Research Report

MEDIATION OF ADULT AGE DIFFERENCES IN COGNITION BY REDUCTIONS IN WORKING MEMORY AND SPEED OF PROCESSING

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Abstract—*Three studies, involving a total of 672 adults between 20 and 84 years of age, were conducted to evaluate the relative importance of working memory and perceptual comparison speed in the age-related differences in selected measures of cognitive functioning. The same measures of working memory and comparison speed were used in each study, but the studies differed in the specific cognitive measures examined. A common finding across all studies was that the magnitude of the age-related cognitive differences was greatly reduced by statistically controlling measures of working memory and perceptual comparison speed. Many of the age differences in process or fluid aspects of cognition therefore appear to be mediated by age-related reductions in working memory, which may in turn be largely mediated by age-related reductions in the speed of executing simple processing operations.*

Several recent articles have reported that adult age differences in various measures of cognitive functioning are either moderately (Salthouse, Kausler, & Saults, 1988; Salthouse & Mitchell, 1990) or substantially (Hertzog, 1989; Schaie, 1989) attenuated by statistical control of variables reflecting the speed of simple perceptual comparisons. Results of this nature are potentially of considerable importance because to the extent that age differences in moderately complex aspects of cognition are mediated by age-related differences at more elementary levels, the greatest progress in understanding the causes of age differences in cognition may be achieved by focusing on the causes and consequences of differences in these presumably basic processes.

Although the previous results have been fairly consistent, several characteristics of the earlier studies lead to questions about the generality and meaning of the linkages that seem to have been established among age, speed, and cognition. For example, in a number of studies the cognitive measures were derived from highly speeded tests in which it is likely that most of the variance in performance reflected the number of items attempted (which may be another manifestation of speed), rather than the percentage of attempted items successfully answered (which might provide a better estimate of cognitive power). A second problem is that in none of the studies cited above were there any attempts to explicate the mechanisms responsible for the speed–cognition relation.

The research reported here was designed to address both of these perceived limitations. An attempt was made to resolve the first problem by analyzing cognitive performance both in terms of the total number of items answered correctly, and in terms of the accuracy of the items attempted. Measures of working memory were also included to examine the possibility that speed of processing might exert its effects on cognition by altering the functioning of working memory.

Figure 1 is helpful in clarifying the primary question investigated in the current studies. Notice that several alternative pathways are portrayed that might be responsible for the negative relations between age and fluid or process aspects of cognition. A major goal of this research was to determine the relative importance of each of these pathways as determinants of the age–cognition relation.

Two analytical methods were used to evaluate the contribution of speed and working memory factors to the age differences in cognition. One method was hierarchical regression, in which the amount of age-related variance in cognition was examined before and after controlling the variance associated with the measures of perceptual comparison speed and working memory. The reasoning is that the difference between the two estimates of age-related variance can be used as an indication of the importance of the controlled variable in the age–cognition relation. The second analytical method was path analysis. This technique, assuming that the theoretical constructs are adequately represented by composite variables created by averaging z-scores for two or more measures intended to assess each construct, provides quantitative estimates of the magnitude of each of the structural coefficients portrayed in Figure 1. That is, the path coefficients indicate the amount of standard deviation change in one variable associated with a change of one standard deviation in another variable, after considering all other relations in the model.

METHOD

Subjects

Newspaper advertisements were used to recruit between 220 and 230 adults ranging from 20 to 84 years of age in each of three studies. Means (and standard deviations) of the ages in each study were: Study 1, 48.5 (17.4); Study 2, 50.3 (17.7); and Study 3, 49.2 (17.6). All participants were asked to report the number of years of education they had received, and to assess their own health status. Mean years of education in the three studies ranged between 15.3 and 15.6, and self-assessed health ratings averaged between 2.04 and 2.18 on a scale ranging from 1 for excellent to 5 for poor. Although health status was significantly correlated with age in Studies 1 and 2, there was little effect on the relations between age and cognition after adjusting for health and education by entering these variables first in a multiple regression equation. Health and education were therefore ignored in all subsequent analyses.

