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Influence of working memory on adult age differences in matrix reasoning

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The four studies reported in this article, involving a total of 401 adults ranging between 18 and 80 years of age, were designed to investigate how working memory might mediate adult age differences in matrix reasoning tasks such as the Raven's Progressive Matrices Test. Evidence of this mediation is available in the finding that statistical control of an index of working memory reduces the age-related variance in matrix reasoning performance by approximately 70 per cent. Because the age differences were nearly constant across items of varying difficulty, it was concluded that the factors responsible for variation in item difficulty were distinct from those responsible for the age differences. However, young adults were found to be more accurate than older adults at recognizing information presented earlier in the matrix reasoning trial, thereby supporting the interpretation that working memory exerts its influence by contributing to the preservation of information during subsequent processing.

Speculations about the role of working memory in adult age differences in cognition can be traced at least as far back as Welford's (1958) book (see Salthouse, 1990, for a review of research on adult age differences in working memory). It has only been in the last several years, however, that convincing empirical evidence for the influence of working memory on age differences in cognition has become available. Examples are recent studies by Salthouse (1991*a*) and Salthouse, Mitchell, Skovronek & Babcock (1989) in which the magnitude of the age differences in several measures of cognitive functioning was found to be greatly attenuated by statistical control of a measure of working memory.

Although the statistical relations seem to be well documented, relatively little is yet known about the processes responsible for those relations. The principal goal of the current research was therefore to investigate the mechanisms by which working memory might mediate the age differences in a specific cognitive task. Three types of analyses are reported. The first focuses on item variation because items can be assumed to vary in the demands placed on working memory, and hence age × item interactions might be expected if high-demand items exceed the reduced working memory capacities of older adults, but are still within the capabilities of young adults. A second type of analysis is based on an examination of the alternatives selected on incorrectly answered items. Just as items can be postulated to vary in their working memory demands, so might the probability of selecting particular foils or incorrect alternatives differ according to the working memory requirements

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imposed by each incorrect alternative and the working memory capabilities of the individual. Finally, because working memory is usually defined in terms of the simultaneous storage and processing of information, one should expect young adults, who tend to have high levels of working memory, to be better able to preserve previously presented information than older adults, who are presumed to have lower levels of working memory.

In addition to examining possible consequences of different levels of working memory, the results of these studies can also be used to investigate one possible cause of age-related variations in working memory. This is the idea that age differences in many cognitive tasks originate because of an age-related reduction in the speed of executing relevant cognitive operations. Some evidence for this interpretation was reported by Salthouse (1991*a*) and Salthouse & Babcock (1991) in which age differences in working memory were substantially reduced by using statistical procedures to equate people on a measure of perceptual comparison speed. The contribution of perceptual speed was examined in the current project by contrasting the degree of attenuation of the age differences in cognitive performance achieved by statistical control of a working memory measure with that obtained with control of a perceptual speed measure, and also by examining the additional attenuation attributable to working memory after the variance associated with perceptual speed had been removed.

Matrix reasoning tasks were selected as the criterion cognitive activity in this project because: (*a*) matrix reasoning tests such as the Raven's Progressive Matrices are a common and highly g-loaded (e.g. Jensen, 1982) measure of intelligence; (*b*) substantial age-related differences in Raven's Progressive Matrices performance have been reliably documented; (*c*) there are both theoretical and empirical reasons for expecting working memory to be important in the solution of these kinds of problems; (*d*) extensive development of the Raven's Progressive Matrices Test has resulted in a systematic progression of item difficulty from the early to the late items in the test; and (*e*) many of the incorrect alternatives in the Raven's problems were constructed to be informative about the causes of poor performance.

Research involving comparisons of adults of different ages on the Raven's Progressive Matrices Test has recently been reviewed by Salthouse (1992*c*). The median correlation between age and Raven's score across six studies involving samples with a wide range of ages was $-.61$. Five studies were located in which groups of older adults, typically with a mean age of about 70 years, were contrasted with groups of young adults, usually with a mean age of about 20 years. In each study, the performance of the older adults could be expressed in units of the distribution of the performance of young adults. The median across the five studies was -2.84 standard deviation units. Both of these estimates of the magnitude of the age differences are among the largest reported for any cognitive measure.

