# CHAPTER 24

# Effects of Aging on Reasoning

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This chapter reviews empirical research on adult age differences in reasoning. It is important to begin with three disclaimers, however. First, although many types of reasoning have been identified (e.g., deductive, inductive, analogical, and visuospatial; see articles in this volume by Evans, Chap. 8; Sloman & Lagnado, Chap. 5; Buehner & Cheng, Chap. 7; Holyoak, Chap. 6; and Tversky, Chap. 10), few age-comparative studies have included more than two or three different reasoning variables and, as a result, there is little evidence for distinctions among various types of reasoning in studies of aging. Different reasoning tasks therefore are considered together in this chapter, although it is recognized that combining them in this manner may be obscuring potentially important distinctions. Second, the discussion is limited to reasoning tasks with minimal involvement of knowledge. Because knowledge is likely relevant in most everyday reasoning, the tasks discussed may refer to only a subset of real-life reasoning. The third disclaimer is that most of the discussion refers to research derived from my laboratory. This obviously represents only a por-

tion of the relevant literature, but limitations of space preclude comprehensive coverage of all of the research related to the topic of aging and reasoning. A more inclusive review of the earlier literature on this topic can be found in Salthouse (1992a).

Some of the most convincing data on the relations between age and reasoning are those derived from standardized tests because the variables were designed to optimize psychometric properties such as sensitivity, reliability, and construct validity, and the normative samples have typically been moderately large and selected to be representative of the general population (see Sternberg, Chap. 31, for discussion of intelligence tests). Three recent cognitive test batteries have each included at least two measures of reasoning. The tests included in the Kaufman Adult Intelligence Test (Kaufman & Kaufman, 1993) were described on page 6 of the test manual in the following manner: Logical Steps – "Examinees attend to logical premises presented both visually and aurally, and then respond to a question making use of the logical premises;" and Mystery Codes – "Examinees study the identifying codes
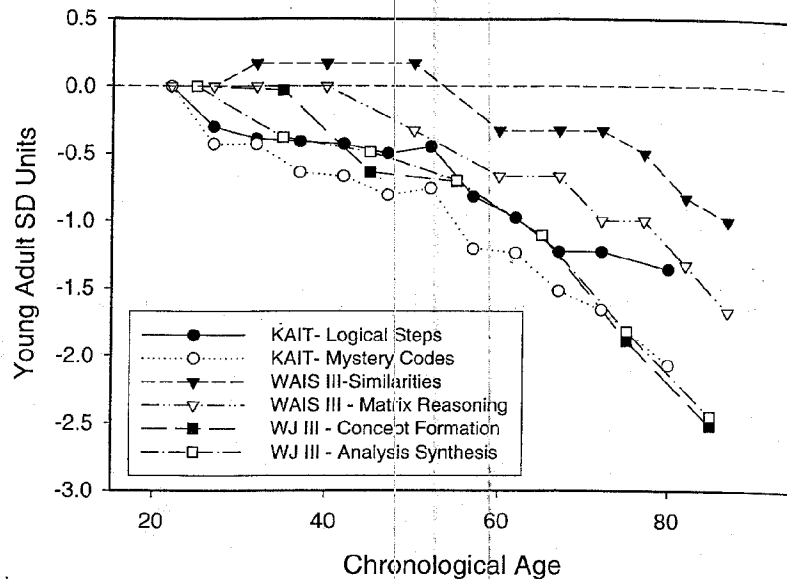
Figure 24.1. Relations of reasoning performance to age in variables from standardized tests. Sample sizes were 1,350 for the Kaufman Adolescent and Adult Intelligence Test (KAIT), 2,050 for the Wechsler Adult Intelligence Scale (WAIS) III, and 2,505 for the Woodcock Johnson (WJ) III.

