Psychology and Aging
1994, Vol. 9, No. 2, 303-314

0882-7974/94/$3.00

Analysis of Adult Age Differences on the Raven's Advanced Progressive Matrices Test

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The purpose of this project was to examine the nature of performance, and specifically, age-related performance, on the Raven's Advanced Progressive Matrices (APM) Test (Raven, Court, & Raven, 1983). In the 1st of 2 studies, 2 tests presumed to measure each of 4 hypothesized components of the APM and 3 tests presumed to measure processing speed were presented to 165 young adults. On the basis of correlational and confirmatory analyses, 1 of the components was not included in Study 2. The 2nd study was designed to examine the influence of the 3 remaining components, processing speed, and working memory on the individual and age-related differences on the APM. Participants included 183 adults between the ages of 21 and 83. The results suggest that although all 3 components are important to performance on the APM, rule application tasks seem to hold the most promise in accounting for age-related variance on the APM.

The purpose of this project was to examine age-related differences in performance on Raven's Advanced Progressive Matrices (APM)[1] Test (Raven, Court, & Raven, 1983). The project consisted of two stages. First, a rational analysis of the APM was performed in which processes or components hypothesized to be necessary for solving Raven's problems were identified. Second, an empirical analysis was conducted in which the role of each of the processes as a contributor to the adult age differences in performance on the APM was evaluated.

Items on the APM could be thought of as a two-dimensional geometric series completion test. An example of the type of problem presented in the APM is shown in Figure 1. The matrix is presented in a 3 × 3 format with the ninth, or last, cell of the matrix left blank. The subject's task is to determine which of eight alternatives best fills in the missing cell of the matrix, such that both row and column rules are satisfied.

The Raven's were designed as tests of an individual's ability to perceive and think clearly at any given time. In this sense, they are commonly referred to as measures of general intelligence. Several studies have confirmed this claim by providing evidence of significant relationships between performance on the Raven's and other tests of general intelligence. However, attempts to determine more precisely what the Raven's actually measure have not been as conclusive. For example, there is conflicting evidence as to whether performance on the Raven's is related to verbal or nonverbal abilities (e.g., Burke & Bingham, 1969; Giles, 1964; Hall, 1957; Knief & Stroud, 1959; McLeod & Rubin, 1962).

A possible reason for the inconsistent evidence regarding the relationship between the Raven's and verbal and nonverbal tests is that different individuals might employ different strategies to solve Raven's problems. That is, some individuals may approach the Raven's as they would other nonverbal tasks, whereas other individuals may approach the Raven's as a reasoning task that involves strategies similar to those utilized on verbal tasks. In fact, Hunt (1974) suggested that there are at least two methods of solving APM–Set I problems. In the first method, Gestalt, a subject attempts to solve a problem by means of visual perception. Hunt found that this holistic algorithm has the capability of solving approximately one half of the APM–Set I problems. A second method of solving the APM–Set I problems consists of an analytic approach in which subjects apply formal operations to elements of the patterns in the matrix. This algorithm has the potential of solving all 12 of the problems in APM–Set I.

The evidence relating memory to performance on the Raven's is also somewhat mixed. A review of studies revealed that correlations between the Raven's and various measures of memory range from about .08 to .96. It is possible that the magnitude of the relationship between the Raven's and memory depends on the type of memory tests used (see, e.g., Kirby & Das, 1978), and/or on the variation of memory ability within the subjects tested (e.g., Baltes, Cornelius, Spiro, Nesselroade, & Willis, 1980; Burke & Bingham, 1969).

In addition, several other studies have examined the factorial structure of the items on the Raven's, as well as their relationship to other tests in factor analyses and have found that the Raven's often loads on factors other than a general factor. The

A brief report of the results of Study 2 was originally published in *Proceedings of the Human Factors Society 36th Annual Meeting* (Babcock, 1992). This research was submitted in partial fulfillment of the requirements for the doctoral degree and was supported by a National Institute on Aging Traineeship (Georgia Institute of Technology) and by National Institute on Aging Grant AG06826 to Timothy A. Salthouse. I gratefully acknowledge the support of my dissertation chair, Timothy A. Salthouse, throughout all phases of this research, the assistance of Karin Koeppen in the data collection, and Cal Garbin for assistance in the analysis phase of the project.

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[1] The abbreviation "APM" is used as a specific reference to the Advanced Progressive Matrices, whereas the abbreviation "Raven's" is used as a general reference to the Raven's Progressive Matrices tests.

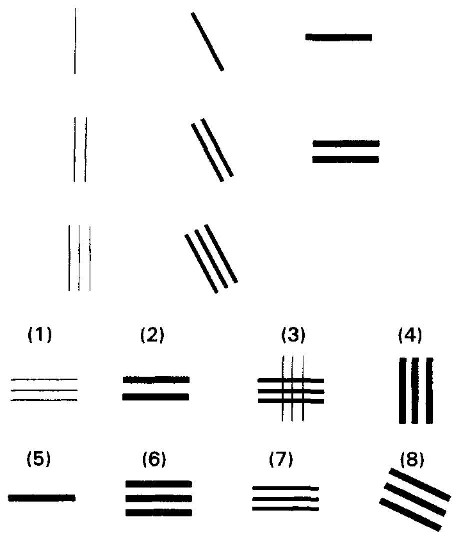

Figure 1. Example of a typical problem on the Raven's Advanced Progressive Matrices. From "An Examination of the Adult Age Differences on the Raven's Advanced Progressive Matrices" by R. L. Babcock, 1992, *Proceedings of the Human Factors Society 36th Annual Meeting, 1,* p. 151. Copyright 1992 by the Human Factors and Ergonomics Society, Inc. Reprinted with permission. All rights reserved.

available studies indicate that there is some evidence to suggest that the Raven's also measure attributes other than *g,* most notably, spatial ability (e.g., Hertzog & Carter, 1982; Lim, 1988; Vernon, 1949; Wilson et al., 1975; Zonderman, Vandenberg, Spuhler, & Fain, 1977). The evidence that the Raven's measure other factors such as processing speed is mixed, with some studies suggesting rather large relationships between this ability and the Raven's (Rimoldi, 1948; Zonderman et al., 1977), but other studies indicating otherwise (Cornelius, Willis, Nesselroade, & Baltes, 1983; Wilson et al., 1975).