It has recently been reported that performance on the Raven's Progressive Matrices Test has increased over historical time (Flynn, 1987; Raven & Court, 1989), and some researchers have interpreted these positive time-lag differences as evidence that age differences observed in cross-sectional comparisons are an artifact of generational change. As discussed in Salthouse (1991*b*), a discovery of generational differences in test performance does not by itself imply that maturational factors do not contribute to the observed age-related differences because such a conclusion depends on several additional assumptions that are seldom tested. Regardless of the distal cause of performance differences among people of varying age, however, it is important to identify the proximal processing characteristics associated with different levels of performance. In other words, even if the age-related differences are an artifact of progressively higher test performance across successive generations, it still remains to be determined how individuals from earlier generations perform differently from individuals from later generations. From the current perspective, therefore, the goal is to specify the factors associated with differences in the observed level of functioning, and not to determine the ultimate source or cause of those differences.

The potential importance of working memory in successful performance of matrix reasoning problems can be illustrated by considering the sample problem in Fig. 1. Notice that all but one of the cells in the matrix of three rows and three columns is filled with geometric forms. The task for the examinee is to select which of the eight answer alternatives presented below the matrix provides the best completion of the missing cell of the matrix. One way to conceptualize the processing required in matrix reasoning problems such as this is in terms of the three components discussed by Jacobs & Vandeventer (1972): discrimination among elements, identification of relations and combination of relations. Working memory could be involved in each of these components because cell attributes have to be preserved in order to determine similarities and differences across cells, similarities and differences have to be preserved in order to determine the relations among cells in a given row or column, and relations have to be preserved in order to coordinate row and column relations to predict the pattern of the missing cell. Another theoretical analysis in which an aspect of working memory concerned with the management of subgoals was postulated to be critical for the solution of difficult matrix problems was also recently published by Carpenter, Just & Shell (1990). Finally, empirical support for the hypothesized relation between working memory and matrix reasoning performance is available in the moderate (.30 to .59) correlations reported by Larson and colleagues (e.g. Larson, Merritt & Williams, 1988; Larson & Saccuzzo, 1989) between Raven's performance and several measures postulated to reflect working memory abilities.

Evidence that items in the Raven's Test vary in item difficulty is available from Raven, Court & Raven (1985). These investigators reported that the average accuracy in the Advanced Set II version of the test was 98 per cent for item 1, 88 per cent for item 10, 59 per cent for item 20, and only 26 per cent for item 30. This substantial variation in item difficulty means that comparisons can be made at several points along the difficulty continuum. Moreover, to the extent that the item variation is at least partially attributable to differential demands on working memory, one might expect the effects associated with age to be greatest on the most difficult items. In other words, if one of the reasons for the low accuracy of difficult items is that those items place greater demands on working memory than less difficult items, then accuracy on those items should provide the greatest discrimination across people of different ages who are assumed to vary in their working memory abilities.

The sample problem in Fig. 1 can be used to illustrate how the particular incorrect

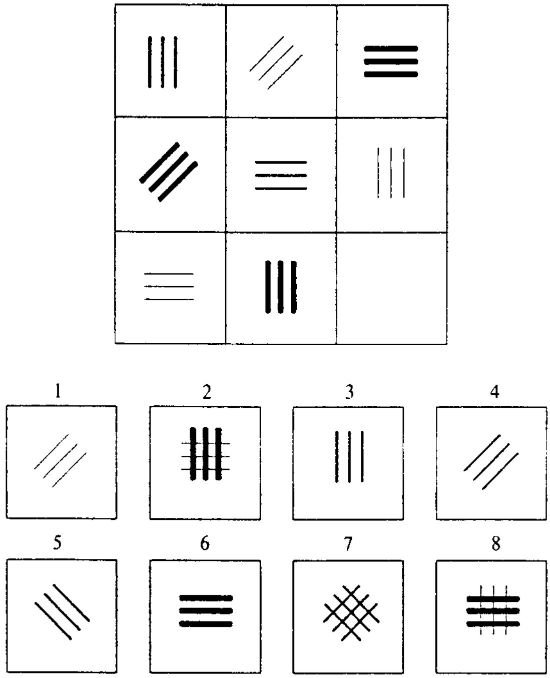

Figure 1. Examples of the type of problem in the Raven's Progressive Matrices Test.