associated with a set of pictorial stimuli and then figure out the code for a novel pictorial stimulus." Two reasoning tests included in the latest version of the Wechsler test battery, the Wechsler Adult Intelligence Scale III (Wechsler, 1997) were described in Table 24.1 of the Administration and Scoring Manual as follows: Similarities – "A series of orally presented pairs for which the examinee explains the similarity of the common objects or concepts they represent;" and Matrix Reasoning – "A series of incomplete gridded patterns that the examinee completes by pointing to or saying the number of the correct response from five possible choices." Finally, two reasoning tests included in the Woodcock–Johnson III (Woodcock, McGrew, & Mather, 2001) battery were described in Table 4.2 of the Examiner's Manual as follows: Concept Formation – "Identifying, categorizing, and determining rules;" and Analysis–Synthesis – "Analyzing puzzles (using symbolic formulations) to determine missing components."

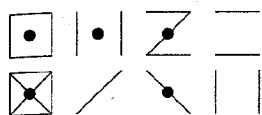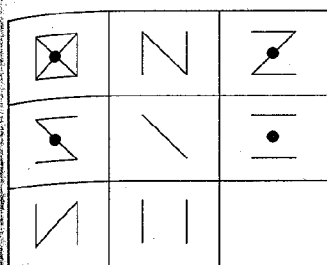To allow across-variable comparisons, the variables must be converted into the same scale, and a convenient scale for this purpose is standard deviation units. (These particular variables could have been expressed in units of percentage correct, but that scale is not as widely applicable because, for example, it is not meaningful when the variables are measured in units of time.) The manuals for these tests did not present the normative data in a form that would allow conversion of the scores to standard deviation units of the total sample. However, it was possible to express the scores in standard deviations of a young adult group, which has the advantage that the magnitude of the age-related effect can be expressed relative to the peak level of performance achieved across all ages. Age relations in the six reasoning tests just described therefore are portrayed in Figure 24.1 in standard deviation units of a reference group of young adults.

Examination of the figure reveals that all of the variables exhibit the same trend of lower performance with increased age. In particular, for most of the variables, the average seventy-year-old is performing about one standard deviation below the average

## Matrix Reasoning

## Analytical Reasoning

Jason and Jessica are planning a dinner party and have invited six guests: Mark and Meredith, Christopher and Courtney, and Shawn and Samantha. Their table seats three people on each side and one at each end. In planning the seating arrangements they need to: have Jason and Jessica sit at opposite ends of the table; place Christopher at a corner with no one on his left; not have Mark seated next to Samantha; and have Courtney seated next to Meredith.

Which of the following is an acceptable arrangement of diners along one side of the table?
- Jason, Samantha, Mark
- Christopher, Jessica, Shawn
- Mark, Courtney, Samantha
- Meredith, Shawn Courtney
- Shawn,Christopher,Meredith

## Series Completion

13 – 15 – 20 – 28 – 39 - **???**

## Integrative Reasoning

F and G do the SAME
E and F do the OPPOSITE
G and H do the OPPOSITE
If E increases will H decrease?

Figure 24.2. Examples of problems in four different reasoning tasks used in studies by Salthouse and colleagues. See text for details.

of the young adults. The age trends are not completely uniform because the age effects appear to be later and smaller for some variables (e.g., Similarities) than for other variables (e.g., Analysis–Synthesis). However, it is important to note that there is also considerable across-sample variation because the age gradients are shallower for both Wechsler subtests (i.e., Similarities and Matrix Reasoning) than for the subtests from the other batteries.

Relations between age and measures of reasoning can also be illustrated with four reasoning tasks used in several studies in my laboratory. Examples of problems in each type of task are portrayed in Figure 24.2. In matrix reasoning tasks (such as Raven's Progressive Matrices, Raven, 1962), the examinee attempts to select the best completion of the missing cell from the alternatives presented below the matrix. The goal in series completion tasks (such as the Shipley Abstraction Test, Zachary, 1986) is to deter-

mine the item that provides the best continuation of the sequence of items. In analytical reasoning tasks, the examinee uses the presented information to determine which of several alternatives best satisfies the specified constraints. Finally, examinees in integrative reasoning tasks use the information in the premises to answer a question about the relation between two of the variables. Although no formal evidence is available, it seems likely that these four tests represent somewhat different types of reasoning, and they certainly involve different requirements and types of material.