In yet another attempt to explain the processes involved in solving a matrix-style figural relations problem, Jacobs and Vandeventer (1972) suggested that subjects must be able to discriminate among the elements of the figure, identify relations among the elements to form rules, and combine the relations in order to solve the problem. The ability to discriminate among elements of a geometric figure can be viewed as a type of disembedding task in that the subjects must be able to discriminate various attributes of the figure as distinct elements. There is evidence that indicates that this ability may be related to performance on the Raven's (Hooper, Hooper, & Colbert, 1984; Pande & Kothari, 1969).

Age differences on the Raven's, indicating that young people typically perform better than older individuals, have been well documented. The magnitude of the age differences on the Raven's is fairly large, with correlations usually ranging from −.27 to −.63.[2] There have been several attempts to understand the adult age differences on the Raven's. For example, Horn (1975) indicated that successful performance on the Raven's involves the accurate perception of the relations between the rows in the matrix, the maintenance of this information while determining the relations between the columns of the matrix, and finally, the integration of the relations of both the rows and the columns. It is possible from Horn's description that the age differences could be due to any of these three components. In support of a memory component that is responsible for the maintenance of information while solving the problem, both Bromley (1953) and Chown (1961) have suggested that poorer performance on the Raven's may be partially due to the inability to hold several ideas or aspects of problems simultaneously.

As Horn (1975) suggested, accurate perception of the relations among the rows and the columns may be necessary in order to solve a Raven's problem. Because there are many potential relations between the elements of a geometric figure, this perception would seem to include the ability to determine which relations are relevant to the solution of the problem. Other researchers have indicated that older subjects are generally less capable of distinguishing relevant dimensions from irrelevant dimensions in a Raven's problem. For example, Anderson, Hartley, Bye, Harber, and White (1986) reported that in an examination of protocols from subjects solving Raven's problems, older subjects often appeared to have more difficulty determining the relevant dimensions on which elements of a problem differed. Anderson et al. attempted to reduce the age differences on the Raven's by training subjects to attend to all of the dimensions of the problem. Although the training appeared to improve overall performance on Raven's problems, the age differences on the task were unaffected. Anderson et al. concluded that inattention to relevant dimensions did not account for the age differences on the Raven's.

Still other studies have examined the possibility that the age differences on the Raven's are caused by the abstract quality of the geometric figures used in the Raven's problems. In fact, the results of Arenberg's (1968) study, in which he varied the meaningfulness of the dimensions in a concept formation task, suggested that older adults' performance on some tasks may be improved if the materials used are meaningful. Harber and Hartley (1983) attempted to determine whether the age differences on the Raven's would be reduced if the items used in the matrices were more meaningful than the abstract geometric forms that are standard in Raven's problems. What they discovered, however, was that the meaningful figures improved the performance of the younger subjects, but not that of the older subjects. Their results suggest, then, that the age differences on the Raven's may not be caused by a lack of meaningfulness in the problems.

The preceding review indicates that although several suggestions have been made as to the nature of the age differences on the Raven's, none of these hypotheses have yet been supported with convincing evidence. Therefore, the goal of this project was to attempt to specify more precisely the nature of the adult age differences on the Raven's.

One method of accounting for individual differences in a criterion task, such as the Raven's, is to obtain measures of what are presumed to be more fundamental abilities or constituent processing components hypothesized to be involved in performance on the criterion task. Based on the results of the studies in the preceding review, a rational analysis of the APM test was conducted in order to identify a number of its components,

[2] Studies that obtained weaker correlations usually had restricted age ranges.

though it was not assumed that these exhaust the components that might be involved in the APM. Performance on each of the hypothesized components was then measured, as was performance on the criterion task (i.e., APM). In addition, two constructs, presumed to be related to performance on both the APM and the hypothesized components, were also measured.

Proposed Processes

Four component processes were hypothesized to be involved in solving APM problems. In addition to the hypothesized components of the APM, performance on tasks presumed to assess processing speed was also measured.

Decomposition of Figures Into Elements

The first process, decomposition, involves decomposing the figures within the cells of the matrix into elements. That is, the subject must be able to identify various components of each of the figures as potentially distinct elements in order to determine relations between the elements or before being able to identify rules. Two tasks were chosen to measure the subject's ability to decompose figures into elements: Hidden Figures and Hidden Patterns (Ekstrom, French, Harman, & Dermen, 1976). Both tasks are described by Ekstrom et al. as measures of "the ability to hold a given visual percept or configuration in mind so as to disembed it from other well defined perceptual material" (p. 19). In the Hidden Figures test, the subject is shown five geometric figures and asked which of the five figures is embedded in a more complex geometric pattern. In the Hidden Patterns test, the subject is presented with a single target shape and asked to determine if that shape is embedded in a more complex pattern of lines.

In both of these tasks it is important that the subject identify the various attributes as distinct elements. Similarly, in the APM, the subject must be able to identify various components of each of the figures as potentially distinct elements. For example, in the problem portrayed in Figure 1, if the subject had not identified line orientation as a separate element, he or she might have chosen Response Number 4 or 8, rather than the correct alternative, Response Number 6. Because age differences have been established on many embedded figures tests (e.g., Axelrod & Cohen, 1961; Bogard, 1974; Botwinick & Storandt, 1974; Eisner, 1972), it is hypothesized that the decomposition process is a potentially important determinant of the age differences on the APM.

Rule Identification

The rule identification process includes noting similarities, and inferring relations, between adjacent cells. The subject must generate rules for the rows or columns based on the results of the decomposition process (Babcock, 1992). The Figure Classification test and the Letter Sets test (Ekstrom et al., 1976) were chosen to measure the ability to identify rules; these tests of induction are assumed to measure "the factor [that] identifies the kinds of reasoning abilities involved in forming and trying out hypotheses that will fit for a set of data" (p. 79). In the Figure Classification test, items consist of two or three groups each containing three geometrical figures. The task is to decide the rules that constitute each of the groups, and then to classify a series of eight geometric figures into one of the groups. In the Letter Sets test, items consist of five sets of letters, each set containing four letters. The subject is to decide which one of the five sets is dissimilar in that it does not follow a rule used to generate the other four items.

The rule identification process measured by these tasks is hypothesized to be similar to that performed in the APM in that in each task the subject must identify the rule or rules that apply to a group of figures or elements. For example, in Figure 1 the subject must realize that the row rules consist of both a change in line orientation and in line width.