choices selected might be informative about the causes for poor performance. Notice that the correct answer is alternative 4 because that pattern satisfies the critical principle of one of each type of line thickness and line orientation in each row and column. Alternative 6 is merely a repetition of a pattern from the matrix, and its selection may reflect a response based on the property of familiarity rather than a relevant principle. Alternatives 1 and 3 are also repetitions, but in addition can be considered partial solutions because they would have been correct if one dimension had not been neglected (i.e. line thickness in alternative 1, and line orientation in alternative 3). Alternative 5 is another example of a partially complete solution, in this case because the pattern does not incorporate the correct value for the relevant dimension of line orientation. Finally, alternatives 2, 7 and 8 are combinations created by applying an incorrect principle of addition. Some of these error types seem more likely to be a consequence of working memory limitations than others, and thus examination of the pattern of incorrect choices may prove informative about the influence of working memory on matrix reasoning performance. For example, a failure to notice a relevant attribute might occur equally often for people with effective and ineffective working memory systems, but people with more limited working memory systems might be expected to have a greater number of errors associated with a failure to coordinate the simultaneous application of multiple rules.

Results from four studies are reported in this article. Study 1 is a more detailed report of Study 1 from Salthouse (1991*a*), and focuses on the influence of working memory and age at the level of individual items in the Raven's Progressive Matrices

Test. The matrix reasoning task was implemented on a computer in Studies 2 through 4 in order to obtain separate measures of time and accuracy, and to allow for the presentation of probes of previously displayed information. Because recognition probes could be presented with either simultaneous or sequential displays of the stimulus matrix, and because both methods differ substantially from the more traditional paper-and-pencil format for presenting matrix reasoning problems, a primary purpose of Study 2 was to explore interrelations among measures of performance in the different presentation modes. Study 3 then examined accuracy of probe decisions after simultaneous displays of the matrix, and Study 4 examined probe decisions after sequential displays of the matrix. Participants in all studies also performed two perceptual speed tasks to allow comparisons of the influence of perceptual speed and working memory as possible mediators of age differences in matrix reasoning.

STUDY 1

The purpose of this initial study was to examine the influences of age and working memory on performance of the Raven's Progressive Matrices Test at the level of individual items. If the solution of certain items, or the selection of particular incorrect alternatives, depends on the individual's working memory ability, then the accuracy and error patterns should vary as a function of age and level of working memory.

Method

Subjects

Newspaper advertisements were used to recruit adults interested in participating in a research project concerned with relations among ageing, memory and cognition. Complete data were obtained from 221 adults (61 per cent women) ranging from 20 to 80 years of age. Each decade was represented by between 34 and 39 individuals. All participants reported the number of years of education they had received, and rated their health on a five-point scale (ranging from 1 for excellent to 5 for poor). Means of these variables and their correlations with age were 15.6 years and $r = -.04$ for education, and 2.04 and $r = .20$ ($p < .01$) for self-rated health. Analyses revealed that the patterns among the variables of primary interest were not significantly altered after adjusting for amount of education or rating of self-reported health, and consequently these measures are reported primarily to assist in description of the research sample.

Procedure

Research participants were tested in groups of about four to 30, and all performed the tasks in the same sequence. The tasks, in the order in which they were presented, were: Digit Symbol Substitution Test (Wechsler, 1981), Letter Comparison, Pattern Comparison, Computation Span, Listening Span Abstraction Test (Shipley, 1986) and Raven's Advanced Progressive Matrices, Set II (Raven, 1962). The Digit Symbol and Shipley Abstraction Tests were included for purposes unrelated to the current project and will not be discussed further in this report.