Because the tasks were each administered in two or more studies from my laboratory, the data have been combined across studies. The research participants in the studies were all similar in that they ranged from 18 to over 80 years of age, had an average of between 14 and 17 years of education, and generally reported themselves to be in good to excellent health.
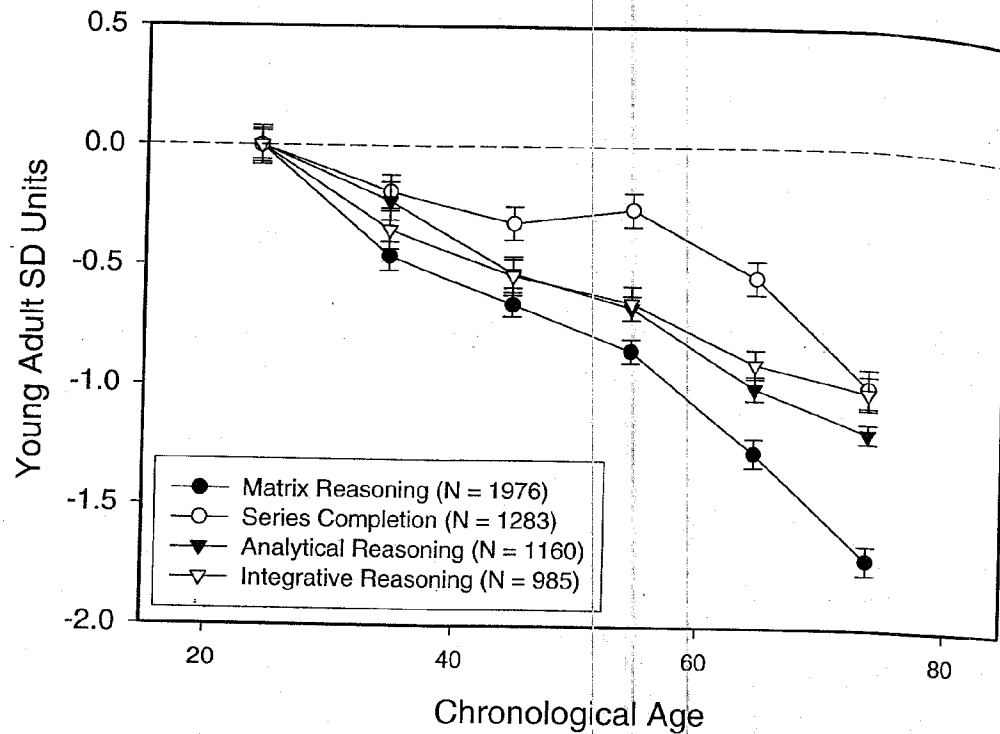
Figure 24.3. Means and standard errors of performance in four different reasoning tasks as a function of age. Data from various studies by Salthouse and colleagues.

Age relations in these four tasks are portrayed in Figure 24.3 in the same format used to display results of the tests from the psychometric test batteries. It can be seen that the pattern with these data closely resembles that from the normative samples in the standardized test batteries. In particular, there is an approximately linear decline in performance with increased age, such that the average at age seventy is about one standard deviation below the average of the reference group of young adults.

The age relations for three of the variables in Figure 24.3 were nearly identical, but the age function was shallower for the series completion variable. This may be because several items in the Shipley Abstraction series completion test (from which these data were derived) have considerable reliance on verbal knowledge, which tends to be relatively well preserved across this age range. For example, some of the items in that test involve determining relations among letters in reverse alphabetical sequence, or among words with particular semantic relations. Additional support for this differential-involvement-of-knowledge interpretation of the different age trends is provided by the correlations of the reasoning variables with a composite vocabulary variable, as the correlations were 0.37 for matrix reasoning, 0.23 for analytical reasoning, 0.24 for integrative reasoning, and 0.66 for series completion.