Application of Rules to a New Row or Column

After identifying the rules from the rows and/or columns, the subject must apply the rules to a new row or column. To accomplish this task the subject must, among other things, mentally transform figures according to the previously determined rules. The subject must then compare this transformation either to the final cell of a row or column (in the case of applying a rule to a completed row or column for validation purposes), or to the eight alternate responses (in the case of applying a rule to the final row or column in order to fill in the missing cell; Babcock, 1992).

Two new tasks, the Geometric Transformation task and the Pattern Transformation task (see Figure 2), were developed to examine whether a subject could, given a specified rule, visually transform spatial information. The two tasks are identical except for the type of item to be transformed: geometric figures in the Geometric Transformation task and line patterns in the Pattern Transformation task. The patterns in the Pattern Transformation task consist of nine-line segments and the to-be-added or to-be-subtracted patterns consist of three-line segments. The figures in the Geometric Transformation task con-

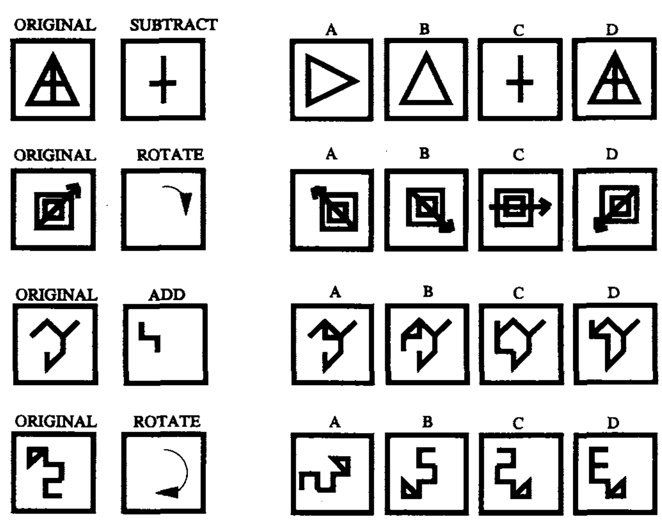

Figure 2. Examples of problems on the Geometric and Pattern-Transformation tasks. From "An Examination of the Adult Age Differences on the Raven's Advanced Progressive Matrices" by R. L. Babcock, 1992, *Proceedings of the Human Factors Society 36th Annual Meeting, 1*, p. 152.

sist of simple geometric figures similar to those used in the APM. The to-be-transformed items are followed by the representation of a transformation rule that should be mentally applied to the original figure. The transformations were either the addition or subtraction of a smaller figure or pattern or a 90° or 180° rotation of the figure or pattern. In the addition and subtraction problems, the transformation rule (add, subtract) was placed above a picture of the to-be-added or subtracted figure or pattern. In the rotation problems, the rule (rotate) was placed above an arc with an arrow indicating the degree of rotation to be performed.

Coordination of Rules

In the Raven's tests, the subject is often asked to combine two or more rules in order to solve a problem successfully. Therefore, the ability to coordinate rules may play an important role in the individual differences on the Raven's (Babcock, 1992).

The tests used to measure this ability were the Calendar test and Following Directions (Ekstrom et al., 1976). Ekstrom et al. claimed that these tests measure an integrative process factor that represents "the ability to keep in mind simultaneously or to combine several conditions, premises, or rules in order to produce a correct response (p. 87)." In the Calendar test, "The subject is asked to select certain dates on a calendar by following a fairly complex set of directions" (p. 88). The Following Directions test is similar in that the subject must combine a set of rules in order to select a letter from a pattern of letters.

The coordination of rules may be important to performance on most of the APM problems because many of the problems contain more than one rule. In addition, the relative importance may vary across items because for some problems, both row and column rules must be coordinated in order to solve the problem correctly (as in Figure 1).

Processing Speed

The influence of processing speed on performance on the APM was also examined in this project, although this construct was not viewed as a distinct component of APM performance. Rather, according to the results of Salthouse (1991), it is possible that this more general construct might be relevant to the age-related differences in performance on the APM. In addition, because all of the tests used in this project were speeded, one could argue that many of the measures of the hypothesized components are not distinct from a processing-speed component. However, processing speed is not likely as the only source of variance on the hypothesized components because similar measures were included in other studies that found distinct factors for processing speed and constructs similar to the hypothesized components of the APM (Carroll, 1976; Messick & French, 1975; Mos, Wardell, & Royce, 1974; Wilson et al., 1975; Zonderman et al., 1977).

The tasks chosen to measure processing speed were the Identical Pictures and Number Comparison tests (Ekstrom et al., 1976) and the Line Marking test (Salthouse, 1992). In the Identical Pictures task, subjects are asked to select which of five pictures is identical to a picture presented to the left of the alternatives. In the Number Comparison test, subjects are asked to compare pairs of numbers as quickly as possible, placing the letter *S* on the line between them if they are the same or the letter *D* if they are different. In the Line Marking test, subjects are presented with a page of either vertical or horizontal lines and are asked to make a mark across each line in order to form a + shape.

Study 1

The purpose of Study 1 was to establish evidence that the two measures chosen to represent each component were more highly related to one another than to the measures of the other components. In other words, it was felt that before using the tasks in the examination of adult age differences on the APM, it was necessary to provide evidence that each of the tasks best represented its respective hypothesized component. In addition, the relationship between the hypothesized components and processing speed was also examined in order to provide evidence that the tasks represent measures other than processing speed.

Method

Subjects

Subjects were 165 undergraduate students (mean age = 20.46 years) enrolled in psychology courses who received extra credit for their participation.

Procedure

In order to administer all tasks in a single 2-hr session, only the first of the two sets of each of the Factor-Referenced Cognitive Tests (Ekstrom et al., 1976) were presented. The order of presentation and time limits (as suggested by Ekstrom et al. where appropriate) for each of the tasks were as follows: Hidden Figures (12 min), Letter Sets (7 min), Geometric Transformation (3 min), Calendar test (7 min), Identical Pictures (1.5 min), Line Marking (30 s for each of four parts), Number Comparison (1.5 min), Following Directions (7 min), Pattern Transformation (3 min), Figure Classification (8 min), and Hidden Patterns (3 min). The scores on each of the tasks were recorded as the number of correct responses.

The standard instructions for each of the Factor-Referenced Cognitive Tests were presented at the beginning of each task. Instructions for the two new tasks (Pattern Transformation and Geometric Transformation) were presented with examples intended to portray the nature of the tasks and to represent each of the possible transformations required in the tasks.

