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The Role of Representations in Age Differences in Analogical Reasoning

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Age-related declines in the efficiency of a number of cognitive tasks have been postulated to be attributable to decreases with age in the quality of internal representations used to mediate performance on those tasks. This proposal was investigated in a geometric analogies task by manipulating variables (i.e., the number of elements per term and the temporal delay between presentation of pairs of terms) assumed to affect the quality or stability of internal representations. As expected, the performance of older adults was impaired more than that of young adults by these manipulations. Further analyses revealed that these representational deficits may be due to a reduction of approximately 40% in the quantity of some type of processing resource between, approximately, 20 and 70 years of age.

Researchers have recently proposed that qualitative differences in cognitive performance between young and older adults may be a consequence of inadequate formation and maintenance of accurate and complete internal representations. For example, Salthouse and Prill (1987) suggested that age differences in accuracy of solving series completion problems may be attributable to older adults constructing flimsier and less precise internal representations of the relational structure among elements than do young adults. Moreover, evidence that young and older adults differ in the ability to construct or use internal representations was provided by Salthouse (1987) in studies using a mental synthesis task. The major finding of these studies was that with increases in the number of integration operations, and presumably in the complexity of the constructed representation, older adults experienced greater losses in accuracy (and increases in time) than did young adults.

The present study was designed to examine the role of representational factors in adult age differences in geometric analogy tasks. Several theorists (e.g., Mulholland, Pellegrino, & Glaser, 1980; Spearman, 1923; Sternberg, 1977) have postulated that analogy tasks of the A:B::C:D form are solved by first decomposing and encoding the elements of each term, inferring relations between corresponding elements in the A and B terms, and then mapping or applying those relations to the appropriate elements in the C and D terms. These processes can be conceptualized as involving the construction of a representational structure indicating the relations among elements within the first two or last two terms (i.e., A with B and C with D), and also across pairs of terms (i.e., A–B with C–D). One possible means of illustrating these relations in the form of a simple neural-netlike circuit is portrayed in Figure 1.

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Processing in this circuit can be postulated to begin when the terms in the analogy are coded by a binary value according to whether the element has a standard (0) or nonstandard (1) value for a given feature. This encoding at the initial units or nodes in the circuit can then be considered to spread, or be propagated in some fashion, to all connecting nodes, with the convention that lines ending in a dark circle represent inhibition or negative activation, whereas lines without a dark circle terminus represent excitation or positive activation.

Notice that if all of the terms have the same values, there will be no activation at the Level 3 nodes because the excitatory connections will be completely balanced by the inhibitory connections. However, the Level 3 nodes will receive substantial activation if the A and B or C and D terms have different values, and thus these nodes can be termed *difference detectors*. A similar pattern of connections is also used in Levels 3, 4, and 5 to determine whether the A–B relation is the same as the C–D relation. That is, the node at Level 5 receives activation from the Level 4 nodes only when the A–B relation is different from the C–D relation. This node can therefore be considered a *decision* node because it is activated when the A–B relation is different from the C–D relation and the analogy is *false*. (Note that all problems in the task involved an invariant sequence of differences from the A–B to the C–D terms because problems in which the direction of differences varied across term pairs—e.g., size decreased from A to B and increased from C to D—proved to be very confusing to subjects in pilot research, and consequently were not presented in the experiment.)

The representational structure proposed in Figure 1 is very abstract and is simplified in a number of respects. For example, the circuit in Figure 1 obviously does not represent a complete model of the analogy task because it deals only with *different* or *false* decisions, and the illustration portrays the hypothesized structure for analogy problems involving only a single element. These omissions are primarily for the sake of simplicity because it is assumed that responses of *same* or *true* could be produced by the addition of connections to respond to the absence of activation in the critical units, and that problems with multiple elements could be represented by creating replicas of the basic circuit for each additional element in the problem.

