 refers to Lag 1 with the 750 ms presentation duration.

and between accuracy at adjacent presentation times for each lag (except Lag 1 with 150 and 300 ms presentation times). Of particular interest were the relations from speed and age. It can be seen that speed was not related to accuracy at Lag 1 and instead exerted its effects through accuracy at Lag 0. The apparent implication is that speed does not contribute to the loss of accuracy from Lag 0 to Lag 1 after its effects on Lag 0 are controlled. The fact that the speed relations were significant on each Lag 0 variable even after controlling the influence of Lag 0 accuracy with the next shorter presentation time suggests that there were unique or independent effects of speed at each successive presentation time.

The most important result from Figure 4 is that there were no direct effects of age on any of the associative memory variables. That is, when speed and accuracy in other associative memory conditions were entered as predictors before age, there was no unique influence of age on associative memory. Instead, all of the age-related variance in associative memory appears to be mediated through the index of processing speed.

Associative learning. Table 5 indicates that age was significantly related to several measures of associative learning performance. Means across successive age groups for the trials-to-criterion and percentage correct measures were 8.6 and 51.3%, respectively, for ages 19 to 39; 9.2 and 41.1%, respectively, for ages 40 to 59; and 9.7 and 31.5%, respectively, for ages 60 to 82.

The probability of forgetting previously correct responses also increased with age. Mean percentages for successive age groups were 31.2% for adults between ages 19 and 39, 43.0% for adults between ages 40 and 59, and 55.9% for adults between ages 60 and 82. The relative frequency of perseveration responses was low, but these errors also increased with increased age. Means for successive age groups were 6.5% for ages 19 to 39, 9.8% for ages 40 to 59, and 12.4% for ages 60 to 82. Perseverations are an interesting type of error because the fact that the response is the same as that produced the last time this stimulus was presented suggests that some information was retained but apparently not the information that the response was incorrect. The higher proportion of perseverations with increased age may be due to a greater tendency to respond on the basis of idiosyncratic associations to physical characteristics of the symbols. Because the placement of the response symbols varied from trial to trial, these errors cannot be attributed to position biases.

Correlations among the frequencies of the three types of errors were .38 between forgetting and perserverations, −.12 between forgetting and discrimination failure, and −.06 between perserverations and discrimination failures. This pattern is very similar to the results with the student data, even with respect to the low reliability of the discrimination failures.

The proportion of variance associated with age in prediction of the trials-to-criterion measure was .080, but this was reduced to .007 after the measure of forgetting was controlled. Forgetting therefore appears to be a key factor in the age differences in associative learning.

Hierarchical regression analyses. Results of hierarchical regression analyses illustrating the proportion of age-related variance before and after control of various measures of speed are displayed in Table 6. Notice that there was a large attenuation of the age-related variance in nearly all variables after control of the speed measures. To illustrate, for the primary measure of trials-to-criterion, the R^2 for age when it was considered alone was .080, and this was reduced to .016 after control of the RT speed measure. Because many subjects had scores at the ceiling of 10, the measure of percentage correct in the first four trials is probably a more sensitive measure of associative learning in this task. Age was associated with 16.5% of the variance in this measure when age was the only predictor, but with only 3.2% of the variance when age was entered in the regression equation after the RT speed measure.

It is also apparent in Table 6 that the reduction in age-related variance is generally greater when the speed measures have more cognitive involvement. That is, the residual age-related variance is smaller in 8 of 10 comparisons involving associative memory and associative learning variables with the perceptual speed measure compared with the motor speed measure, and it is smaller in 10 of 10 comparisons with the Digit Symbol measure in comparison with the Digit Digit measure. However, the degree of attenuation of the age-related variance was not noticeably greater for the substitution (Digit Symbol–Digit Digit) measure. This was surprising because the substitution difference score might have been expected to provide a purer index of cognitive processing speed. It is possible that, rather than reflecting the time to access previously learned associations in memory, this score represents a relatively peripheral process of visually searching the code table.

Path analysis. The model-testing procedure in fitting the data of the adult sample is summarized in Table 4. The initial model was identical to the final model for the students after a path was added from age to speed. This model did not provide a very good fit, and thus the paths from age or speed that could be altered to improve the fit were determined by examining the matrix of standardized residuals. The final model, Model 7, is displayed in Figure 5. The fit of the final model with the composite paper-and-pencil speed measures was similar: χ^2 (18, N = 240) = 35.93 with the perceptual speed composite and χ^2 (18, N = 240) = 40.04 with the motor speed compos-

Table 6
Age-Related Variance Before and After Control of Various Speed Measures (n = 240), *Study 1*

		R^2 for age after control of:					
		Computer				Paper and pencil	
Variable	Age alone	*DD*	*DS*	*RTSpd*	*Sub*	*MSpd*	*PSpd*
Paper and pencil MSpd	.277*	.096*	.088*	.071*	.180*	—	.053*
Paper and pencil PSpd	.323*	.101*	.052*	.052*	.141*	.091*	—
RT speed	.348*	.015*	.003	—	.107*	.134*	.071*
Substitution	.213*	.109*	.004	.009	—	.117*	.044*
Associative Memory							
Lag 0 (150,300)	.045*	.007	.000	.001	.007	.005	.003
Lag 0 (600,750)	.120*	.022	.006	.006	.038*	.033*	.002
Lag 1 (600,750)	.077*	.030*	.005	.010	.016	.022	.005
Lag 0 (1,000)	.123*	.012	.005	.002	.045*	.033*	.003
Lag 1 (1,000)	.052*	.013	.001	.002	.009	.017	.001
Lag 2 (1,000)	.025	.005	.000	.000	.004	.005	.000
Associative Learning							
Trials-to-criterion	.080*	.025	.019	.016	.045*	.018	.023
% correct	.165*	.051*	.038*	.032*	.091*	.068*	.059*
% forget	.129*	.032*	.030*	.022	.079*	.073*	.044*
% perseverations	.131*	.054*	.053*	.044*	.095*	.071*	.089*

Note. DD refers to Digit Digit, DS to Digit Symbol, RTSpd to the average of the *z* scores from Digit Digit and Digit Symbol, Sub to the difference between Digit Symbol and Digit Digit. MSpd is the average of the *z* scores from Boxes and Digit Copy, and PSpd is the average of the *z* scores from Letter Comparison and Pattern Comparison.
*p < .01.