Results

The correlations among the tasks presumed to measure the hypothesized components are presented in Table 1. Because most tasks representing some type of intellectual ability tend to be correlated, it was expected that many of the tasks would correlate at least moderately with one another. The correlations were, therefore, intended to act as "alarms" that indicated the possibility that two tasks assumed to measure the same construct were *not* significantly related. Of each of the tasks, only the measures from those tests intended to assess the construct of rule identification (Letter Sets and Figure Classification) were not significantly correlated with one another. Measures from the tasks assessing the other three hypothesized components correlated at least moderately well with their respective pair (see

Table 1
Differentiation of Hypothesized Components in Study 1: Correlations of the Measures of the Hypothesized Components

Measure	1	2	3	4	5	6	7	8	9	10	11
1. Hidden Patterns	—										
2. Hidden Figures	**.34**	—									
3. Letter Sets	.26	.18	—								
4. Figure Classification	.36	.33	**.13**	—							
5. Geometric Transformation	.43	.32	.21	.38	—						
6. Pattern Transformation	.49	.40	.21	.43	**.63**	—					
7. Calendar Test	−.04	.15	.23	−.07	.14	.08	—				
8. Following Directions	.08	.15	.20	−.07	.20	.17	**.38**	—			
9. Identical Pictures	.53	.14	.17	.26	.45	.46	−.02	.09	—		
10. Line Marking	.47	.15	−.01	.09	.21	.19	−.11	−.04	**.46**	—	
11. Number Comparison	.50	.19	.18	.28	.34	.32	−.02	.22	**.47**	**.36**	—
M	115.06	8.10	11.98	70.18	11.90	12.52	8.10	8.33	38.28	313.62	29.38
SD	23.98	3.68	1.89	18.76	3.39	3.74	1.31	1.56	7.02	39.66	5.57

Note. Values less than .20 are not significantly different from 0 at $\alpha = .01$. The numbers in boldface are correlations between the pair of measures representing the same hypothesized component.

statistics in boldface print in Table 1). The correlations between the measures of processing speed also indicated that these tasks appeared to measure similar processes.

An additional way of determining whether the measures represent differentiable components is to use confirmatory techniques, such as oblique multiple-groups component analyses (OMG; Gorsuch, 1983; see, also, Bernstein & Garbin, 1985; Garbin, Robertson, & Bernstein, 1986; Meerdink, Garbin, & Leger, 1990) to determine if the measures represent their respective hypothesized factors. The OMG procedure is an unweighted least squares method that involves comparing the solution from a user-defined model (i.e., the hypothesis matrix) to the solution from a principal-components analysis and to the solutions from models consisting of randomly defined pseudofactors.

In the currently proposed hypothesis matrix, there were five factors (processing speed and the four hypothesized components). In the hypothesis matrix, measures were given a weight equal to 1 to indicate that a variable was proposed to be a member of that factor or a weight equal to 0 to indicate that a variable was not a member of that factor (Gorsuch, 1983). In addition to the hypothesized factor solution, results from a principal-components analysis (when specifying the number of factors to be equal to that in the hypothesized solution) and results from pseudofactor matrices were also obtained. The pseudofactor matrices were generated by randomly assigning variables to the factors in such a way as to preserve the *structure* of the factors in the hypothesis matrix (i.e., three variables on Factor 1, two on Factor 2, etc.) without representing the *content* of the hypothesis matrix.

Although a variety of statistics can be used to evaluate the models, the percentage of variance accounted for by each model is commonly used as a goodness-of-fit index (Bernstein & Garbin, 1985; Garbin et al., 1986; Meerdink et al., 1990). Specifically, the total amount of variance accounted for by the hypothesized solution is compared to the variance accounted for by the principal-component solution and to the variance accounted for by the pseudofactor solutions. A good hypothesized solution should account for nearly as much total variance as the principal-components solution when specifying the number of factors equal to the number defined in the hypothesis matrix, and should account for substantially more total variance than do the pseudofactor solutions (Bernstein & Garbin, 1985).

In addition, interfactor correlations should be higher among the pseudofactors than they are among the hypothesized factors because, due to randomization, related variables will be defined by different pseudofactors causing a correlation between them. However, in the hypothesized factor solution it is expected that the related variables will be defined by the same factor (Garbin et al., 1986).

The results of the confirmatory analysis are summarized in Table 2. The total amount of variance accounted for by a five-factor exploratory principal-component solution was 74%.[3] The interfactor correlations (represented by phi in the table) indicated that the factors were not highly correlated, with the possible exception of the first two factors, which were composed of the processing-speed tasks and Hidden Patterns (Factor 1) and the rule application tasks, Identical Pictures, and Figure Classification (Factor 2; $r_{\text{Factor 1, Factor 2}} = .39$).

The amount of variance accounted for by the hypothesized factor solution (i.e., one processing-speed factor and the four hypothesized components) was nearly as large as that obtained from the principal component solution: 70%. The interfactor correlations increased somewhat, however. The analyses indicated that the factors most highly correlated were processing speed and disembedding ($r = .52$) and rule identification and rule coordination ($r = .56$). The amount of variance accounted for by the pseudofactor solutions averaged approximately 62%, considerably less than either the hypothesized factor solution or the principal-component solution. In addition, the average interfactor correlation increased to approximately .42.

It seems, therefore, that the hypothesized factor solution provides a better fit to the data than do random pseudofactors. However, as appeared evident in the correlational analyses, the

[3] It should be noted that using a criterion of minimum eigenvalue of 1.00 in the exploratory principal-component analysis, only three factors were retained. These first three factors accounted for 59% of the variance. The eigenvalues for the fourth and fifth factors were .863 and .787, respectively.

Table 2
Differentiation of Hypothesized Components in Study 1: Oblique Multiple-Groups Component Analysis for Variables (Comparison of Confirmatory, Exploratory, and Pseudofactor Solutions)

Source	Total var	ϕ Min	ϕ Max	ϕ Avg
5-Factor PC	.7407	.000	.389	.165
5-Factor HYP	.7020	.031	.559	.321
5-Factor PSEUDO 1	.6298	.114	.639	.408
5-Factor PSEUDO 2	.6019	.272	.666	.444
5-Factor PSEUDO 3	.6188	.291	.646	.421

Note. Total var = total amount of variance accounted for by the five factors in the given solution; ϕ Min = minimum interfactor correlation; ϕ Max = maximum interfactor correlation; ϕ Avg = average interfactor correlation; PC = exploratory principal-components solution; HYP = hypothesized factor solution; PSEUDO = factor solutions in which variables were randomly assigned to factors.

confirmatory techniques used here indicate that the hypothesized factor solution consists of factors that were not adequately differentiable. That is, it appeared that the measures from at least one of the tasks designed to assess the disembedding component (Hidden Patterns) was not differentiable from the processing-speed factor. In addition, the correlational analyses revealed that measures from the tasks designed to assess rule identification (Figure Classification and Letter Sets) were not significantly correlated, and performance on the Figure Classification test was more strongly associated with the factor consisting of the rule application tasks (in the principal-component solution) than with the hypothesized rule identification factor.