Figure 1 is also intended only to correspond to geometric

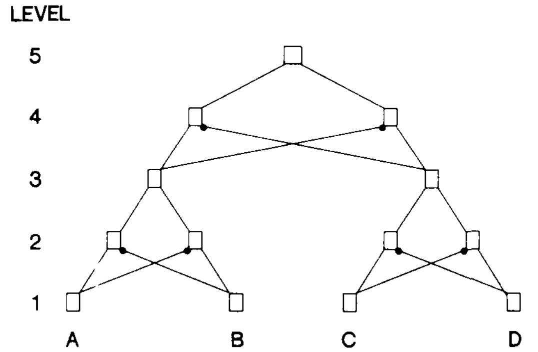

Figure 1. Illustration of a possible network structure for representing geometric analogy problems.

analogy problems in a verification format. The structure for verbal analogies would be more complex because the relations among elements would have to be retrieved from one's semantic knowledge system rather than directly abstracted from physically present features as is possible with geometric analogies. That is, when the relations and connections among elements or terms have to be established by forming linkages with one's prior knowledge base, the relational structures are presumably more complex than when relations can be equivalent to the transformations used to change the element in one term into the corresponding element in the other term. Figure 1 also portrays a verification format, involving true and false or yes and no decisions, which is obviously simpler than a multiple-choice or generation format in which the representational structure must reflect the generation and selection of the ideal D term, or the successive evaluation of alternative D terms to identify the correct solution.

Despite the relative simplicity of the structure in Figure 1, it has the advantage of providing a more integrated perspective of the processing involved in geometric analogy tasks than that implied by models with temporally discrete and qualitatively distinct processing components. Moreover, because in network models internal representations can be considered equivalent to a pattern of activation in the relevant nodes of the network, this conceptualization of processing stresses the importance of complete, accurate, and stable internal representations. For example, it is obvious in the circuit portrayed in Figure 1 that effectiveness of processing would be severely disrupted (a) if certain nodes malfunctioned and were unreliable, (b) if the timing of inputs to the various levels was not synchronized, or (c) if the overall level of activation within the network was too low to support stable linkages. Because the effects of aging in cognitive functioning are often attributed to analogous limitations of working memory, rate of processing, or attentional capacity, the neural circuit metaphor may prove useful in conceptualizing research on cognitive aging.

The primary goal of the current study was to investigate, in samples of young and older adults, the consequences of manipulations that might be expected to affect the stability or precision of structures such as that illustrated in Figure 1. One such manipulation is the number of elements in each term of the analogy because structures with more elements are likely to be more complex, and presumably more difficult to construct or maintain, than simpler structures with fewer elements. If the problem representations of older adults are initially less stable or less accurate than those of young adults, the former might be predicted to suffer more than the latter by increases in the number of relevant elements in the analogy problems. Actually, this hypothesis was tested, and strongly supported, in recent studies reported by Salthouse (in press), but it was considered desirable to attempt to replicate these results with better control and more precise measurement than that available with the earlier paper-and-pencil procedures.

Another manipulation designed to affect the stability of the inferred representational structures involved the variable of temporal delay between pairs of terms in the analogy. If the integrity of the constructed representation decays over time, one might expect successive presentation of the two pairs of terms (i.e., A–B and C–D) of the problem to cause greater difficulty for individuals for whom the structures are initially less stable. In other words, people with fragile representations (i.e., weak patterns of activation in the relevant circuits) should suffer greater performance impairments than should people with more durable or stable representations when the first pair of terms is removed several seconds before the presentation of the second pair of terms. Expressed in the notation of the hypothesized structure in Figure 1: If a time interval elapses between the presentation of the A–B and C–D terms, information about the A–B relation may become less reliable (and more so when the structure was initially of low stability), with the consequence that judgments about the identity or nonidentity of the relations in the two pairs of terms become less accurate. In other words, a delay may destroy the balance in the magnitude of the inputs to Level 4 in the circuit, thus resulting in inappropriate activation of the Level 5 decision node. This reasoning led to the hypothesis that older adults should experience greater performance impairments than should young adults with successive presentation of the analogy problems compared with simultaneous presentation.