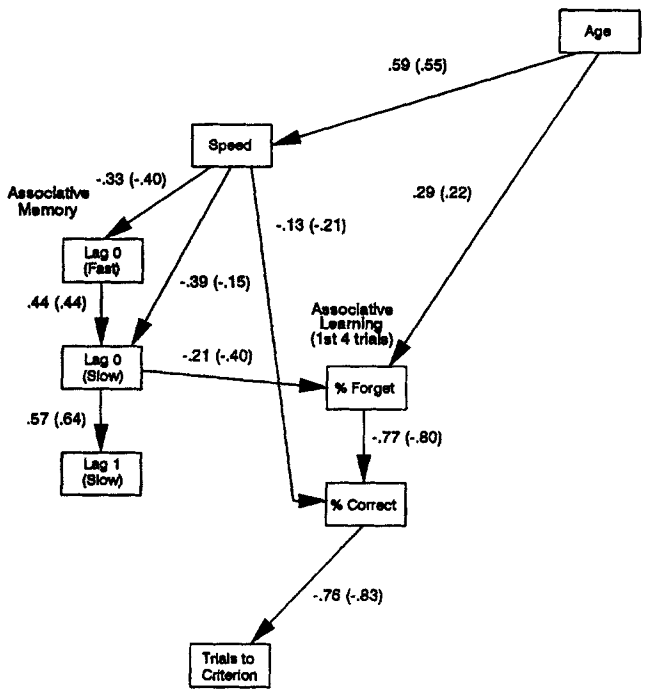

Figure 5. Path model indicating relations among variables in the adult data. Values in parentheses are coefficients from Study 2. All coefficients are significantly different from 0.

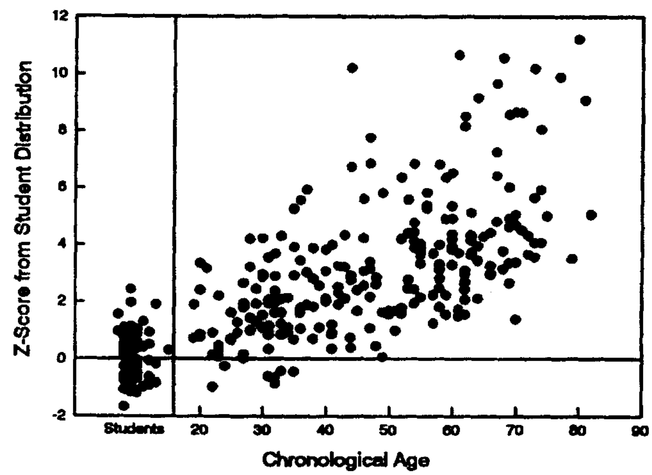

Figure 6. Reaction time speed scores in standard deviations of the student distribution, Study 1.

ite—although it was somewhat poorer with the substitution speed measure—χ^2 (18, N = 240) = 46.80, all ps < .01.

A primary difference from the model for the student data is the existence of direct relations from speed to accuracy at Lag 0 with the slow (1,000 ms) presentation time and from speed to percentage correct in associative learning. These additional linkages may be a consequence of the greater range of speed in the adult sample (discussed here later).

There is also evidence of a direct age-related influence, independent of speed, on percentage forgetting. Comparison of the initial and residual age-related variance in percentage forgetting after control of the speed measures in Table 6 suggests that between 17% and 35% of the age-related variance in the forgetting measure is independent of the RT speed and perceptual speed measures. An explanation distinct from speed therefore appears to be needed to account for at least some of the age-related influences on forgetting in the Associative Learning task.

Speed variability. To examine the variability of the speed measures, the RT speed scores for both the student and the adult samples were converted to standard deviations of the student distribution. These scores are plotted as a function of age in Figure 6. It is clear from this figure that the variance in the speed measures was considerably greater in the adult sample than in the age-restricted sample of students.

Summary

A major finding of this study was that age and speed do not affect associative learning directly but instead exert their effects through a series of indirect influences. Furthermore, the pattern of influences or relations is consistent with the proposed interpretation. That is, increased age is associated with a slower speed of processing, which is related to lower accuracy in immediate tests in associative memory, particularly when presentation times are brief. Lower accuracy in associative memory is related to more frequent forgetting in associative learning, which is related to lower accuracy across the first four trials, which is related to a greater number of trials to reach the criterion in associative learning.

Study 2

The primary purpose of the second study was to replicate and extend the major results of Study 1. In addition, several new questions were addressed. One was whether the speed influence on associative learning occurred because of the relatively brief duration of the feedback indicating the correct response (1.5 s). This question was investigated by using a self-paced duration for the presentation of feedback in the associative learning task. A second question was whether the speed influence on associative memory would be eliminated with self-paced stimulus presentation durations. Addition of a self-paced condition in associative memory allowed this question to be examined. The third question was whether the relations between associative memory accuracy at short presentation durations and the other measures would be stronger if the measure of accuracy at short durations were more reliable. This was addressed by increasing the number of observations at each presentation duration.