The Letter Comparison, Pattern Comparison, Computation Span and Listening Span tasks were identical to those described in Salthouse & Babcock (1991). The Letter Comparison and Pattern Comparison tasks consisted of pages containing pairs of three, six, or nine letters, or pairs of patterns composed of three, six or nine line segments. One-half of the pairs were identical, and one-half were different because of a change in one of the letters or line segments. The task for the participant was to classify each pair as SAME or DIFFERENT by writing an S or a D on a line between the two members of the pair as rapidly as possible. Trials with three, six or nine elements were separately timed (30 s for

32 pairs), and the scores were averaged to provide a single measure for each type of comparison (letter or pattern).

The Computation Span and Listening Span tasks were designed to assess working memory by requiring participants to remember information while also carrying out specified processing. In the Computation Span task arithmetic problems were presented auditorily, and the task was to select the answer to the arithmetic problem from three alternatives on the response form while also remembering the last digit in each problem. Short sentences were auditorily presented in the Listening Span task, with participants instructed to answer a question about the sentence, printed on the response form along with three answer alternatives, while also remembering the last word in each sentence. Target items were recalled by writing them, in the order in which they were presented, on designated lines on the back of the response form. The number of arithmetic problems or sentences increased from one to seven, with three trials at each sequence length. An individual's span was determined by the greatest number of digits or words that could be remembered on two of the three trials for a particular sequence length, given that he or she was also correct in the answers to the relevant arithmetic and sentence comprehension questions. This latter requirement ensured that the scores represented both storage and processing.

As noted above, the Raven's Advanced Progressive Matrices Test consists of displays of 3×3 matrices of geometric forms with the bottom right cell missing. The task for the examinee is to select the correct pattern to complete the missing cell from a set of eight alternatives displayed below the matrix. Three sample problems (Items 6, 8 and 12 from the Raven's Advanced Progressive Matrices Set I) were provided, followed by the 36 problems of Set II. Twenty minutes were allowed to work the problems in Set II. Although a time limit of 40 min is usually recommended, the steep difficulty gradient across successive items suggests that few responses were likely to have been correct on later items had they been attempted. Furthermore, comparisons of the average number of items answered correctly in college student samples with 20 min (a pilot study, and Studies 2 and 4 of the present report), 40 min (Larson & Saccuzzo, 1989; Palmer, MacLeod, Hunt & Davidson, 1985) and no time-limit (Jensen, 1983, 1987; Paul, 1985) administrations revealed relatively small differences related to the time allowed for completion of the items. Finally, similar age trends were reported by Heron & Chown (1967) with 20 min and 40 min administrations of the standard Raven's Progressive Matrices Test.

Results and discussion

Distributions of the frequency of number-correct scores on the Raven's Progressive Matrices Test for each of three age groups ($N = 77$, 73 and 71, respectively) are displayed in Fig. 2. Also portrayed in Fig. 2 for purposes of comparison is the distribution of scores obtained in a pilot sample of 83 college students (mean age = 19.9 years, mean of 13.7 years of education). It is apparent in this figure that college students have the highest scores, and that increased age is associated with a systematic downward shift of the entire distribution.[1]

The initial step in the analyses of the data involved creating composite measures of the working memory and perceptual speed constructs. This was accomplished by averaging the individual's z scores from the Listening Span and Computation Span tasks to produce a working memory composite, and averaging his or her z scores from the Letter Comparison and Pattern Comparison tasks to produce a perceptual speed composite.

Table 1 contains the correlation matrix summarizing the relations among the variables of subject age, the two composite variables, and both the number of correct

[1] The higher scores for the sample of students relative to the sample of adults between 20 and 39 years of age may be a consequence of their younger age (i.e. mean of 19.9 years versus 29.1 years), or of the fact that they had been selected partially on the basis of intellectual ability for admission to a relatively competitive university. If the latter is the case then comparisons between students and older adults recruited according to the procedures in this study may overestimate the absolute magnitude of age-related differences.