Although not apparent in Figures 24.1 and 24.3, other results indicate that the age relations on variables assessing reasoning are as large or, in some cases, even larger than the age relations on other types of cognitive variables. For example, Verhaeghen and Salthouse (1997) reported a meta-analysis in which the weighted correlation (based on 9,342 individuals across thirty-eight studies) between age and measures of reasoning was −.40, and the weighted correlation (based on 5,871 individuals across

twenty-nine studies) between age and measures of episodic memory was $-0.33$. Furthermore, in analyses to be described later, the correlations between age and factor scores were very similar for factors based on memory ($r = -0.48$) and reasoning ($r = -0.49$) variables.

Despite their similar magnitude, age differences in reasoning are not as widely recognized as age differences in memory. A possible reason may be that considerable knowledge is required in many everyday situations that involve reasoning, such that any age effects might not be noticed either because of a large positive relation between age and knowledge, or because any deficiencies are attributed to lack of relevant knowledge instead of to problems of reasoning.

The primary question in light of age differences such as those apparent in Figures 24.1 and 24.3 is, "What is responsible for the large negative relations between age and performance on measures of reasoning?" Much of the research that has been conducted to address this question can be classified into one of two broad categories. One category consists of investigations of the influence of factors such as comprehension, speed, strategy, and working memory on the age differences in the performance of a particular reasoning task. The second category of research has involved examining age-related effects on measures of reasoning in the context of age-related effects on other cognitive abilities. In the remaining sections of this chapter, the two approaches are illustrated with research from my laboratory.

## Process-Oriented Research

The majority of the empirical research in the area of cognitive aging has focused on a single cognitive variable (with different studies concentrating on different variables), and has attempted to determine the relative contribution of different processes to the age differences on that particular variable. Among the potential determinants of age differences in reasoning variables that have been investigated in this manner are comprehension, speed, strategy, and working memory. Empirical research relevant to each of these potential determinants is briefly summarized in this section.

### Comprehension

It is conceivable that at least some of the age differences in reasoning are simply attributable to greater difficulties associated with increased age in understanding exactly what is required to perform the task successfully. This is an important possibility to consider because age differences in reasoning would probably not be of much theoretical interest if they merely reflected comprehension problems.

The primary means by which the comprehension interpretation has been investigated restricted comparisons to individuals for whom there is evidence that they understood the task requirements. For example, participants with accuracy less than some criterion value have been excluded from the analyses in integrative reasoning (Salthouse, 1992b, 1992c) and matrix reasoning (Salthouse & Skovronek, 1992) tasks, and analyses have been restricted to participants with correct responses on the first two items in the matrix reasoning (Salthouse, 1993) task. In each of these cases, strong negative age relations were evident among the participants who understood the tasks well enough to answer several problems correctly. These results therefore suggest that age differences in simple comprehension probably are not responsible for much, if any, of the age differences observed in measures of reasoning.

### Speed

Another relatively uninteresting possibility is that age differences in measures of reasoning might merely reflect a slower rate of reading or of responding, without any detrimental effects on the quality of performance. Because effects of age-related slowing have been extensively documented (e.g., Salthouse, 1996a), it is important to consider whether age differences in reasoning

might be attributable to slower peripheral processes associated with encoding or responding to the information.

One way in which the role of slower rates of input or output has been investigated involves examining age relations on reasoning tasks administered under untimed, or self-paced, conditions. Most of the comparisons have revealed significant age differences even when the participants are allowed to control the duration of the stimulus presentation, and take as long as they want to respond. Age differences in decision accuracy under these conditions have been found in geometric analogies (Salthouse, 1987), series completion (Salthouse & Prill, 1987), matrix reasoning (Salthouse, 1993; 1994; Salthouse & Skovronek, 1992), and integrative reasoning (Salthouse, 1992c; Salthouse et al., 1989; 1990) tasks, and in the Wisconsin Card Sorting Test (WCST; Salthouse et al., 1996; Fristoe, Salthouse, & Woodard, 1997; Salthouse et al., 2003).