A fourth question was whether some of the relation between speed and measures of associative learning performance might be due to associative learning in the Digit Symbol task. This issue was investigated in two distinct ways. First, the associative learning task was moved to the beginning of the session, and then the same pairings of digits and symbols from the Associative Learning task were used in the Digit Symbol task. It was expected that this manipulation would reduce the associative learning component in the Digit Symbol task and thus possibly provide a purer measure of processing speed.

A second method of investigating the role of associative learning in the Digit Symbol task involved administering another set of Digit Digit and Digit Symbol speed tests at the end of the session, with different pairings of the digits and symbols. The contrast with performance after associative learning should be informative about whether the same factors contribute to performance in the Digit Symbol task when the relevant associations have been learned. That is, if the correlation between the Digit Symbol measures before and after associative learning is high relative to the reliabilities of the measures, one could conclude that similar processes are involved. Another associative learning test was administered after the Digit Symbol test, with the same digit symbol pairs, to allow an examination of the amount of incidental learning of the associations during the performance of the Digit Symbol task.

Other changes introduced from the procedure of Study 1 were as follows. The same stimuli (digits and symbols) were used in all tasks instead of, as was the case in Study 1, digits and symbols in the Digit Symbol task, letters and digits in the Associative Memory task, and symbols and symbols in the Associative Learning task. A smaller set of presentation times was used in the Associative Memory task to allow more trials at each time in an attempt to increase reliability. Only Lags 0 and 1 were used in the Associative Memory task because measures of performance in Lags 2 and 3 were not reliable in Study 1. The number of trials in the first set of practice trials in the Associative Learning task was reduced to avoid fatigue. And fewer stimulus pairs were used in the initial Associative Learning task because only a small percentage of subjects achieved the learning criterion in Study 1. In all other respects, however, the tasks were similar to those of Study 1.

Method

Subjects

Descriptive characteristics of the samples of 67 students and 125 adults who participated in this study are summarized in Table 1.[3] It should be noted that the average amount of education for the adults in this study was greater than that in Study 1 (i.e., 15.5 years vs. 13.9 years). Nevertheless, the correlation between age and amount of education was only .03, and that between age and health was .11.

Procedure

All subjects performed the tasks in the following order: Boxes, Pattern Comparison, Letter Comparison, Digit Copying, Associative Learning, Digit Digit, Digit Symbol, Digit Symbol, Digit Digit, Associative Memory, Digit Digit, Digit Symbol, Digit Symbol, Digit Digit, and Associative Learning.

The paper-and-pencil speed tests were identical to those described in Study 1. The procedure for the Digit Digit and Digit Symbol trials was also similar to that of Study 1 except that only eight pairs of digits and digits, or digits and symbols, were used in this study. The digit–symbol pairs in the first administration of the task were the same as those learned in the first Associative Learning trials. When the task was administered at the end of the session, the pairings of digits and symbols were different from the earlier pairs but identical to those used in the Associative Learning task that followed this task.

The procedure in the Associative Learning task was similar to that of Study 1 except that the first (practice) set of trials contained a maximum of three complete sequences with letter and digit stimuli, and the next two sets contained four digits (i.e., 1, 3, 5, and 7 in the first set, and 2, 4, 6, and 8 in the second set), each with four different symbols. The associative learning trials administered at the end of the session consisted of a single set of eight digits and eight symbols to allow an assessment of the amount of incidental learning during the most recent Digit Symbol trials. The digits and symbols in this version of the task were the same as those used in the other tasks in the study, and the pairings were the same as those from the immediately preceding Digit Symbol task but different from those used in the initial Associative Learning and Digit Symbol tasks.

The Associative Memory task was also similar to that of Study 1 except that the stimuli were the same digits and symbols used in the Associative Learning and Digit Symbol tasks. In this task, however, the pairings of digits and symbols continuously changed from trial to trial instead of remaining constant as in the other tasks. All trial blocks had 16 tests at Lag 0 and 16 tests at Lag 1. The blocks were presented in the sequence of self-paced, 750 ms, 500 ms, and 250 ms, and then the same presentation times again in the reverse order.

Results and Discussion

Student Data

Means, standard deviations, and estimates of the reliabilities for all measures are presented in Table 7. As anticipated, reliabilities of the associative memory measures were higher than those in Study 1, although they were still only in the low-to-moderate range.

There was little evidence of a between-subjects speed–accuracy trade-off in the RT tasks because the correlations between time and accuracy were generally small (i.e., initial Digit Digit = .23, final Digit Digit = .28, initial Digit Symbol = −.05, and final Digit Symbol = −.06). To maximize comparability with Study 1, the Digit Digit and Digit Symbol scores from the first administrations of these tasks were used to form the composite RT speed measure. Correlations among the original and composite speed measures are presented in Table 3, where it can be seen that the patterns are generally similar to those of Study 1.

Correlations were also computed between the RT speed measures at the beginning of the session, after an opportunity to learn the digit–symbol associations in the Associative Learning task, and at the end of the session, before having a chance to learn the relevant associations. The correlations were .82 for the Digit Digit measure and .57 for the Digit Symbol measure. This latter correlation is not very high in relation to its reliability (see Table 7), and therefore it appears that some of the variation in performance in the Digit Symbol task could be attributable to differential learning of the associations.