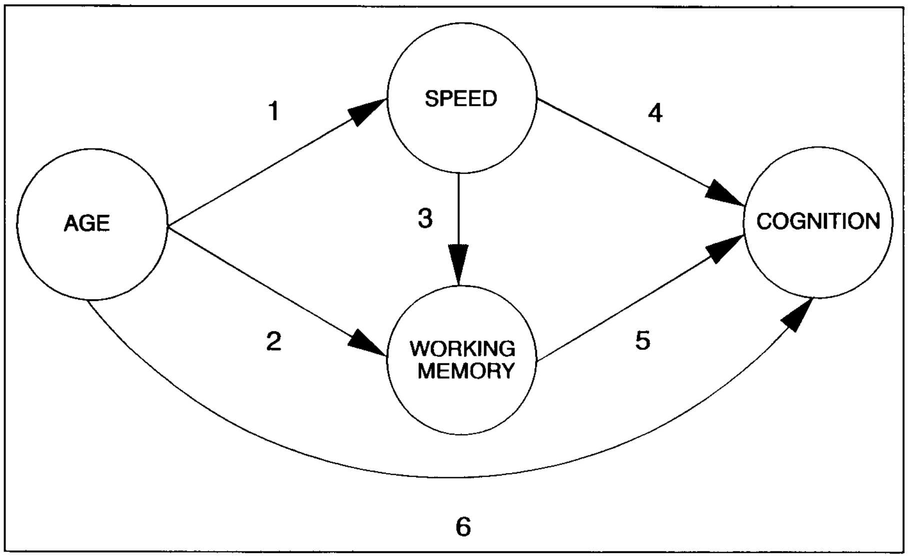

Fig. 1. Path diagram illustrating hypothesized relations among adult age, speed of processing, working memory, and fluid or process aspects of cognition.

Procedure

The tasks used to measure perceptual comparison speed and working memory were identical to those used in Study 2 of Salthouse and Babcock (1990). Comparison speed was measured with paper-and-pencil tasks requiring Same/Different decisions about pairs of three, six, or nine letters, and about pairs of patterns composed of three, six, or nine line segments. Three separately timed (20 sec each) trials were administered with each task, and the numbers of correct responses on each trial were averaged to produce a single score with each type (letter or pattern) of comparison. Correlations between the letter comparison and pattern comparison scores in the three studies of this project ranged from .74 to .80.

Working memory was assessed with the Computation Span and Listening Span tasks. Both of these tasks required the research participant to carry out specified processing while also remembering target information. The processing in the Computation Span task involved the solution of auditorily presented arithmetic problems, and the to-be-remembered information was the last digit in each problem. Processing in the Listening Span task involved answering questions about auditorily presented sentences, and the to-be-remembered information was the last word in each sentence. In both tasks, three trials each were presented with sequences of one to seven arithmetic problems or sentences. Spans were determined by the largest number of items recalled in the correct sequence on at least two of the three trials, given that the processing (i.e., arithmetic or questions about sentences) was also performed correctly. This last requirement was introduced to ensure that the research participants actually carried out the requested processing. Correlations between the two span measures in the current studies ranged from .55 to .63.

Different measures of, or methods of assessing, cognition were used across the three studies. Standard psychometric tests were used in Study 1; the participants in this study performed the Shipley Abstraction Test (Shipley, 1986), and the Raven's Advanced Progressive Matrices Set II (Raven, 1962) with a 20-min time limit. Both tests are designed to assess reasoning, with the first containing series completion items with different kinds of materials, and the second containing matrices of geometric figures, with the examinee attempting to select the best alternative to complete the missing cell. Studies 2 and 3 involved four specially created paper-and-pencil cognitive tests. The four tests were: Integrative reasoning, in which one to three premises were presented, followed by a question asking about relations between terms described in the premises (similar to Salthouse, Mitchell, Skovronek, & Babcock, 1989); paper folding, in which displays of one to three successive folds of paper were illustrated, followed by a representation of a hole punched through the folded paper and a pattern of holes in an unfolded paper (also similar to Salthouse et al., 1989); cube assembly, in which the six squares comprising a cube were displayed, and the task was to decide whether arrows in two of the squares would touch if the squares were assembled into a cube (similar to Shepard & Feng, 1972); and geometric analogies, in which one to three geometric symbols were displayed in each of four squares, and the task was to decide if the transformations carried out from the first to the second squares were identical to those carried out from the third to the fourth squares (similar to Mulholland, Pellegrino, & Glaser, 1980). Three levels of complexity were created in each task by varying the number of premises in the reasoning task, the number of folds in the paper-folding task, the number of folds required to assemble the cube in the cube assembly task, and the number of symbols per term or square in the geometric analogies task. In Study 2, the 24 problems at each complexity level were presented intermixed in a single set, with a 4-min time limit for each task. The 24 problems at each complexity level were presented separately in Study 3, with 90 sec allowed for each complexity level in each task.

RESULTS AND DISCUSSION

Cognitive performance in each study was analyzed both in terms of the total number of correct items, and in terms of the percentage of attempted items answered correctly. Composite measures of cognitive performance, with both the number-correct and percentage-correct measures, were created by averaging the z-scores for each cognitive measure (i.e., across two measures in Study 1, and across four measures in both Studies 2 and 3). The two available measures of perceptual comparison speed and working memory were also converted to z-

scores and averaged to provide composite measures of each of these constructs.