The role of speed on age differences in matrix reasoning was examined more closely in two studies by Salthouse (1994) by obtaining separate measures of study time, decision time, and decision accuracy from each participant. Not only were significant age differences found on each measure, but analyses revealed that some of the age-related effects on the decision accuracy measure were statistically independent of the age-related effects on the study time and decision time measures. At least in this project, therefore, older adults took longer than younger adults to work on the problems and to communicate their decisions, and their decisions were less accurate.

A second method of investigating the role of limited time on age differences in reasoning involves examining age differences in the percentage of items answered correctly only for attempted items, as inferred by the presence of an overt response. Strong negative age relations have been found even when only attempted items were considered in integrative reasoning (Salthouse, 1992b), geometric analogies (Salthouse, 1992b), and matrix reasoning (Salthouse, 1991; 1993;

1994) tasks, and on the accuracy of early items in matrix reasoning and analytical reasoning tests that were attempted by everyone (Salthouse, 2000, 2001).

Taken in combination, the results just described suggest that adult age differences in reasoning are not simply attributable to slower rates of reading or responding. The speed of internal mental operations may be a factor in some of the performance differences (see Salthouse, 1996a), but because sizable age differences in accuracy are found when there are no external time constraints, the differences do not appear to be solely the result of slower rates of input or output.

## Strategy

One of the most popular interpretations of age differences in cognitive functioning, at least in part because it implies that the age differences might be amenable to intervention, attributes them to the use of different strategies by adults of different ages. It is important to consider two issues when evaluating this distinction: whether or not adults of different ages actually do use different strategies when performing the task and, if so, what is responsible for those differences.

Information about the existence of possible strategy differences has been obtained by examining the distribution of study times across different parts of the reasoning problem. For example, the research participant could be instructed to press a key to view each element of the problem, and then the time between successive keystrokes could be recorded to determine the time devoted to inspecting or studying each element. Variants of this method have been used in a number of reasoning tasks with comparable outcomes. Specifically, the relative distribution of inspection or study times has been found to be similar in young and old adults in series completion (Salthouse & Prill, 1987), integrative reasoning (Salthouse et al., 1990), and geometric analogies (Salthouse 1987). To the extent that relative time allocation across different elements of a problem can be considered as evidence of a particular

strategy, therefore, these results imply that young and old adults were using a similar strategy.

Additional evidence relevant to the strategy interpretation of age-related differences in reasoning is based on an examination of possible age differences in the pattern of incorrect alternatives selected when choosing a response. The rationale is that adults of different ages might be expected to differ in the frequency of selecting particular incorrect alternatives if they were relying on different rules or strategies to select their answers. However, no age differences in the relative percentages of different types of errors in a matrix reasoning task were found by Salthouse (1993; also see Babcock, 2002), which suggests that adults of different ages were probably using the same strategies but that the effectiveness of the strategies was lower with increased age.

Finally, a study by Fristoe, Salthouse, & Woodard (1997) was designed to investigate the manner in which young and old adults performed the WCST. The WCST is a concept identification test in which the stimuli consist of cards that vary in the number, color, and shape of objects. An unusual feature of the test is that the rule (i.e., number, color, or shape) used to determine the correct sorting of the cards changes after every 10 correct sorts without informing the participant. The participants in the Fristoe, Salthouse, & Woodard (1997) study were asked to indicate the dimension that they were using in making their decisions about how to sort stimulus cards. By combining this information with the responses selected and the feedback received after each response, it was possible to determine the percentage of times each participant maintained the same hypothesis after receiving positive feedback (i.e., "win–stay"), and the percentage of times he or she changed hypotheses after receiving negative feedback (i.e., "lose–shift").