[3] Data from 2 subjects in the adult sample, one age 20 and one age 33, were excluded because they were outliers on the RT speed measure (i.e., greater than 3.5 studentized residuals) and also had extreme scores on several other variables.

Table 7
Descriptive Statistics of Major Variables for 67 Students, Study 2

Variable	*M*	*SD*	Estimated reliability
Paper and pencil speed tests			
Boxes	60.4	12.2	.92
Digit Copy	58.3	7.4	.92
Letter Comparison	12.0	2.6	.70
Pattern Comparison	20.7	3.1	.46
Computer speed tests			
After Associative Learning 1			
Digit Digit RT	539	53	.80
Digit Symbol RT	920	156	.80
Digit Digit % correct	96.6	2.2	.47
Digit Symbol % correct	95.9	3.4	.45
Substitution (Digit Symbol RT–Digit Digit RT)	381	137	.76
Before Associative Learning 2			
Digit Digit RT	514	48	.92
Digit Symbol RT	1120	180	.85
Digit Digit % correct	95.6	3.6	.70
Digit Symbol % correct	93.7	4.5	.77
Substitution (Digit Symbol RT–Digit Digit RT)	606	163	.82
Associative Memory			
Lag 0 (Self-paced time)	767	344	.70
Lag 1 (Self-paced time)	773	334	.64
Lag 0 (Self-paced)	90.8	8.3	.60
Lag 1 (Self-paced)	74.4	13.9	.60
Lag 0 (750)	87.3	8.6	.44
Lag 1 (750)	68.2	12.3	.68
Lag 0 (500)	83.4	9.6	.55
Lag 1 (500)	62.7	9.7	.17
Lag 0 (250)	76.8	11.4	.52
Lag 1 (250)	58.0	11.0	.36
Associative Learning			
Before Digit Symbol			
Trials-to-criterion	6.7	1.8	.37
First four trials			
% correct	69.3	15.4	.62
% forget	18.3	18.0	.44
Other error %			
Unsuccessful guesses	67.4	18.0	.06
Discrimination failures	11.3	11.6	0
Perseverations	3.7	6.0	.13
% correct Trial 1	37.7	20.9	—
After Digit Symbol			
Trials-to-criterion	6.4	2.7	—
First four trials			
% correct	82.2	21.9	—
% forget	11.8	16.3	—
Other error %			
Unsuccessful guesses	31.7	30.5	—
Discrimination failures	19.4	25.9	—
Perseverations	3.7	6.5	—
% correct Trial 1	74.6	30.5	—

Note. RT = response time.

Associative memory. The average inspection time for the stimulus pairs in the self-paced condition in the Associative Memory task was 770 ms. As can be seen in Table 7, accuracy in this condition was slightly higher than in the 750 ms presentation time condition. Accuracy decreased as presentation time decreased, and Lag 1 accuracy was always about 15% to 20% lower than accuracy with Lag 0.

Associative learning. Correlations between the different types of errors were .45 between percentage forgetting and perseverations, .24 between forgetting and discrimination failures, and .04 between perseverations and discrimination failures. This pattern of correlations is very similar to that reported in Study 1.

Table 7 indicates that accuracy on the first exposure to associative learning after performing the Digit Symbol task was about 75%. It can therefore be inferred that substantial incidental learning of the associations occurred during the Digit Symbol task. Comparisons with accuracy on the first exposure in associative learning prior to performing the Digit Symbol task (at the beginning of the session) are complicated because the eight pairs were presented in two blocks of four each rather than, as was the case in the Associative Learning task at the end of the session, in a single block containing all eight pairs. Despite these differences, accuracy was only about one half as high (i.e., 37.7%) when the pairs were tested before performing the Digit Symbol task.

Path analysis. The 250 ms presentation time condition was used as the fast presentation time in associative memory, and the self-paced condition was used as the slow presentation time. The model derived to fit the student data in Study 1 was found to provide an adequate fit to these data (see Table 4). Parameters from the model applied to the data of this study are contained in parentheses in Figure 3. Similar fits were obtained with the other speed measures—χ^2 (15, N = 67) = 19.07 with the perceptual speed composite, χ^2 (15, N = 67) = 20.83 with the motor speed composite, and χ^2 (15, N = 67) = 28.82 with the substitution speed measure.

The primary difference from Study 1 is that in this study the path from speed to accuracy at Lag 0 with fast presentation time was not significantly different from 0. This discrepancy is puzzling because examination of Tables 2 and 7 reveals that the variances in the two samples were similar for the speed and Lag 0 (fast) accuracy measures.

Adult Data

Means, standard deviations, estimated reliabilities, and age correlations for all variables are summarized in Table 8. Each of these variables was examined for nonlinear age trends and for interactions between age and gender, health, and education. None of these effects was significant. As in Study 1, variables with higher reliabilities tended to have larger correlations with age (i.e., r = .51).

There was little evidence of a between-subjects speed–accuracy trade-off because the correlations between time and accuracy were small (i.e., initial Digit Digit = .09, final Digit Digit = .09, initial Digit Symbol = −.19, and final Digit Symbol = −.11). Correlations among the original and composite speed measures are presented in Table 3. As in Study 1, the correlations are higher in the adult sample than in the student sample.

The correlation between the initial and final Digit Digit speed measure was .81, and that between the initial and final Digit Symbol speed measure was .80. These values are higher than those from the student sample, but they are still lower than the reliabilities of the measures.