Method

Subjects

A total of 15 young women and 9 young men between the ages of 18 and 24 years (M = 19.2 years), and 16 older women and 8 older men between the ages of 60 and 75 (M = 68.2 years), participated individually in a single experimental session of approximately 1½ hr. The young adults were college students participating to satisfy a course requirement, and the older adults were community residents who received a nominal monetary compensation for their time and travel expenses. Self-reported health status, ranging from *excellent* (1) to *poor* (5), averaged 1.5 for the young adults and 2.0 for the older adults, with 100% of both groups reporting themselves to be in average or better-than-average health (i.e., a rating of 3 or less). The range of education in the young group was from 12 to 15 years (M = 12.5 years), and that in the older group, from 8 to 22 years (M = 16.5 years).

Scores on the Wechsler Adult Intelligence Scale (Wechsler, 1958) Digit Symbol Substitution test averaged 69.6 (SD = 9.77) for the young adults, and 47.6 (SD = 9.31) for the older adults. Performance on a Spatial Memory test involving the reproduction of seven target positions from a 5×5 matrix (Salthouse, 1974, 1975, in press) averaged 4.61 (SD = 0.86) for young adults and 3.89 (SD = 0.64) for older adults. These differences in favor of young adults (i.e., t[46] = 7.97 for Digit Symbol, and 3.28 for Spatial Memory, both ps < .01) are quite similar to those found by Salthouse (in press) and other investigators, and provide some assurance that the samples of individuals in the current study are fairly typical of those available for testing in studies of cognitive aging. Moreover, the members of the older group were relatively homogeneous on these variables, despite a 15-year age range, because neither of the correlations between age and Digit Symbol (r = .26) and between age and Spatial Memory (r = −.14) approached statistical significance.

Procedure

Each subject was administered the following sequence of tasks: Digit Symbol Substitution subtest from the Wechsler Adult Intelligence Scale, Spatial Memory test, practice on the analogy problems with both simultaneous and successive presentation, 40 analogy problems with simultaneous presentation, 80 analogy problems with successive presentation, and finally, another 40 analogy problems with simultaneous presentation.

The analogy problems were presented on a computer-controlled display monitor with the terms presented in a horizontal row of boxes having horizontal and vertical dimensions of approximately 5.5 cm. Elements within terms consisted of the letters A–D with a height of approximately 2 cm in their normal or standard version.

Problems were presented in a verification format; that is, the subject was to decide whether the supplied D term was correct for the rest of the analogy. Transformations between the letter elements in the A and B or C and D terms consisted of alterations in size (normal or reduced 50%), completeness (normal or deletion of the right half), rotation (upright or rotated clockwise 90°), or black and white reversal (light figure on dark background or vice versa). The number of elements (and, hence, the number of possible transformations because a given element could only be subjected to one transformation) per term was randomly varied across problems with the constraint that there were a total of 20 problems each with one, two, three, and four elements per term in both the simultaneous and successive presentation conditions.

Problems in the simultaneous presentation condition had all of the terms of the analogy (i.e., A, B, C, and D) displayed concurrently, and the complete display remained visible until the subject entered a response (rightmost key on the bottom row of the keyboard for true, or leftmost key on the bottom row of the keyboard for false).

In the successive presentation condition, the first two terms (i.e., A and B) of the problem were displayed until the subject indicated, by pressing the *return* key, that he or she was ready for the next two terms. This response caused the erasure of the first display and 5 s then elapsed until the display of the last two terms (i.e., C and D). This display remained visible until the subject entered a response to indicate a decision about the validity of the analogy.

Instructions in both simultaneous and successive presentation conditions stressed accuracy more than speed as subjects were told that they should try to respond accurately and as soon as they knew the answer, but they were allowed as much time as necessary to respond. A reminder of the assignment of decisions to keys (i.e., *false* on the left and *true* on the right) was always displayed on the bottom of the screen when the subjects were to make a response.