An additional goal of the first study was to address the issue of whether the tasks used to measure each hypothesized component reflected variance other than that attributed to processing speed. The amount of variance on each of the variables accounted for by a composite measure of processing speed (based on the average z scores of the three processing-speed tasks) revealed that in most cases processing speed accounted for less than 1% of the variance on the tasks (R^2 = .003–.07 for Hidden Figures, Letter Sets, Figure Classification, Calendar Test, and Following Directions). However, processing speed did account for 18% and 17% of the variance on the Geometric Transformation and Pattern Transformation tasks, respectively; processing speed accounted for 41% of the variance on the Hidden Patterns task.

Discussion

There were two primary goals of Study 1. The first was to determine if the pair of tasks chosen to measure each hypothesized component could reasonably be assumed to reflect performance on a similar factor. The tasks chosen to measure rule application (the Geometric and Pattern Transformation tasks) and rule coordination (the Calendar Test and Following Directions) appeared to relate sufficiently well to indicate that the measures represented like factors.

However, although the tasks chosen to measure disembedding (Hidden Patterns and Hidden Figures) correlated moderately well (r = .34), both tasks had equal or higher correlations with other tasks. In addition, processing speed accounted for a relatively large proportion of the variance on the Hidden Patterns test, indicating that this task may represent largely a processing-speed factor, rather than primarily a disembedding factor. Therefore, the disembedding component was not included in Study 2 because at this time there does not seem to be convincing evidence that these tasks represent a factor unique from processing speed.

The relatively weak relationship between the measures of the two tasks chosen to assess rule identification (Letter Sets and Figure Classification; r = .13) may have been caused by the different nature of the tasks. Figure Classification requires the abstraction of rules concerning geometric figures, whereas Letter Sets requires the abstraction of rules involving verbal information. Because of the nature of the other tasks, it was considered desirable to eliminate the figural component of rule identification by replacing Figure Classification with a rule identification task that would be more verbal in its content (e.g., Shipley Abstraction Test; Shipley, 1986).

Study 2

The purpose of Study 2 was to determine the amount of the age-related variance on the APM that could be accounted for by age-related variance on the three hypothesized components outlined in the discussion of Study 1. In addition, although processing speed did not seem to account for a significant amount of the variance on most of the tasks examined in Study 1, these tasks were included in Study 2 because it is possible that age-related variance associated with processing speed may account for age-related differences on the APM. A second construct hypothesized to be important to performance on both the APM and the hypothesized components was working memory. In a study by Salthouse (1991), variations in working memory appeared to account for much of the age-related differences on performance on the APM. Although time limitations did not allow working-memory performance to be assessed in the context of this study, all of the participants had participated in studies within the preceding 6 to 12 months in which working memory and processing speed were measured and these data were available for analyses in the current project.

Method

Subjects

The subjects who participated in Study 2 had previously participated in one of three studies in which both working memory and processing speed were assessed. Subjects for the current study were recruited through both letters and telephone calls. Of the original 686 subjects, 188 responded and participated in Study 2. Three of those subjects were omitted from the analyses because of lack of previous data on working-memory and/or processing-speed performance, and 2 of the subjects were omitted from the analyses because they did not follow the directions for the tests. The final 183 subjects, whose data were included in the analyses, ranged from 21 to 83 years of age and included 93 men and 89 women. The age distribution was approximately rectangular with the number of subjects per decade ranging from 20 to 47, with the exception of the 80-year-olds (n = 2), who were included in the 70- to 80-year-old group. The mean years of education for all of the subjects was 15.55 (SD = 2.35) and age was not significantly correlated with education (r = −.03). Subjective health rating was assessed using a scale from *excellent*

(1) to *poor* (5). The mean health rating given by all subjects was 1.99 (SD = 1.13) and age was not significantly correlated with health (r = −.02). Subjects received $10 for participation in this project.

Tasks

The tasks used to assess performance on the hypothesized components are described in Study 1. In addition to the processing-speed measures in Study 1, data were also available on the subjects' performance on three other processing-speed measures and two working-memory measures.

Two of the tasks, the Letter Comparison and Pattern Comparison, are similar to Number Comparison and are described in Salthouse and Babcock (1991). The third processing-speed task used in the previous study was the Wechsler Adult Intelligence Scale (WAIS) Digit Symbol Substitution task (Wechsler, 1981). Briefly, in the Letter Comparison task, the subject is asked to compare two sets of letters, placing an *S* on the line between them if they are the same, or a *D* on the line between them if they are different. The sets consist of either three, six, or nine letters. The Pattern Comparison task is performed in a similar manner. The patterns in the comparisons are line drawings consisting of either three, six, or nine lines each. In the WAIS Digit Symbol Substitution task, the subject is presented with a set of numbers and corresponding symbols followed by several rows of numbers with blank spaces below them. The task is simply to write the corresponding symbol below each number.

The tasks used to measure working memory in the previous studies were the Computation Span task and the Listening Span task described in Salthouse and Babcock (1991). In the Computation Span task, subjects are asked to solve simple arithmetic problems while simultaneously remembering the final number in each of the problems. The Listening Span task is a modification of the Reading Span task developed by Daneman and Carpenter (1980), in that subjects answer simple questions about auditorily presented sentences while simultaneously remembering the final word of each of the sentences.

Procedures

In addition to the tasks outlined in the discussion of Study 1, subjects also performed the APM–Set I (with a 5-min time limit, intended for practice) and the APM–Set II (with a 20-min time limit). A 20-min time limit was chosen for the APM–Set II because Heron and Chown (1967) found that the pattern of age differences using a 20-min time limit was similar to that obtained using the standard 40-min time limit. To avoid a confounding of subjec' and task order, all participants performed the tasks in the same order.