Additional analyses were conducted to determine whether there was unique or independent age-related variance in the

Table 8
Descriptive Statistics of Major Variables for 125 Adults, Study 2

Variable	M	SD	Estimated reliability	Age correlation
Paper and pencil speed tests				
Boxes	47.5	12.6	.95	−.12
Digit Copy	49.0	9.4	.95	−.34*
Letter Comparison	9.7	2.7	.80	−.43*
Pattern Comparison	15.3	3.6	.77	−.58*
Computer speed tests				
After Associative Learning 1				
Digit Digit RT	712	157	.78	.47*
Digit Symbol RT	1465	435	.94	.56*
Digit Digit % correct	97.8	1.8	.37	.10
Digit Symbol % correct	96.7	2.5	.57	−.02
Substitution (Digit Symbol RT–Digit Digit RT)	754	332	.86	.51*
Before Associative Learning 2				
Digit Digit RT	659	116	.91	.52*
Digit Symbol RT	1562	414	.97	.43*
Digit Digit % correct	97.6	2.2	.44	.15
Digit Symbol % correct	95.4	6.0	.91	−.09
Substitution (Digit Symbol RT–Digit Digit RT)	903	339	.95	.35*
Associative Memory				
Lag 0 (Self-paced time)	1224	699	.82	.23*
Lag 1 (Self-paced time)	1208	686	.88	.24*
Lag 0 (Self-paced)	86.5	13.6	.68	−.09
Lag 1 (Self-paced)	71.0	15.5	.77	−.11
Lag 0 (750)	78.8	14.5	.74	−.17
Lag 1 (750)	63.1	11.3	.46	−.06
Lag 0 (500)	76.3	13.7	.77	−.19
Lag 1 (500)	59.8	11.5	.40	−.14
Lag 0 (250)	69.0	13.2	.66	−.29*
Lag 1 (250)	57.2	9.4	.06	−.08
Associative Learning				
Before Digit Symbol				
Trials-to-criterion	7.5	2.2	.70	.32*
First four trials				
% correct	60.5	21.0	.66	−.34*
% forget	30.2	27.2	.65	.26*
Other error %				
Unsuccessful guesses	60.3	21.6	.41	−.24*
Discrimination failures	9.9	11.9	.32	.26*
Perseverations	8.4	10.9	.54	.20
% correct Trial 1	37.5	16.6	—	−.14
After Digit Symbol				
Trials-to-criterion	8.7	2.1	—	.26*
First four trials				
% correct	56.0	26.2	—	−.35*
% forget	32.4	27.7	—	.25*
Other error %				
Unsuccessful guesses	46.0	25.4	—	.22
Discrimination failures	15.1	13.1	—	.03
Perseverations	8.2	9.3	—	.19
% correct Trial 1	45.3	31.5	—	−.34*

Note. Estimated reliability computed from Spearman-Brown formula. Negative reliability estimates replaced by value of 0.
*$p < .01$.

two Digit Symbol measures. The Digit Symbol score before Associative Learning (at the end of the session) was therefore predicted from the Digit Symbol score after Associative Learning (at the beginning of the session). The R^2 for age when age was the only predictor in the regression equation was .188, but it was .000 when Digit Symbol score after Associative Learning was controlled. All of the age-related variance in the Digit Symbol task when it was performed before learning the digit–symbol pairs is therefore shared with the variance in the Digit Symbol task when it is performed after having an opportunity to learn the pairs. The apparent implication is that associative learning is not an important factor contributing to age-related effects in Digit Symbol performance. A similar conclusion was reached by Salthouse and Kersten (1993) on the basis of different types of analyses.

Associative memory. Figure 7 displays the mean levels of accuracy for Lags 0 and 1 at each presentation time for subjects in four age groups. It is apparent in this figure that there were large age differences in the average time taken to inspect the stimulus pairs in the self-paced condition. Furthermore, there were no significant age differences in accuracy in this condition (see Table 8). With shorter presentation times, age differences in accuracy do emerge, but they are relatively small, and none except for that for Lag 0 at the shortest presentation time was statistically significant.

The only significant effects in an Age (20–39, 40–59, 60–89) × Lag (0, 1) × Time (250 ms, 500 ms, 750 ms, self-paced) ANOVA were Lag, $F(1, 122) = 438.18$, $MS_e = 126.91$; and Time, $F(3, 336) = 103.46$, $MS_e = 100.12$. Separate Age × Lag ANOVAs at each time revealed significant lag effects at all times, and a significant Age × Lag interaction at the 250 ms time but no significant age effects. These results differ from those of Study 1, where significant age effects were found at presentation times of 450, 600, and 750 ms. One possible explanation for the discrepancy is the different average levels of education in the samples from the two studies (discussed here later).

Results of the series of hierarchical regression analyses with accuracy at the shorter lag, accuracy at the shorter presentation time, speed (RT composite), and age as predictors of each associative memory variable are summarized in Figure 8. The fit of the complete model was good—$\chi^2(34, N = 125) = 63.97$; adjusted RMS = .0800; adjusted population $\Gamma = .9583$; adjusted GFI = .8565. These results resemble those of Study 1 (Figure 4) in that age was only related to speed, and speed was only related to accuracy at Lag 0. Speed was not directly related to Lag 0 accuracy in the self-paced condition, perhaps because subjects were able to compensate for a slower speed of processing by spending more time inspecting the stimulus pairs.

Associative learning. Correlations among the associative learning errors were .58 between forgetting and perseverations, −.04 between forgetting and discrimination failures, and .10 between perseverations and discrimination failures. This pattern is similar to that found in the student samples in both studies and in the adult sample in Study 1.

The proportion of age-related variance in the trials-to-criterion measure was .104, but it was only .019 after the forgetting measure was controlled. This finding replicates the similar result from Study 1 and again suggests that forgetting is a key factor in the age differences in associative learning.