Results from the hierarchical regression analyses on the composite scores are summarized in Table 1. The three columns within each study represent the cumulative R^2 for prediction with all variables up to that step, the increment in R^2 associated with an added variable, and the F ratio evaluating the statistical significance of R^2 for the first variable or the increment in R^2 for the second or third variable. For example, the entries under Number Correct for Study 1 indicate that Age was associated with 30.5% of the variance in the composite number-correct measure and Speed with 40.4% when each was considered alone, but 44.8% of the variance was accounted for when Age was entered into the equation after Speed. The increment in R^2 associated with Age after controlling Speed is therefore 4.4%. Similarly, 51.7% of the variance was associated with the Working Memory measure alone, increasing to 55.4% when Age was entered following Working Memory, and so on.

The most interesting aspects of the data in Table 1 for the current purposes are the values of R^2 associated with age before controlling any other variables, and the values of R^2 for age after removing the variation associated with measures of speed and working memory. In all cases, the attenuation of the age-related effects was substantial, with a reduction from nearly 31% of age-associated variance to less than 5%. By expressing the final measure as a percentage of the original measure, it can be inferred that only between 0% (i.e., for the percentage correct measure in Study 1) and slightly more than 18% (i.e., for the percentage correct measure in Study 3, 1 − [.045/.246] = .183, and .183 × 100 = 18.3%) of the total age-related effects on various measures of cognitive functioning were *not* mediated by age-related reductions in working memory and/or simple perceptual comparison speed. It is also apparent in Table 1 that, as in the studies by Salthouse and Babcock (1990), the age-related differences in the current measures of working memory

Table 1. *Results of hierarchical regression analyses predicting cognitive performance and working memory*

	Study 1 (n = 221)			Study 2 (n = 228)			Study 3 (n = 223)		
	R^2	Incr. R^2	F	R^2	Incr. R^2	F	R^2	Incr. R^2	F
Number Correct									
Age	.305		96.31*	.169		45.80*	.255		75.74*
Speed	.404		159.40*	.227		66.99*	.343		121.91*
Age	.448	.044	17.20*	.238	.011	3.16	.380	.037	13.14*
Working Memory	.517		252.62*	.117		32.53*	.184		58.36*
Age	.554	.037	18.70*	.193	.076	21.23*	.305	.121	38.31*
Speed	.404		214.97*	.227		67.00*	.343		122.06*
Working Memory	.583	.179	95.46*	.232	.005	1.62	.351	.008	2.61
Age	.592	.009	4.73	.241	.009	2.58	.384	.033	11.83*
Percentage Correct									
Age	.155		40.03*	.149		39.42*	.246		72.19*
Speed	.211		59.84*	.184		51.62*	.220		68.35*
Age	.231	.020	5.79*	.197	.013	3.73	.292	.072	22.44*
Working Memory	.405		149.08*	.275		87.71*	.393		156.90*
Age	.408	.003	1.27	.295	.020	6.28	.449	.056	22.33*
Speed	.211		78.28*	.184		59.01*	.220		87.41*
Working Memory	.415	.214	75.64*	.297	.113	36.09*	.404	.184	73.08*
Age	.415	.000	0.12	.301	.004	1.40	.449	.045	17.94*
Working Memory									
Age	.292		90.25*	.254		76.87*	.208		57.91*
Speed	.354		129.46*	.350		123.84*	.381		138.20*
Age	.404	.050	18.42*	.364	.014	5.12	.393	.012	4.13

Note. Incr. R^2 indicates the increment in R^2 associated with adding the variable to the regression equation; the F value evaluates the statistical significance of R^2 for the first variable entered or the increment in R^2 associated with the addition of the second or third variable.
*$p < .01$.

were greatly attenuated by controlling the variance associated with the perceptual comparison speed measures. The percentage of variance in the composite working memory measure associated with age before and after controlling the variance associated with the perceptual comparison speed measures was 21.1% and 1.1% in Study 2 of Salthouse and Babcock (1990), and the values in Table 1 ranged from 20.8% to 29.2% before control of speed, and from 1.2% to 5.0% after partialling out the comparison speed variance.

A second set of analyses involved the computation of standardized path coefficients for all paths represented in the path analysis model illustrated in Figure 1. (Standardized coefficients were used because the interesting comparisons are across variables rather than across samples.) The means and standard errors of these coefficients, derived from the EZPATH statistical program (Steiger, 1989), are summarized in Table 2.