Results and Discussion

The primary dependent variables were the percentage of erroneous decisions and the median response latency across varying numbers of elements in the simultaneous and successive conditions. The means of these variables across subjects in each age group are displayed in Table 1. Nearly identical patterns were evident in analyses of variance on the two variables (with latency in the successive condition measured from the display of the C–D pair of terms). The main effects of age, $F(1, 46)$ = 6.31, MS_e = 13.8, for errors, and $F(1, 46)$ = 40.22, MS_e = 20,516,383.4, for latency; presentation condition, $F(1, 46)$ = 32.68, MS_e = 2.9, for errors, and $F(1, 46)$ = 273.44, MS_e = 4,408,534.4, for latency; and number-of-elements, $F(3, 138)$ = 56.14, MS_e = 2.0, for errors, and $F(3, 138)$ = 369.89, MS_e = 1,179,089.6, for latency, were all significant (p < .01), as were the interactions of Age × Presentation Condition, $F(1, 46)$ = 4.26, MS_e = 2.9, for errors, and $F(1, 46)$ = 13.62, MS_e = 4,408,534.4, for latency; and Age × Number-of-Elements, $F(3, 138)$ = 11.63, MS_e = 2.0, for errors, and $F(3, 138)$ = 19.03, MS_e = 1,179,089.6, for latency. In addition, the interaction of Presentation Condition × Number-of-Elements was significant (p < .01) for both variables, $F(3, 138)$ = 9.63, MS_e = 1.6, for accuracy, and $F(3, 138)$ = 87.46, MS_e = 936,834.7, for latency, but the interaction of Age × Presentation Condition × Number-of-Elements was not significant for either variable.

Table 1
Mean Latencies (in seconds) and Error Percentages in Successive and Simultaneous Presentation Conditions for Young and Older Adults

No. of elements/ Age group	Latency: Successive A:B	Latency: Successive C:D	Latency: Simultaneous A:B::C:D	Error (%): Successive	Error (%): Simultaneous
1					
Young	2.14	2.13	3.55	2.7	3.7
Older	3.61	3.53	6.00	5.2	3.7
Difference	1.47	1.40	2.45	2.5	0.0
2					
Young	3.72	2.70	4.75	4.6	3.1
Older	6.18	4.67	7.95	9.4	4.6
Difference	2.46	1.97	3.20	4.8	1.5
3					
Young	4.97	3.45	6.11	12.3	6.2
Older	8.62	5.72	9.85	16.4	7.3
Difference	3.65	2.27	3.74	4.1	1.1
4					
Young	7.30	4.23	9.11	12.9	6.6
Older	12.74	7.16	14.62	27.7	16.0
Difference	5.44	2.93	5.51	14.8	9.4

Inspection of the trends in Table 1 indicate that the interactions of Age × Presentation Condition and Age × Number-of-Elements with the error variable were attributable to larger age differences with successive than with simultaneous presentations, and to the age differences increasing with a greater number of elements. Because the analyses with the latency variable in the successive condition were based on data from only the C–D terms, the Age × Presentation Condition interaction in this case represented larger age differences in the simultaneous than in the successive condition. However, examination of the data in Table 1 reveals that the age differences were larger in the successive condition when total time per problem (i.e., A–B plus C–D) are considered. These trends support the hypotheses presented earlier, and thus are consistent with the interpretation of age differences originating because of age-related difficulties in the formation and maintenance of complete and accurate internal representations of the to-be-solved analogy problems.