Optimal performance in this type of feedback-based concept identification situation would be manifested in high percentages of "win–stay" and "lose–shift" behavior.

Compared with young adults, older adults had lower percentages of both types of behavior, and statistical control of a composite measure of feedback usage reduced the age-related variance in a measure of WCST performance by 74%. These results clearly indicate that the young and old adults in this study performed the task in a somewhat different fashion and that the difference was related to success in the task. However, because there was no evidence that the older adults were as capable as the young adults of performing in the same optimal manner, it is questionable whether the differences observed in the way the task was performed should be considered evidence for differences in strategy, which has a voluntary or optional connotation.

Although only a limited amount of relevant evidence is currently available, it does not appear that much, if any, of the age-related differences in reasoning can be explained by differences in the strategies used to perform the task. Furthermore, it is important to recognize that, even if evidence of strategy differences were available, interpretations based on strategy differences are likely to be somewhat ambiguous unless an explanation is also provided for why people of different ages used different strategies. That is, if strategy differences were to be found, a critical question is whether the most effective or optimal strategy is still feasible for older adults but not used for some reason, or whether older adults are less able to use the more powerful or optimal strategy than young adults. As a result, a difference in strategy might be viewed merely as a different level of description, such that if age differences were to be found, they would still need to be explained, just as would age differences in measures of overall task performance.

### Working Memory

An interpretation that has generated considerable interest, particularly since a provocative article by Kyllonen and Christal (1990) that reported a very strong relation between

measures of working memory (WM) and measures of reasoning (see Morrison, Chap. 19), is that at least some of the age-related differences in reasoning might be attributable to age differences in WM. Because WM has been defined as the ability to preserve information while processing the same or other information, and because many reasoning tasks require that information be maintained in order for it to be operated upon, interpreting the age differences in reasoning as a function of WM has considerable intuitive plausibility.

One method used to investigate the role of WM in reasoning involves manipulation of the number of premises presented in integrative reasoning problems. The rationale that increasing the number of premises would increase the WM requirements, which might then be expected to increase the magnitude of the age differences in reasoning performance if at least some of those differences are attributable to WM limitations. Support for this expectation was provided in four independent studies (Salthouse, 1992b, 1992c; Salthouse et al., 1989; Salthouse et al., 1990). In each study, reasoning accuracy decreased as the number of premises increased, and the magnitude of this decrease was greater for older adults than for young adults.

Another manipulation incorporated in several integrative reasoning studies involved the presentation of trials in which only one of the premises was relevant to the decision. Consider the problem portrayed in the lower right panel of Figure 24.2, for example. In the version displayed, all of the premises are relevant to the decision and would need to be considered to reach a valid conclusion. If, instead of referring to variables E and H, the question referred to variables E and F, however, all of the information relevant to the decision would have been presented in a single premise. These "one-relevant" trials are interesting because no across-premise integration of information is required for a correct decision, and the major determinant of quality of performance therefore is presumably the ability to maintain the relevant information in

memory until it is needed. (In these particular studies, the task was administered on a computer and only one premise was visible at a time.)

A consistent finding in each of these studies (i.e., Salthouse, 1992c; Salthouse et al., 1989; Salthouse et al., 1990) was that the relation of accuracy to the number of premises was nearly identical when only one premise was relevant and when two or more premises were relevant. Furthermore, this pattern was similar across adults of all ages. These results therefore suggest that the primary reason why accuracy was lower when the problems contained more premises was related to the availability of information and not to difficulties in integrating relevant information. The fact that the pattern was similar in adults of all ages further implies that the age differences in this task are largely attributable to differences in the availability of relevant information.

An additional expectation from the information-availability interpretation is that age differences should be evident in the shape of the serial position functions relating decision accuracy to sequential position of the relevant premise. In fact, Salthouse et al. (1990) did find that young adults exhibited a classical serial position function, with higher accuracy for the more recent premises, whereas the function for older adults was flat. However, for reasons that are not yet clear, this pattern was not replicated in a later study by Salthouse (1992c).