The significant age effects on percentage correct on the first associative learning trial after the Digit Symbol task (i.e., last entry in Table 8) indicates that older adults exhibited less incidental learning of the associations during the Digit Symbol task. A similar finding was reported by Salthouse and Kersten

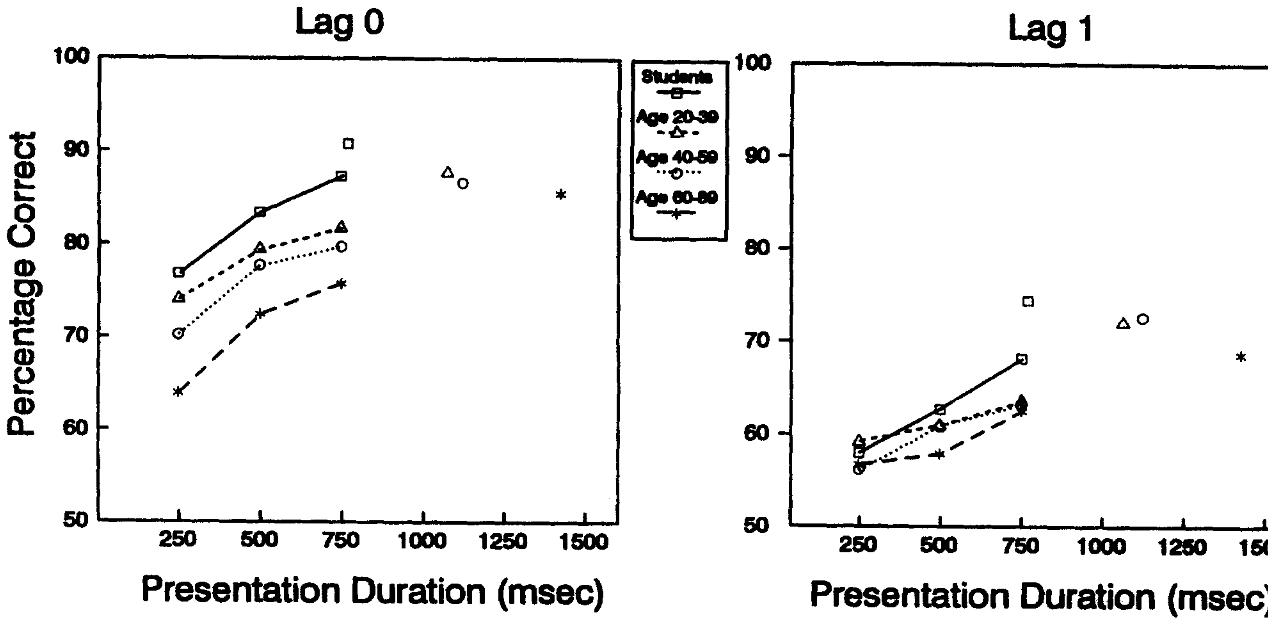

Figure 7. Percentage correct in associative memory as a function of stimulus presentation time for students and adults, Study 2. Unconnected symbols represent data from the self-paced condition.

(1993). Accuracy on the first associative learning trial before performing the Digit Symbol task was somewhat lower, and the correlation of this measure with age was not significant.

Hierarchical regression analyses. Results of the hierarchical regression analyses after control of the speed measures are summarized in Table 9. As in Study 1, the speed influences were widespread. For example, the age-related variance in the trials-to-criterion measure was reduced from .104 to .058 after control of RT speed, and in the percentage correct measure it was reduced from .117 to .044.

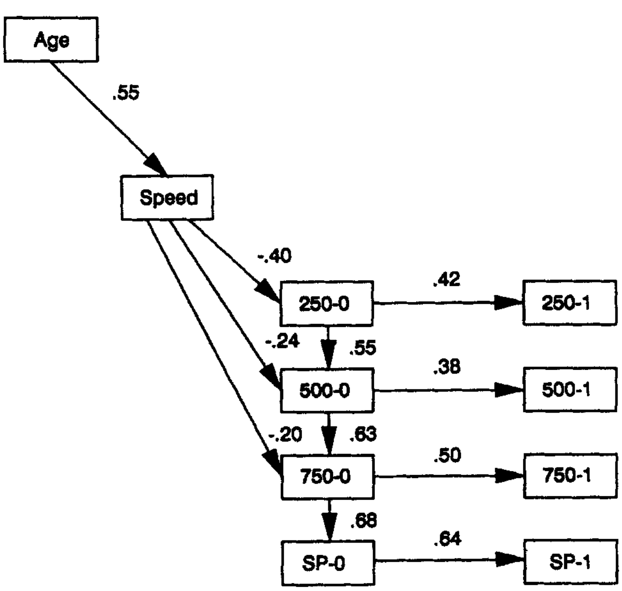

Figure 8. Relations among age, speed, and accuracy at Lags 0 and 1 for each presentation time in the adult sample, Study 2.

The amount of residual age-related variance in the associative memory and associative learning variables was smaller after control of perceptual speed than after control of motor speed in 11 of 12 comparisons. It was smaller after control of Digit Symbol than after control of Digit Digit in 6 of 10 comparisons (with two ties).

Path analysis. The model derived from the adult data in Study 1 provided an adequate fit to the data of this study (see Table 4). Parameters for the model applied to the current data, displayed in parentheses in Figure 5, were generally quite similar to those from Study 1. Models with the composite perceptual speed index (i.e., χ^2 [18, N = 125] = 50.89) and the substitution speed measure (i.e., χ^2 [18, N = 125] = 52.32) had similar fits, but the model could not be fit with the composite motor speed measure without altering several paths because of the weak relations between this speed measure and the measures from the Associative Memory and Associative Learning tasks.