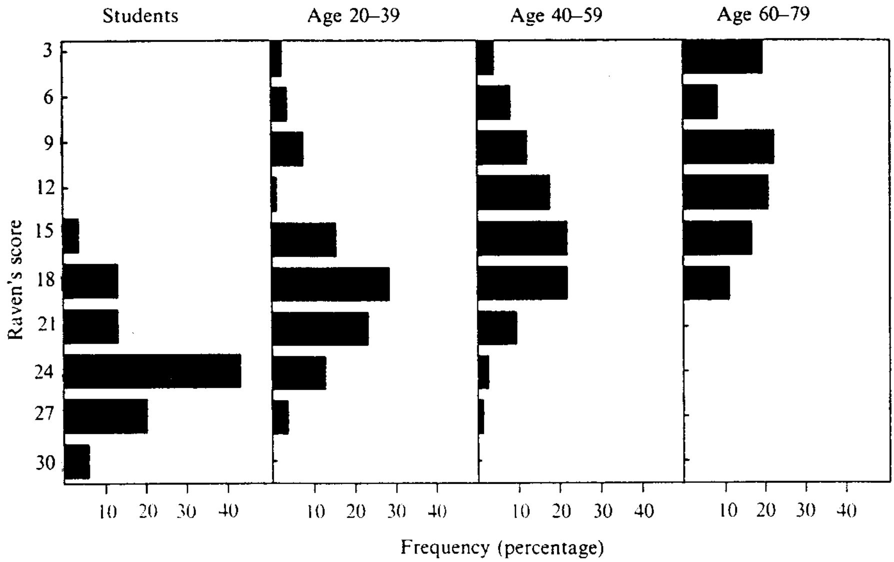

Figure 2. Distribution of scores on the Raven's Progressive Matrices Test as a function of age, Study 1.

responses and the percentage of attempted items answered correctly in the Raven's Progressive Matrices Test. It should be noted that each measure had at least moderate reliability, and that all correlations were in the medium to large range. Moreover, the significant negative correlation between age and percentage of items answered correctly indicates that not all the age variation in Raven's performance is due to differences in the number of items attempted.

Table 1. Correlation matrix for variables in Study 1 ($N = 221$)

Variable	1	2	3	4	5
1 Age	×	−.57*	−.36*	−.54*	−.61*
2 RPM no.C		(.91)	.84*	.69*	.62*
3 RPM % C			(.86)	.60*	.45*
4 WMem				(.71)	.59*
5 Speed					(.85)
Mean	48.5	14.0	63.3	0.00	0.00
SD	17.4	6.2	23.7	0.88	0.93

* $p < .01$.

Note. Reliabilities in the diagonals were estimated by using the Spearman–Brown formula to boost the correlation between the two component measures (for Perceptual Speed and Working Memory) or between the scores for odd and even items (for the number-correct and percentage-correct variables). *Key*. Speed = Average of z scores for Letter Comparison and Pattern Comparison; WMem = Average of z scores for Computation Span and Listening Span; Rav no. C = Number of items correct in Raven's Test; Rav % C = Percentage of attempted items correct in Raven's Test.

A series of hierarchical multiple regression analyses was conducted to determine the amount of variance in measures of Raven's performance associated with age when considered alone, and after controlling the variance associated with the composite measure of working memory and/or the composite measure of perceptual speed. The R^2 values in these analyses are summarized in the top row of Table 2, where it can be seen that partialling the variance associated with working memory reduced the R^2 for age from .322 to .053. This degree of attenuation of the age effects is clearly consistent with a mediational influence of working memory on the age differences in matrix reasoning. It is also apparent in Table 2 that the attenuation of the age differences was nearly as large after statistical control of the perceptual speed variable. Implications of this finding will be considered in the General Discussion.

Table 2. R^2 estimates associated with age in prediction of matrix reasoning performance

Study	Variable	Alone	After WMem	After PSpeed	After WMem & PSpeed
All subjects					
1	Raven's Num. Correct	.322*	.053*	.056*	.017*
2	Raven's Num. Correct	.678*	.389*	.201*	.162*
	Simult. Matrix Acc.	.347*	.108*	.062	.031
	Sequent. Matrix Acc.	.228*	.066	.021	.007
3	Simult. Matrix Acc.	.375*	.086*	.111*	.021
Only subjects satisfying accuracy criterion					
1	Raven's Num. Correct	.303*	.109*	.083*	.048*
2	Raven's Num. Correct	.701*	.482*	.134*	.117*
	Simult. Matrix Acc.	.258*	.157*	.111	.107
	Sequent. Matrix Acc.	.138	.049	.005	.002
3	Simult. Matrix Acc.	.273*	.137	.058	.039

* $p < .01$.