Because the successive presentation condition involved independent measurement of the time taken by the subjects to process the first two terms in the problem, these data were examined to determine whether young and older adults differed with respect to the distribution of processing durations on the A:B terms relative to the C:D terms. For this purpose, the data were transformed into ratios of C:D latency to A:B latency and an analysis of variance was then conducted on the resulting ratios. The overall ratio increased from 1.03 with one element per term to 1.37, 1.50, and 1.77 with two, three, and four elements per term, respectively, $F(3, 138) = 48.08$, $MS_e = 0.1$, $p < .01$, but neither the age nor the Age × Number of Elements effects were significant (i.e., both $Fs < 1.0$). The absence of significant age differences in this ratio suggests that young and old adults were comparable with respect to the relative amount of time they spent processing the first and second pairs of terms in the problems. To the extent that different patterns of processing time across problem elements reflect alternative strategies of performing the task, these results provide no indication that young and older adults used different strategies in this task.

Although the preceding results are consistent with the proposal that older adults perform poorly relative to young adults, because they are less able to construct and maintain accurate internal representations of the problem components, the reasons for these inferred representational weaknesses are still not known. That is, although deficient representations might be the proximal cause of age differences in accuracy of performance, it remains to be determined why increased age appears to be associated with poorer quality (i.e., simpler and less stable) internal representations.

Salthouse and Prill (1987) suggested that an age-related reduction in the quantity of some type of processing resource might be a major contributor to the hypothesized structural weaknesses in the internal representations of older adults. Specifically, they proposed that the constructed representations might be deficient because

> (a) limitations of working memory lead to unreliable components; (b) there is insufficient attentional energy to link the components firmly together; or (c) a slower speed of operation results in the products of earlier operations disintegrating before later processing is complete. (Salthouse & Prill, 1987, p. 50)

The view that the quality of internal representations is dependent on the quantity of available processing resources has at least three interesting, and potentially testable, implications. One implication is that if both accuracy and speed of performance are consequences of the quantity of a single entity such as processing resources, and if the average amount is greater in young adults than in older adults, then there should be a lawful and meaningful relation between the performance levels of young and older adults across all relevant measures. In fact, although it is impossible to assess the absolute amount of available resources without knowing the demands placed by different tasks, it may be feasible to derive estimates of the relative quantity of resources in the two groups. That is, if young and old adults experience equivalent demands for processing resources, and measures of errors or time are inversely related to the quantity of available resources, then the ratio of old to young performance should provide an estimate of the amount of resources available to young adults relative to that available to older adults. (See Salthouse, in press, for further discussion of this reasoning.)

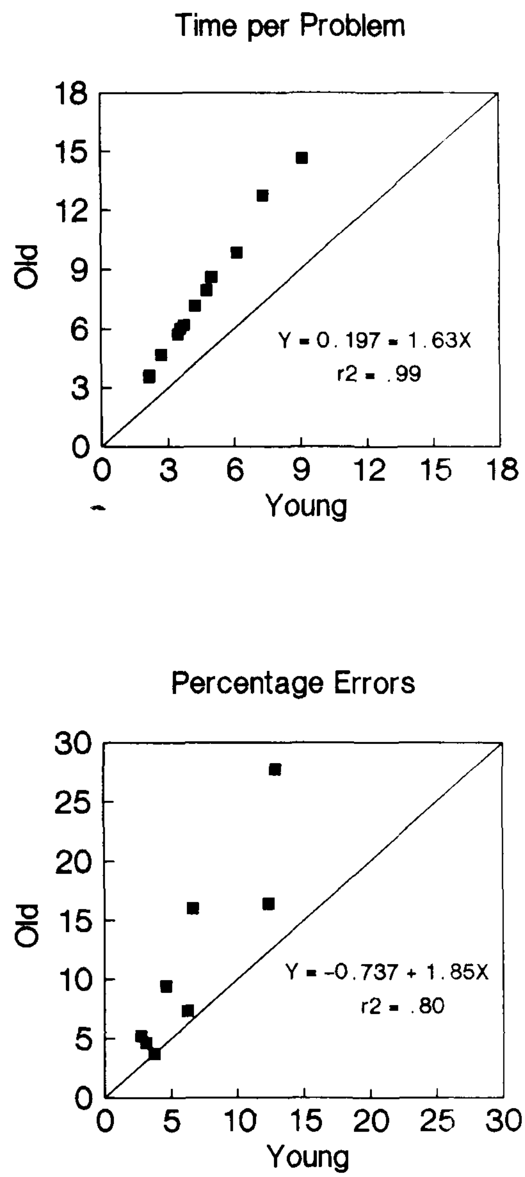

Figure 2. Performance of older adults as a function of performance of young adults for the variables of response time and percentage errors.