Speed variability. As in Study 1, there was much greater variability in the speed measures among the sample of adults than among the students. Figure 9 illustrates the composite RT scores of all participants in this study expressed in standard deviation units of the student distribution. The pattern is nearly identical to that observed in Study 1 in that there is a systematic shift toward higher scores with increased age.

General Discussion

Before discussing implications of the current results, it is important to point out that very similar patterns were evident in the two studies despite different samples, stimuli, and

Table 9
Age-Related Variance Before and After Control of Various Speed Measures (n = 125), Study 2

Variable	Age alone	R^2 for age after control of: Computer DD	DS	RTSpd	Sub	Paper and pencil MSpd	PSpd
Paper and pencil MSpd	.065*	.023	.010	.011	.016	—	.003
Paper and pencil PSpd	.320*	.085*	.052*	.045*	.083*	.198*	—
RT speed	.304*	.007*	.004	—	.036*	.241*	.034*
Substitution	.213*	.037*	.003	.000	—	.157*	.013
Associative Memory							
Lag 0 (250)	.085*	.019	.008	.007	.016	.064*	.008
Lag 0 (500)	.035	.000	.008	.006	.002	.023	.001
Lag 0 (750)	.030	.001	.013	.012	.005	.016	.003
Lag 0 (Self-paced)	.008	.000	.005	.004	.003	.005	.002
Lag 1 (250)	.007	.000	.000	.000	.002	.007	.000
Lag 1 (500)	.019	.000	.000	.000	.000	.026	.004
Lag 1 (750)	.003	.002	.007	.008	.004	.000	.009
Lag 1 (Self-paced)	.013	.001	.000	.000	.000	.013	.000
Associative Learning							
Trials-to-criterion	.104*	.078*	.050*	.058*	.052*	.097*	.051*
% correct	.117*	.062*	.042	.044	.051*	.099*	.049
% forget	.067*	.052*	.035	.039	.036	.057*	.043
% perseverations	.039	.028	.017	.020	.019	.022	.004

Note. DD refers to Digit Digit, DS to Digit Symbol, RTSpd to the average of the *z* scores from Digit Digit and Digit Symbol, Sub to the difference between Digit Symbol and Digit Digit. MSpd is the average of the *z* scores from Boxes and Digit Copy, and PSpd is the average of the *z* scores from Letter Comparison and Pattern Comparison.
*$p < .01$.

variations in procedure. This was even true in the path analyses in which the structural models derived to fit the data of Study 1 were found to provide good fits to the independent data from Study 2. Moreover, it is possible that some of the differences that did occur across studies could have been attributable to differences in the average amount of education because this variable had significant correlations with measures of associative learning and memory performance (e.g., the correlations between education and associative memory accuracy at Lag 0 in the slow presentation duration were .24 in Study 1 and .25 in Study 2).

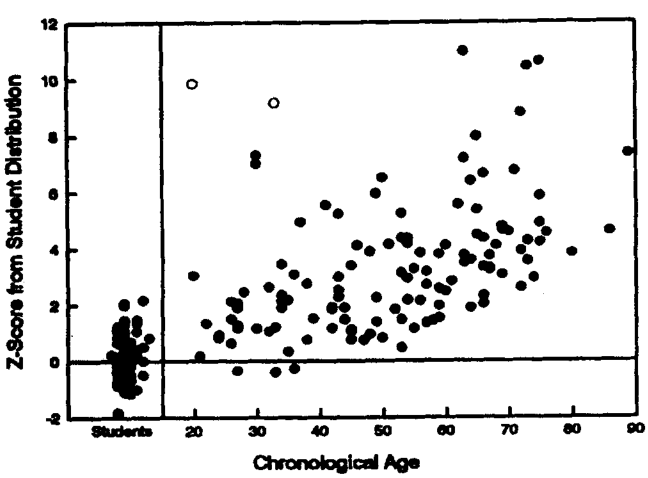

Figure 9. Reaction time speed scores in standard deviations of the student distribution, Study 2. Open circles indicate the two outliers who were omitted from the analyses.

As expected, a strong influence of speed on the relations between age and associative learning was confirmed in these studies. To illustrate, inspection of Tables 6 and 9 reveals that the age-related variance in the trials-to-criterion measure was reduced after control of the RT speed measure by 80% in Study 1 and by 44% in Study 2. Comparable values with the percentage-correct measure across the first four trials were 81% attenuation in Study 1 and 62% attenuation in Study 2.

The results of these studies suggest that much of the influence of age on associative learning is due to a failure to retain relevant information from one presentation or trial to the next. That is, when percentage forgetting was controlled, the residual age-related variance in trials-to-criterion measure was not significant in either study and was reduced by 91.3% (from R^2 of .080 to .007) in Study 1 and by 81.7% (from R^2 of .104 to .019) in Study 2. Results from the Associative Memory tasks suggest that a major reason for the poorer retention with increased age in associative learning is that relevant information was never adequately registered or encoded.

At least some of the encoding difficulty may be related to a slower speed of processing, which could reduce the amount of elaboration, or formation of associations to other information, that can be accomplished within the available time. The functions relating accuracy to presentation time in Figures 3 and 7 indicate that accuracy is higher for younger adults at every time. It can therefore be inferred that with increased age there is less of an opportunity to conduct additional processing on the stimulus information because of the longer duration for the initial processing. For example, if subsequent processing is only effective if the initial processing yields an accuracy at Lag 0 of at least 80%, then the results in Figure 3 suggest that the average adult over the age of 60 would not be able to engage in more extensive processing with stimulus presentation times of less than 1,000 ms.