In an attempt to minimize the possibility that the relations between working memory and Raven's performance might have been a consequence of a failure on the part of some subjects to understand fully the task requirements, the analyses were repeated after eliminating subjects with errors on either of the first two items in the Raven's Set II problems. Results from this restricted sample of 166 subjects are summarized in the bottom portion of Table 2. Notice that the pattern is qualitatively very similar to that evident in the complete sample.

Additional analyses were conducted to examine performance on the Raven's Test at the level of individual items. These analyses were limited to items 1 through 22 because fewer than 50 per cent of the research participants responded to later items, and the range of ages for those who did respond was greatly restricted because few older individuals attempted many of the later items.

The percentages of correct responses as a function of item across the three age groups are displayed in Fig. 3. The most striking feature of these data is that although

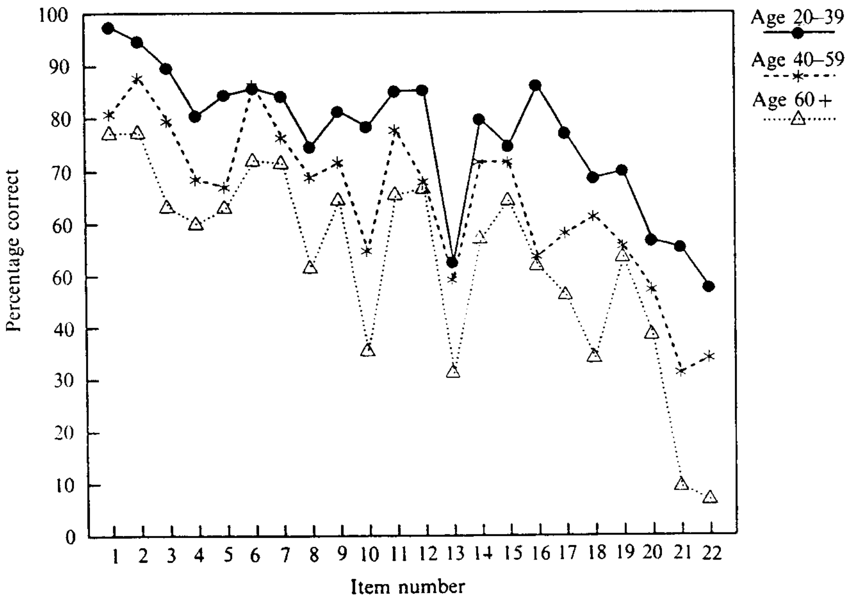

Figure 3. Mean accuracy for individual items in the Raven's Progressive Matrices Test as a function of age, Study 1.