One means by which this implication can be examined is to plot performance of older adults as a function of the performance of young adults across the various experimental conditions. If the data points can be accurately described by a linear equation, then the reciprocals of the slopes of these young–old functions might be interpretable as a reflection of the quantity of resources available to older adults relative to that available to young adults. Graphs of this type for the time values (which may reflect the duration of generating or accessing the representations) and the error values (which may reflect the probability of a representational failure) from Table 1 are illustrated in Figure 2.

The most interesting aspects of the data in Figure 2 are that

Table 2
Correlations Between Age and Analogy Performance With and Without Statistical Control of Digit Symbol Score

Type of presentation	No. of elements 1	2	3	4
% incorrect decisions				
Simultaneous				
r (age–performance)	−.00	.14	.09	.41**
r (age–performance, Digit Symbol)	−.20	−.02	−.18	.24
Successive				
r (age–performance)	.24	.28	.16	.44**
r (age–performance, Digit Symbol)	−.18	−.14	−.27*	.12
M time per problem				
Simultaneous				
r (age–performance)	.60**	.63**	.57**	.62**
r (age–performance, Digit Symbol)	.14	.11	.04	.15
Successive				
r (age–performance)	.61**	.70**	.70**	.68**
r (age–performance, Digit Symbol)	.17	.35**	.33**	.30*

* $p < .05$. ** $p < .01$.

the functions with both speed and error measures are reasonably linear (i.e., the r^2 are .99 for the speed measures and .80 for the error measures), and have roughly similar slopes of 1.63 and 1.85, respectively. In both respects, these findings are consistent with those of earlier studies. For example, the regression equations for the combined data across two studies of a similar task in Salthouse (in press) were as follows: old = 1.16 + 1.56 (young), r^2 = .93, for time; and old = 2.93 + 1.79 (young), r^2 = .79, for errors. Numerous analyses of reaction time data have also generally revealed quite linear functions with slopes derived from adults in their 60s and adults in their early 20s of between 1.5 and 2.0 (e.g., Cerella, 1985; Cerella, Poon, & Williams, 1980; Salthouse, 1978, 1985a, 1985b).

The consistency with which slopes of between 1.5 and 2.0 have been discovered in comparisons of the performance of adults in their 20s with adults in their 60s suggests that some type of relevant processing resource diminishes to about 1/2.0 to 1/1.5, or roughly 50% to 67%, the peak level from about age 20 to about age 70. Of course, there is no assurance that the entity that declines by this amount is equivalent to what has been referred to as *processing resources*, or is responsible for the inferred representational deficits discussed earlier, but the apparent reliability of these quantitative patterns across measures of both speed and accuracy of performance indicates that something important for successful processing does diminish by about this magnitude with increased age.

A second implication of the resource-based interpretation of age differences in cognition is that statistical control of an index of resource quantity should eliminate, or at least greatly attenuate, the effects of age on the measure of cognitive performance. That is, if reductions in resource quantity mediate the effects of age on a cognitive task, then statistical control of resource quantity should substantially reduce the magnitude of those effects. A third implication is that correlations between various measures of performance and an index of resource quantity should increase in magnitude in both young and old groups as the demands on resources increase, as is postulated to be the case when the number of elements is increased or the terms are presented successively rather than simultaneously. In other words, even within a group that is relatively homogeneous with respect to age, a relation might be expected between resource quantity and performance, with the magnitude of that relation varying with the resource requirements of the task.