The path analyses revealed an independent influence of age on the percentage forgetting measure in both studies. Although the residual age-related variance after control of the RT speed measure was not significantly greater than 0 (at $p < .01$) in either study (cf. Tables 6 and 9), in both cases the effects were significant with a more liberal significance criterion ($p < .05$). It therefore seems possible that a separate explanation, not involving speed, may be needed to account for at least some of the age-related influences on the measure of forgetting in the Associative Learning task. The mechanisms for the speed-independent age-related effects on forgetting are not yet clear, but lapses in attention or concentration during presentation or test is a possibility worth considering.

As expected from the results of previous studies, the speed influences were greater for the measures with more cognitive components (i.e., Perceptual Speed compared with Motor Speed, and Digit Symbol compared with Digit Digit). The speed involved in the mediation of relations between age and associative learning therefore seems to reflect cognitive processes more than sensory or motor processes.

A comparison of Figures 2 and 5 reveals that speed was related to more variables in the data from the adult samples than in the data from the student samples. Furthermore, the linkage between speed and accuracy at short presentation times was stronger in the adult sample than in the student sample. Two possibly related factors are likely contributing to these results. One is the much greater range of speed in the adult samples, as reflected by the patterns in Figures 6 and 9. Relations among two variables are often larger when the variation in one or both variables is not restricted. A second possibility is that speed could be a broader construct in the age-heterogeneous adult sample. For example, the correlations among the speed measures in Table 3 are higher in the adult sample than in the student sample. A similar finding has been reported in other studies (e.g., Birren, Riegel, & Morrison, 1962; Salthouse, 1993a, 1993b; White & Cunningham, 1987) and has been interpreted as a reflection of a more pervasive influence of speed with increased age. That is, whereas speed may have relatively local and discrete effects in a sample of young adults, the effects could be much more diffuse and widespread in a sample of age-heterogeneous adults.

Previous research has generally revealed small-to-nonexistent age differences in rate of forgetting using procedures similar to those of the Associative Memory task in the current project (e.g., Craik, 1971; Erber, 1978; Ferris, Crook, Clark, McCarthy, & Rae, 1980; LeBreck & Baron, 1987; Lehman & Mellinger, 1986; Poon & Fozard, 1980; Salthouse, 1992c; Wickelgren, 1975). Because few of the Age × Lag interactions were significant, and because there was no independent influence of age on Lag 1 accuracy after Lag 0 accuracy was controlled, the present results are consistent with those of earlier studies. However, significant age differences were found in the measure of forgetting in the Associative Learning task in both studies of the current project and in the reanalyses of the data from the Salthouse and Kersten (1993) study.

In attempting to account for these different outcomes, it is instructive to consider the procedures involved in the two types of forgetting assessment. Both tasks involved similar types of information (i.e., associations between pairs of letters, digits, or symbols), and recognition tests. In the Associative Memory procedure, forgetting is inferred from the decrease in accuracy as a function of number of intervening items across relatively short intervals between presentation and test. Forgetting in the Associative Learning task was assessed in terms of the percentage of times a correct response to a given stimulus on one trial was followed by an incorrect response to the same stimulus on the following trial. Because the interval between presentation and test in the Associative Learning test was longer than in the Associative Memory tests, the length of the retention interval is one factor that may be contributing to the different patterns of forgetting in the two measures of forgetting.

A second difference between the two sets of procedures was that the pairings continuously changed in the Associative Memory task but remained constant across trials in the Associative Learning task. This may have led to substantial accumulation of proactive interference in the Associative Memory task. However, because the age differences in forgetting were larger in the Associative Learning task than in the Associative Memory task, it seems unlikely that proactive interference was an important factor contributing to the different patterns of results in the two tasks.

A third factor that may be involved in the different patterns of age influences is the reliability of the forgetting measures. Forgetting in the Associative Learning task is reflected directly by the forgetting measure, and the reliability of this measure was .65 in both studies (cf. Tables 5 and 8). In the Associative Memory task, forgetting was represented by the difference in accuracy across lags. Estimates of the reliability of the Lag 0 − Lag 1 difference score can be computed for the slowest conditions (i.e., 1,000 ms and self-paced) in each study. These values, derived by boosting the correlation between the difference scores in each trial block by the Spearman-Brown formula, were .26 in Study 1 and .29 in Study 2. The low reliability of the Associative Memory measures therefore raises the possibility that the small-to-nonexistent age differences in this measure may be at least partially attributable to a lack of systematic variance available for association with other variables.

Conclusion

In summary, the results of these studies help explain the well-documented influence of speed on the relations between adult age and cognitive functioning. The focus in this project was on associative learning, and as with other cognitive measures, statistical control of measures of processing speed reduced the age-related variance by between 40% and 80%. The availability of detailed measures of associative learning and of associative memory allowed the influences of speed and age to be traced. On the basis of the hierarchical regression and path analysis results, it appears that speed primarily contributes to the effectiveness of encoding information in both associative memory and associative learning. The age-related effects in associative learning were largely mediated through this reduced effectiveness of encoding, although an independent influence of age may be evident on the probability of forgetting in the first four trials of associative learning. Finally, the discovery that meaningful and interesting results were obtained from relational analyses at the level of task components suggests that these types of methods should be pursued with other criterion tasks and with other types of individual differences.

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