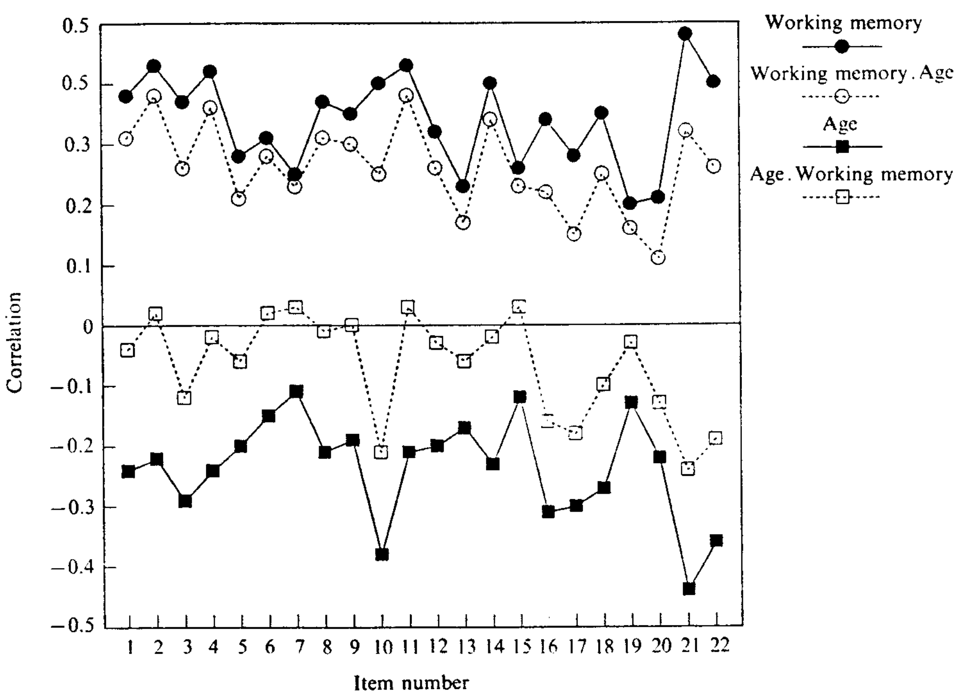

Figure 4. Correlations of age and working memory with accuracy of individual items on the Raven's Progressive Matrices Test, Study 1.

Table 3. First and second most frequently chosen incorrect alternatives for each item by age group

	Number of errors			1st frequent			2nd frequent		
Item no.	Y	M	O	Y	M	O	Y	M	O
1	3	13	15	1	1,7	1	—	1,7	6,7,8
2	4	9	15	2,4	2,4,6	2	2,4	2,4,6	6
3	9	14	25	8	8	8	4	1,5,6	3
4	17	20	26	8	8	5	7	2	8
5	13	23	24	1	1,7	7	2	1,7	1
6	11	10	19	7	7	7	2	6,8	2
7	14	14	21	2	2	2	5	5	4
8	21	19	32	2	2	3	8	3,5	5
9	15	20	23	1	1	1	7	3	7
10	18	30	39	8	8	8	2	2	7
11	13	14	21	7	7	7	4	4,6	1,3,4
12	13	21	21	5	5	5	8	3,8	8
13	37	37	43	5	5	5	6	6,7	6
14	16	19	25	4	4	4,7	7	7	4,7
15	21	18	19	8	8	6	6	1,4	4,7
16	11	29	27	5	5	5	6,7	1	6
17	17	27	29	3	3	3	4	4	4
18	25	20	27	1	1	1	3	5	5
19	23	25	19	5	5	5	8	6	1,6,7,8
20	30	27	24	2	2	2	4	4	4
21	31	30	29	1	1	1	4	4	4
22	37	24	27	8	8	8	2,5	4	1

there is substantial variation in average level of accuracy, ranging from about 85 per cent on item 1 to approximately 35 per cent on item 22, the functions for the three groups appear remarkably parallel. This impression was reinforced with the results of a group (young, middle, old) × item (items 1 to 22) analysis of variance. Both main effects of age group ($F(2,218) = 30.94$, $MSE = 1.07$, and item, $F(21,4578) = 47.69$, $MSE = 0.15$) were significant ($p < .01$) in this analysis, but their interaction was not ($F(42,4578) = 1.41$).

A second analysis consisted of determining the simple and partial correlations between accuracy for each item and the age and working memory variables. These correlations, displayed in Fig. 4, serve to confirm the inference from Fig. 3 of nearly constant age effects across items. It is also interesting that partialling working memory from the age correlations reduced most of them to near zero, but that the reduction in working memory correlations after partialling age was much smaller. Medians of the 22 correlations were −.22 for age alone, −.04 for age after partialling working memory, .35 for working memory alone, and .26 for working memory after partialling age.

Patterns of errors on items with overt responses (i.e. excluding errors of omission) were also examined. Analyses were conducted to determine whether subjects of varying ages differed in the particular incorrect alternatives selected with the greatest frequency. Table 3 contains the identities of the alternatives for each item with the highest, and second highest, frequency of occurrence in each age group. It is apparent that there was a great deal of consistency in the particular incorrect alternatives chosen by adults of different ages. The young and middle-aged groups selected the same incorrect alternative most frequently on all 22 items, and there was agreement between the young and old groups, and between the middle-aged and old groups, on 19 of the 22 items. Furthermore, there was agreement in the alternatives selected with either the highest or the second highest frequency in 21 of the 22 items both for middle-aged and old groups, and for young and old groups.