In Study 1 several subjects were able to finish the tasks perfectly within the allotted time leading to a measurement ceiling. Therefore, the time limits for some of the tasks were changed for Study 2. The order of the tasks and their time limits were as follows: APM–Set I (5 min), APM–Set II (20 min), Letter Sets (5 min), Geometric Transformation (4 min), Calendar Test (5 min), Identical Pictures (1.5 min), Line Marking (30 s for each of four parts), Number Comparison (1.5 min), Following Directions (5 min), Pattern Transformation (4 min), and Shipley Abstraction Test (5 min). Performance on the tests was recorded as number correct.

Results

Background Analyses

Differentiation of hypothesized components. As in Study 1, a premise of the remaining analyses is that the tasks selected to measure the hypothesized components represent differentiable constructs. Both correlational and confirmatory factor analyses were used to provide evidence that the measures represented performance on their respective hypothesized components. Correlations among the measures from the tasks are presented in Table 3. First, it should be noted that each of the measures had a significant negative correlation with age. Second, the measures from tasks presumed to assess performance on the same hypothesized component were at least moderately, and often most highly, correlated with their respective pair.

A confirmatory analysis (OMG) was also performed on all of the tasks performed in Study 2. As described earlier, the logic of this technique is to compare the hypothesized factor structure to the exploratory principal-components factor solution and to pseudofactor solutions. The hypothesized factor structure in Study 2 consisted of four factors (the three hypothesized components and processing speed), with the structure defined similar to the hypothesized factor structure of Study 1. That is, the three processing-speed tasks were hypothesized to represent Factor 1 and the two tasks presumed to measure each of the hypothesized components were hypothesized to represent factors 2, 3, and 4. The confirmatory analysis is summarized in Table 4. The amount of variance accounted for by the hypothesized solution was approximately 81%, which was nearly identical to the amount of variance accounted for by the principal-components solution (83%). The average interfactor correlation increased somewhat in the hypothesized solution (i.e., .413–.590), although the increase was even more dramatic among the pseudofactor solutions (i.e., average interfactor correlation = .737). In addition, the pseudofactor solutions accounted for considerably less of the total variance (i.e., approximately 74% of the variance).

The results of these analyses indicated that the tasks yield reasonable measures of performance on the hypothesized components. Therefore, in the following analyses, aggregate scores for each hypothesized component were used. The aggregate scores were based on the average of the z scores of the two tests presumed to measure each component.

Correlations. The correlations between age, working memory, high and low cognitive demand processing speed, and the hypothesized components are presented in Table 5. Several aspects of this correlation matrix should be noted. First, as expected, age was negatively correlated with the hypothesized components and with the measures of working memory and processing speed. Second, all of the hypothesized components have substantial correlations with the APM and with each other.

The measures of processing speed were divided into two separate categories: processing speed with a high cognitive demand and processing speed with a low cognitive demand. The processing-speed measures presumed to involve a relatively low cognitive demand included the Line Marking task. All remaining processing-speed measures were presumed to involve a relatively high cognitive demand. Salthouse (1993) reported that these measures, which might also be thought of as a processing speed (high cognitive demand) versus a motor-speed (low cognitive demand) contrast, could be interpreted as representing distinct factors.

It is interesting to note that the low cognitive demand processing-speed measures have consistently lower correlations with the APM and hypothesized components (rs = .20–.36) than do the high cognitive demand processing-speed measures (rs = .52–.58). This may indicate that performance on motor-speed tasks has a relatively lower influence on performance on

Table 3
Differentiation of Hypothesized Components in Study 2: Correlations of the Measures of the Hypothesized Components

Measure	1	2	3	4	5	6	7
1. Age	—						
2. Letter Sets	−.32	—					
3. Shipley Abstraction	−.39	**.71**	—				
4. Geometric Transformation	−.40	.52	.55	—			
5. Pattern Transformation	−.44	.56	.61	**.75**	—		
6. Calendar Test	−.31	.57	.66	.49	.50	—	
7. Following Directions	−.31	.57	.66	.51	.53	**.64**	—
M	53.71	8.56	13.30	10.39	10.73	6.88	6.43
SD	16.51	2.97	3.51	4.50	4.95	2.05	2.12

Note. The numbers in boldface are correlations between the pair of measures representing the same hypothesized component.

the hypothesized components and the APM than does performance on traditional processing-speed tasks.

Examination of the role of working memory and processing speed on age differences in performance on the hypothesized components. As noted earlier, several of the tasks used to measure each component were potentially related to performance on both processing speed and working memory. It would therefore be informative to examine the age-related variance on the hypothesized components themselves. If the age-related variance on the hypothesized components can be accounted for by age-related differences in performance on processing speed or working memory, then the components might not be more informative in predicting age-related performance on the APM than would processing speed and working memory alone.

The age-related variance (R^2) on each of the hypothesized components, before and after controlling for performance on processing speed and working memory, is presented in Table 6. An interesting finding was that the processing-speed composite consisting of the high cognitive demand processing-speed tasks accounted for the majority of the age-related variance on all three of the components, though a significant amount of age-related variance remained on the rule application component after first controlling for this processing-speed composite.

In addition, although the processing-speed composite reflecting performance on low cognitive demand processing-speed tasks reduced the age-related variance on each hypothesized component, the amount of age-related variance left unexplained was still significant in every case. These results are consistent with the general trend found in the correlational analyses. That is, processing speed that reflects a motor component, as is presumed with the low cognitive demand tasks, may not be as important in predicting performance on the hypothesized components as are the more traditional processing-speed tasks, which are presumed to involve a higher cognitive demand.

One other feature of these regression analyses is worth noting. Working memory accounted for all but a nonsignificant amount of the age-related variance on both the rule identification and rule coordination components. However, as with processing speed, although working memory reduced the age-related variance on the rule application component, a significant amount of the age-related variance was left unexplained.

Table 4
Differentiation of Hypothesized Components in Study 2: Oblique Multiple-Groups Component Analysis for Variables (Comparison of Confirmatory, Exploratory, and Pseudofactor Solutions

Source	Total var	ϕ Min	ϕ Max	ϕ Avg
4-Factor PC	.8281	.218	.589	.413
4-Factor HYP	.8115	.426	.730	.590
4-Factor PSEUDO 1	.7205	.679	.783	.740
4-Factor PSEUDO 2	.7263	.697	.768	.737
4-Factor PSEUDO 3[a]	.7659	.601	.735	.735

Note. Total var = total amount of variance accounted for by the four factors in the given solution; ϕ Min = minimum interfactor correlation; ϕ Max = maximum interfactor correlation; ϕ Avg = average interfactor correlation; PC = exploratory principal-components solution; HYP = hypothesized factor solution; PSEUDO = factor solutions in which variables were randomly assigned to factors.
[a] The third pseudofactor solution contained one of the hypothesized factors among the pseudofactor solutions.