Because the nature of processing resources is still not known, and consequently the validity of any potential resource index is currently only a matter of speculation, it is obviously impossible to provide definitive tests of these hypotheses at the present time. Nevertheless, the availability of the Digit Symbol scores for each participant provided the opportunity to conduct preliminary tests of the hypotheses by assuming that it reflects a resource related to speed of processing. (See Salthouse, in press, for the rationale behind this argument.) This measure also possesses the intriguing property that the current sample of older adults performed at about 68% the level of the sample of young adults, which is nearly the amount of relative difference in resource quantity estimated to exist between the groups on the basis of the computations described earlier.

Correlations relevant to these hypotheses are displayed in Tables 2 and 3. The entries in Table 2 indicate that the predicted pattern of attenuated correlations after statistically controlling for an index of resource quantity was generally found, although three of the four partial correlations with the latency measure under the successive presentation condition were still significantly greater than zero. One way in which these results can be summarized is to report the percentage of age-related variance in performance associated with the median correlation for each measure. The median correlation between age and the error percentage measure was .20, indicating that only about 4.0% of the total variance in error scores was attributable to age. Partialing out the Digit Symbol resource index reduced the median correlation to −.16, or 2.6% of the total variance accounted for by age. A more impressive pattern was evident with the latency

Table 3
Correlations Between Analogy Performance Measures and Digit Symbol Scores

Type of presentation	No. of elements 1	2	3	4
% incorrect decisions				
Simultaneous				
Young	−.50*	−.41*	.48*	.25
Old	.16	.05	.12	.10
Successive				
Young	−.69*	−.47*	.46*	−.11
Old	−.24	.39	.45*	−.37
M time per problem				
Simultaneous				
Young	−.35	−.70**	−.65**	−.67**
Old	−.59**	−.53**	−.57**	.47*
Successive				
Young	−.38	−.34	−.47*	.32
Old	−.56**	−.46*	−.48*	−.50*

* $p < .05$. ** $p < .01$.

variable because the zero-order correlation between age and performance was much higher, that is, $r = .62$, and thus 38.4% of the total variance was associated with age. Partialing out the Digit Symbol resource index reduced the median correlation to .16, indicating that after controlling for the influence of the hypothesized speed resource, age accounted for only 2.6% of the variance in latency measures of performance.

The within-group correlations are displayed in Table 3. It can be seen that the data provide little support for the hypothesis that the relation between resource quantity and performance should be more pronounced when the resource demands are greatest. According to the predictions, the correlations should have increased with more elements per term, and should have been larger with successive presentation than with simultaneous presentation. The data in Table 3, however, indicate that neither of these trends was evident in either the young- or older adult samples. Similar analyses in studies reported by Salthouse (1987, in press) also revealed little or no trend for the magnitude of the relations within age groups to increase as the presumed resource demands increased.

The failure to confirm the resource expectations across individuals within age groups may be attributable to the influence of the resources being smaller within groups that are relatively homogeneous in the quantity of the presumed resource. Alternatively, it could be that the assumption is false that some type of processing resource contributes to cognitive functioning and that its quantity decreases with age. Still another possibility is that the Digit Symbol measure is not a valid reflection of the quantity of processing resources. It is probably too early to determine which of these interpretations is most likely, but the intriguing results in Figure 2 and Table 2 suggest that the resource perspective of age differences in cognition warrants further investigation.

In summary, the results of the current experiment are consistent with the idea that older adults perform poorly in certain cognitive tasks because of imprecise or instable internal representations. It is still not clear what is responsible for these inferred representational deficiencies, but an age-related reduction in the quantity of some type of processing resource is a likely candidate. The nature of that resource cannot yet be specified, but there is evidence that suggests that the relevant resources may decline to about 50% to 67% of the quantity available to 20-year-olds by the ages of 65 to 70.

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