Discussion

The results summarized in Tables 1 and 2 confirm previous results concerning relations among age, working memory, and measures of cognitive performance. Specifically, the finding that the influence of age on cognitive performance was markedly reduced after controlling the variance associated with a measure of working memory suggests that working memory plays an important role in the age difference in at least this cognitive task.

Average solution accuracy varied considerably across the items examined, and it seems reasonable to hypothesize that at least some of the item variation might have been due to increased working memory demands. If age differences are largely mediated by reductions in working memory, then it might have been expected that the differences would be greater for the most difficult items that place the largest demands on working memory. Contrary to this prediction, however, the analyses revealed that the age relations were remarkably constant across the range of items examined. An apparent implication of these findings is that the factors responsible for the variation in item difficulty are independent of the factors responsible for the effects associated with working memory and adult age. Of course, it is not known whether similar results would have been observed in samples with higher average levels of reasoning performance, of if it had been possible to extend the analyses to even more difficult items, but the patterns in Figs 2 and 3 suggest that the influences of age and working memory are relatively constant in this set of data.

The analyses of the error patterns also failed to provide any evidence of deficits in particular kinds of processing, or restricted to specific relational principles. Although some incorrect alternatives were consistently selected more often than others, the same general patterns were evident across the three age groups. It therefore appears that the factors responsible for causing some incorrect alternatives to be chosen more frequently than others were operating in similar ways regardless of the individual's age.

The configuration of results just described presents a challenge for interpretation. On the one hand, there is evidence of moderate to large relations between the measures of working memory and matrix reasoning performance, but on the other hand, the data indicate that these relations are no greater for difficult (low accuracy) problems than for easy (high accuracy) problems. At least three distinct explanations could be proposed to account for these findings. First, it is possible that the lack of a differential relation across items of varying difficulty is a consequence of some type of methodological artifact. For example, the fact that the most difficult items occurred later in the problem sequence means that fewer of them were probably attempted by the slower subjects, who may also have had less effective working memory systems. An attempt was made to minimize distortions of this kind by restricting the analyses to items attempted by the majority of the subjects, but it is nevertheless still possible that various kinds of measurement insensitivity may have contributed to the lack of differential relations of age and working memory across items.

A second potential explanation is that much of the variation in item difficulty may be attributable to factors unrelated to working memory. That is, the working memory influence might have been nearly the same for all items, but item difficulty could have varied because of factors such as salience of the attributes, familiarity of the relational rules, etc.

A third interpretation focuses on the meaning of the relation observed between the working memory measures and performance on the matrix reasoning test. That is, it could be speculated that this relation did not originate because of the involvement of working memory in the reasoning test, but rather was a consequence of a third variable involved in both the working memory and reasoning tests. As an example, instead of the relation occurring because of reliance on working memory in the matrix task, it could have originated because of a temporal aspect in both the matrix reasoning test and in the working memory tests. Consistent with this view is the fact that the 20 min time limit for the Raven's Test was too short for most respondents to attempt all items, and the group administration of the working memory tests necessitated the imposition of limits on the time between presentation of successive stimuli and the time allowed for production of responses. It is therefore conceivable that at least some of the relations observed in this study were a reflection of the common requirements of having to work rapidly, and were not a direct consequence of working memory involvement in the Raven's Matrix Test.

STUDY 2

The remaining studies in this project were designed in part to resolve some of the interpretational ambiguities associated with the results of Study 1. Features of these studies intended to address the concerns discussed above were: (*a*) both the working memory and matrix reasoning tests were administered on a computer with subjects allowed as much time as desired to respond; and (*b*) matrix problems created to vary systematically according to the number of relations among matrix elements were presented in a randomly arranged sequence.

Examples of the problems used in Studies 2 and 3 are illustrated in Fig. 5. Notice that the problems vary with respect to the number of unique relations among cell attributes. That is, cells in the problem on the left vary only in the number of vertical lines, cells in the middle problem vary in the number of filled squares and in the number of surrounding squares, and cells in the problem on the right vary in the