Individual and Age-Related Differences on APM

Examination of the influence of the hypothesized components on individual differences in performance on the APM. Before determining the role that each component plays in the age-related differences on the APM, it was first necessary to establish that each hypothesized component was a significant predictor of performance on the APM. Hierarchical regression analyses were performed to determine the amount of the total variance on the APM accounted for by each of the components (see Table 7). Each of the hypothesized components alone accounted for 51% (rule application and rule coordination) to 55% (rule identification) of the variance on the APM. Various combinations of the hypothesized components (not listed in Table 5) increased the variance accounted for from 61% to 68%.

An additional concern before determining each component's role in the age-related variance on the APM was that performance on the tasks designed to measure the hypothesized components was highly related to performance on both processing-speed and working-memory tasks. It therefore seemed neces-

Table 5
Correlations Between APM, Age, Working Memory, Processing Speed, and Hypothesized Components From Study 2

Measure	1	2	3	4	5	6	7	8	9	10
1. Age	—									
2. Gender	−.02	—								
3. Education	−.03	−.07	—							
4. Health	−.02	.21	−.21	—						
5. APM	−.46	−.02	.30	−.18	—					
6. Working memory	−.42	.10	.25	−.14	.55	—				
7. High PS	−.54	.17	.11	−.03	.56	.59	—			
8. Low PS	−.40	.07	.11	−.07	.31	.29	.55	—		
9. Rule ID	−.39	.06	.30	−.16	.74	.61	.58	.36	—	
10. Rule APP	−.45	−.14	.28	−.20	.71	.48	.57	.33	.64	—
11. Rule COORD	−.34	−.03	.30	−.11	.71	.59	.52	.20	.73	.60

Note. APM = Raven's Advanced Progressive Matrices Test—Set II; High PS = processing speed tasks with high cognitive demand; Low PS = processing speed tasks with low cognitive demand; Rule ID = rule identification composite; Rule APP = rule application composite; Rule COORD = rule coordination composite.

sary to determine whether performance on the hypothesized components accounted for variance on the APM beyond that accounted for by performance on processing speed and/or working memory.

Hierarchical regression analyses were used to determine whether any of the three hypothesized components accounted for a significant amount of the variance on the APM after first controlling for the processing-speed composites and/or working memory. The increments in R^2 variance for each component after first controlling for processing speed and working memory are also presented in Table 7. Although the variance on each of the components was reduced by controlling for processing speed and working memory, it was apparent in every case that the hypothesized components account for significant amounts of variance on the APM beyond that accounted for by processing speed and working memory.

Examination of the influence of the hypothesized components on age-related performance on the APM. Salthouse (1991) found that both working memory and processing speed account for nearly all of the age-related differences on the APM. Given the results of his study, it was necessary to examine the amount of age-related variance on the APM accounted for by each hypothesized component after first controlling for processing speed and working memory.

The hierarchical regression analyses used to examine the relationship between age-related performance on the APM and the hypothesized components after first controlling for processing speed and working memory are presented in Table 8. Age-related variances are given for several combinations of processing speed, working memory, and hypothesized components, as well as the increments in age-related variances after first controlling for these variables.

As noted in Table 8, age alone accounts for approximately 21% of the variance on the APM. Although this value is reduced to about 14% after first controlling for low cognitive demand processing speed, the age-related variance on the APM is re-

Table 6
Regression Analyses Showing Age-Related Variance (R^2) on the Three Hypothesized Components Before and After Controlling for Processing Speed and Working Memory

	Rule ID			Rule APP			Rule COORD		
After control of	R^2	R^2 inc	F inc	R^2	R^2 inc	F inc	R^2	R^2 inc	F inc
None	—	.149	31.79*	—	.203	46.15*	—	.114	23.33*
Low PS	.129	.070	15.75*	.108	.121	28.34*	.042	.078	15.96*
High PS	.335	.008	2.19	.326	.029	8.11*	.269	.005	1.21
WM	.373	.020	5.94	.235	.073	19.16*	.347	.010	2.69
Low PS, High PS	.337	.007	1.91	.326	.029	8.04*	.279	.007	1.83
Low PS, High PS, WM	.451	.001	0.24	.361	.020	5.72	.400	.001	0.23

Note. The first R^2 listed in the first column for each component represents the R^2 on the Raven's Advanced Progressive Matrices Test without age. The R^2 inc and the F inc refer to the increment in R^2 for age. Rule ID = composite of rule identification tasks; Rule APP = composite of rule application tasks; Rule COORD = composite of rule coordination tasks; Low PS = composite of low cognitive demand processing speed tasks; High PS = composite of high cognitive demand processing speed tasks; WM = composite of working-memory tasks performed in prior studies.
* $p < .01$.

Table 7
Increment in Variance (R^2) on the APM for Each Component Before and After Control of Processing Speed and Working-Memory Measures

	Rule ID		Rule APP		Rule COORD	
After control of	R^2 inc	F inc	R^2 inc	F inc	R^2 inc	F inc
None	.550	221.49	.505	184.40	.507	186.22
Low PS	.456	183.59	.415	152.92	.439	170.11
High PS	.026	95.42	.224	74.54	.241	91.91
WM	.267	109.98	.261	105.85	.234	89.88
Low PS, High PS	.261	94.35	.154	73.17	.244	90.83
Low PS, High PS, WM	.195	73.77	.181	66.96	.179	69.97

Note. APM = Raven's Advanced Progressive Matrices Test—Set II; Rule ID = composite of rule identification measures; Rule APP = composite of rule application measures; Rule COORD = composite of rule coordination measures; inc = increment; Low PS = composite of low cognitive demand processing speed measures; High PS = composite of high cognitive demand processing speed measures; WM = working memory.

duced to approximately 4% by first controlling for a high cognitive demand processing speed. Control of working memory also reduced, but did not eliminate, the age-related variance on the APM. However, it should be noted that performance on the working-memory tasks was based on information obtained from the prior studies and may therefore not be a valid indicator of a subject's current working-memory ability. Hence, these results should remain tentative. The most striking feature of the regression analyses is that only combinations of variables that included rule application reduced the age-related variance on the APM to less than 1% (a nonsignificant amount of age-related variance).