Three important points should be noted about the data in Table 2. The first is that the Salthouse and Babcock (1990) results are replicated by the findings that the coefficients for the paths between age and speed (path 1) and between speed and working memory (path 3) are larger than those between age and working memory (path 2). The absolute value of the direct path between age and working memory was smaller in Salthouse and Babcock's (1990) Study 2 (i.e., −.091), but the studies are all consistent in indicating that a large proportion of the age-related differences in the current measures of working memory appears to be mediated by processing speed, as reflected by the time required to carry out relatively simple perceptual comparison operations.

The second noteworthy point about Table 2 is that the influence of speed factors on cognitive performance is smaller when cognition is assessed with measures of the percentage of correct responses than when assessed with measures of the number of correct responses, but the reverse is true for the influence of working memory factors. That is, the value of path 4 is larger in the first row of the data for each study (representing results for the number-correct measure) than in the second row (representing results for the percentage-correct measure), but the value of path 5 is larger in the second row than in the first row. This pattern appears reasonable because working memory would be expected to be most important when accuracy of performance is emphasized, and speed factors would be expected to be of greatest importance as a determinant of the total number of items answered correctly.

Table 2. *Means (and standard errors) of standardized path coefficients for the path analysis model in Figure 1*

	Path					
	1	2	3	4	5	6
Study 1 (*n* = 221)						
Number Correct	−.568	−.249	.398	.269	.526	−.116
	(.050)	(.058)	(.062)	(.059)	(.059)	(.053)
Percentage Correct	−.568	−.249	.398	.109	.560	−.020
	(.050)	(.058)	(.062)	(.067)	(.067)	(.060)
Study 2 (*n* = 228)						
Number Correct	−.669	−.154	.450	.234	.054	−.088
	(.044)	(.067)	(.071)	(.062)	(.053)	(.054)
Percentage Correct	−.669	−.154	.450	.101	.348	−.074
	(.044)	(.067)	(.071)	(.070)	(.060)	(.062)
Study 3 (*n* = 223)						
Number Correct	−.569	−.120	.510	.259	.053	−.142
	(.051)	(.059)	(.062)	(.049)	(.046)	(.041)
Percentage Correct	−.569	−.120	.510	−.004	.421	−.200
	(.051)	(.059)	(.062)	(.056)	(.053)	(.047)

The third interesting aspect of the data in Table 2 is that the coefficients for the unmediated path between age and cognition (path 6) were generally rather small. The coefficients were greater than twice their standard errors only with the number-correct measures in Studies 1 and 3, and with the percentage-correct measure in Study 3. Moreover, decomposition of the direct and indirect effects revealed that only in Study 3 were the direct, or unmediated, effects responsible for more than 22% of the total age-related effects on the measures of cognitive performance. The path analysis findings are therefore in agreement with the results of the hierarchical regression analyses in indicating that only a small proportion of the age-related variance in measures of cognitive functioning is not mediated by reductions in either working memory or perceptual comparison speed.

As with all research, these studies have a number of limitations. For example, the subject samples may not be representative of the general population because the average of more than 15 years of education is much greater than that typically reported for American adults. Although it remains for future research to determine whether the results would generalize to less positively biased samples, it is noteworthy that statistical control of amount of education, and of self-reported health status, did not substantially alter the age relations in the current studies. At least for these samples, therefore, the observed relations between age and cognition are apparently not artifacts of lower levels of health status or educational level with increased age. A second limitation of the present studies is that each of the major constructs of comparison speed, working memory, and fluid cognition was assessed with a small number of measures that may not do justice to the richness of these constructs. This concern is legitimate, but it is important to emphasize that each construct was assessed with at least two independent measures, derived from distinct, and separately administered, tasks. That is, the two speed measures were based on comparisons of letter strings and of line-segment patterns, the working memory measures were based on the accuracy of remembering numbers while performing arithmetic and of remembering words while answering questions about sentences, and the cognitive measures were derived from assorted inductive reasoning and spatial visualization tasks. Reliance on multiple measures of each theoretical construct doesn't necessarily increase the validity with which the construct is assessed, but it does minimize the likelihood that the results merely reflect relatively uninteresting task- or measure-specific variance.

The results of these and other recent studies suggest that many of the differences in measures of cognitive functioning associated with increased age may be mediated by age-related reductions in the speed of executing relatively simple processing operations. An additional contribution of the present studies is the discovery that although decreases in working memory may be responsible for at least some of the age-related declines in cognitive performance, many of the age differences in working memory also appear to be mediated by reductions in the speed of carrying out elementary processing operations. In light of these results, a productive direction for future research may be a focus on the questions of why the speed of elementary operations apparently decreases with increased age during the adult years, how slower speed contributes to impairments of working memory, and how both a slower processing speed and a poorer working memory reduce the effectiveness of several types of cognitive functioning.

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