Table 8
Increment in Age-Related Variance (R^2) on the APM After Statistical Control of Other Variables

After control of	R^2 without age	R^2 inc for age	F inc for age
None	—	.212	48.72*
Low PS	.096	.135	31.54*
High PS	.317	.035	9.75*
WM	.297	.065	18.15*
Low PS, High PS	.317	.036	9.96*
Low PS, WM	.323	.046	12.95*
Low PS, High PS, WM	.387	.022	6.54*
Low PS, High PS, WM, APP	.568	.005	2.24
Low PS, High PS, WM, ID	.582	.017	7.59*
Low PS, High PS, WM, COORD	.566	.018	7.08*
Low PS, High PS, WM, APP, ID	.651	.007	3.79
Low PS, High PS, WM, APP, COORD	.647	.007	3.54
Low PS, High PS, WM, ID, COORD	.628	.016	8.00*
Low PS, High PS, WM, APP, ID, COORD	.678	.008	4.39

Note. APM = Raven's Advanced Progressive Matrices Test—Set II; inc = increment; Low PS = composite of low cognitive demand processing speed tasks; High PS = composite of high cognitive demand processing speed tasks; WM = working memory; APP = composite of rule application tasks; ID = composite of rule identification tasks; COORD = composite of rule coordination tasks.
* $p = .01$.

Discussion

Results from Study 2 reveal that, in addition to being significant predictors of performance on the APM, each of the three hypothesized components also account for variance beyond that accounted for by both working memory and processing speed. The finding that rule coordination accounts for performance on the APM beyond that accounted for by working memory is interesting given the results of Carpenter, Just, and Shell (1990), who suggested that a goal-management process accounted for individual differences in performance on the APM beyond those accounted for by working memory. They viewed goal management as distinct from, but dependent on, working memory; that is, they suggested that goal management involves the generation of goals and subgoals as well as the coordination of the status of attainment of each goal. Similar to the results from the Carpenter et al. study, the results from the current study suggest that a simpler form of goal management (rule coordination), in which dependence on working memory is reduced, also accounts for a significant amount of the variance on the APM.

These results are perhaps most meaningful when considering the difference in the concept of the goal management and rule coordination processes. That is, goal management is described as involving the production and monitoring of fairly complex goals and subgoals, whereas rule coordination is described as organizing a set of conditions to determine the solution to a problem. When viewed in this way, rule coordination could be thought of as a subcomponent of the more complex concept of goal management in that the processes involved in rule coordination are similar to the monitoring involved in goal management.

One other interesting point to note is that whereas Carpenter et al. (1990) found that goal management accounted uniquely for nearly all of the individual differences on the APM, the rule coordination component in the current study was not a better predictor of performance on the APM than were the rule application or rule identification components. It would therefore be interesting to decompose goal management (as perceived by Carpenter et al., 1990) to determine which of the processes involved accounts for the variance on the APM.

The finding that the hypothesized components accounted for variance on the APM beyond that accounted for by working memory is inconsistent with the results of Kyllonen and Christal (1990), who reported that working memory and reasoning ability were nearly identical constructs in four different studies using samples of young adults. In fact, they suggested that prior attempts at localizing individual differences in reasoning ability may not have been completely successful because working-memory capacity may have affected performance on each of the component processes of the reasoning tasks. If their hypothesis that reasoning is "little more than working-memory capacity" were true, then attempts to account for individual differences in reasoning ability beyond those already accounted for by working memory should prove futile.

However, the results of the current project suggest that working memory and reasoning ability (as measured by performance on the APM) are not completely equivalent. Indeed, it appears that the processes represented by the hypothesized components are essential to the explanation of the performance on the APM. This result must be tempered with the fact that the subjects who participated in the Kyllonen and Christal (1990) study were all young adults, whereas the sample in this study consisted of a far broader age range.

As discussed earlier, Salthouse (1991) reported that both working memory and processing speed accounted for nearly all of the age-related variance on the APM. The results of the current study provide a sound replication of Salthouse (1991) in that controlling for performance on both working memory and processing speed substantially reduced the age-related variance on the APM. Specifically, the low cognitive demand processing-speed tasks reduced the age-related variance on the APM from 21% to 14%. However, as with performance on the hypothesized components, the high cognitive demand processing-speed tasks further reduced the age-related variance to only 3%. Therefore, it seems that although age-related differences on the APM may be affected by a decline in motor speed, this slowing does not fully explain performance on the APM.

As expected from the results on the analysis of performance on the hypothesized components, in which age-related performance was accounted for by processing speed and working memory, neither rule identification nor rule coordination reduced the age-related variance on the APM beyond that already accounted for by these constructs. However, in every analysis in which rule application was included, age-related variance on the APM was reduced to a nonsignificant amount. This seems especially interesting when compared to rule identification and rule coordination, which, even in combination, could not reduce the age-related variance to a nonsignificant amount.

To summarize, the results suggest that all three of the hypothesized components are important to performance on the APM, both before and after controlling for working memory and processing speed. In addition, of the three components, performance on the rule application tasks seems to hold the most promise in accounting for age-related variance on the APM for two reasons: (a) the age-related differences on both rule identification and rule coordination were completely accounted for by controlling for performance on either working-memory or processing-speed tasks, though this was not completely true for rule application; and (b) perhaps most important, of the three hypothesized components, only when rule application was controlled was the age-related variance on the APM reduced to a nonsignificant amount.

The current results suggest that the tasks used to assess rule application in this study play an important role in accounting for the age-related differences on the APM. Performance on the rule application tasks was defined, in the current context, as the ability to mentally transform figures according to a given rule. Obviously, the concept of rule application would be more informative if it encompassed a broader range of stimuli than those used in the current project. That is, because both tasks used to assess rule application were geometric or spatial in nature, there is a possibility that the unique relationship between performance on rule application and on the APM was due either to a similarity in the type of stimuli in the problems (e.g., spatial) or to the actual application of a rule, per se. The next logical step in examining age-related performance on the APM might therefore be to distinguish between the ability to apply simple rules and the ability to manipulate spatial information to account for age-related differences in performance on the APM.

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Received May 3, 1993
Revision received October 11, 1993
Accepted October 11, 1993 ■