Manipulation of the number of problem elements has also been examined in geometric analogy and matrix reasoning tasks, with somewhat different patterns of results. To illustrate, three studies found that age differences in measures of decision time, decision accuracy, or both, were larger when there were more relevant elements in geometric analogy problems (Salthouse, 1987, 1988, 1992c). In several studies reported by Salthouse (1993) and in a study by Salthouse (1994), however, age differences in a matrix reasoning task were nearly constant across increases in the number of relations among elements, and in none of these studies was

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there a significant interaction between age and number of relations in the problem. Specific characteristics of the tasks may be responsible for the different patterns of results across integrative reasoning, geometric analogy, and matrix reasoning tasks, but the exact nature of those characteristics is not yet known.

Another method used to investigate the role of WM in reasoning involves assessing on-line availability of information during the performance of the task. For example, Salthouse (1993) and Salthouse and Skovronek (1992) presented a successive version of the matrix reasoning task in which each matrix cell was numbered. To view a cell in the matrix, the participant had to type the corresponding number. In three separate studies, older adults were found to examine the same cell more frequently than young adults, as though the information inspected earlier was no longer functionally available to them. Furthermore, when presented with probes of information examined earlier, older adults were less accurate than young adults in recognizing the contents of previously viewed cells (Salthouse, 1993).

A final piece of evidence relevant to the WM interpretation of age differences in reasoning is that Salthouse (1992c) found a qualitatively similar pattern of differences between young and old adults, and between young adults with and without a concurrent memory load (of five random digits). To the extent that a concurrent memory load is viewed as simulating reduced WM capacity, this finding is consistent with the hypothesis that at least some of the age differences in the integrative reasoning task are attributable to age differences in WM.

In summary, results from a number of different types of comparisons in a variety of reasoning tasks lend credibility to the interpretation that the ability to maintain relevant information during the performance of reasoning tasks likely contributes to at least some of the adult age differences in reasoning. Although the available evidence suggests that working memory is probably involved in the age differences in reasoning, the exact extent of that involvement, and the role of other factors in the age differences, remain to be determined.

## Correlational Analyses

The second major approach to investigating adult age differences in cognition has relied upon correlational data to attempt to specify the number and nature of statistically distinct age-related influences operating on different types of cognitive variables. In this section, results relevant to understanding effects of aging on reasoning based on mediational, componential, correlated-factors, and hierarchical structure models are described briefly.

### Mediational Models

The goal of mediational models is to examine the role of one or more constructs as potential mediators of the age differences in measures of reasoning by means of statistical adjustment. The rationale is that if age-related effects on variable Y are at least partially attributable to age-related effects on variable X, then statistical control of X should reduce the magnitude of the age-related effects on Y. For the purpose of these analyses, X could be a measure of any factor hypothesized to be important in the target variable, Y. Most of the mediational models applied to reasoning have used measures of WM in the role of X because of the assumption that reasoning tasks frequently require that earlier information be preserved when processing later information, and individuals who are better able to do that, as reflected by higher scores on WM tasks, therefore would be expected to perform at higher levels on reasoning tasks.

Several studies in my laboratory have relied upon two tasks to assess WM. Both require participants to remember information while simultaneously processing other information. In the computation span task, for example, arithmetic problems had to be answered while remembering the last digit in each problem, and in the listening span

task, questions about a sentence had to be answered while remembering the last word in each sentence. Measures of performance in these tasks have been found to exhibit good reliability, and to be negatively correlated with age.

Three sets of results are necessary to establish the plausibility of a mediational interpretation of age-related differences in reasoning. The first is the demonstration of age-related differences in the expected direction in measures of the hypothesized mediator, because a construct cannot mediate age differences in other variables or constructs if it is not related to age. The second necessary result is the existence of a moderate relation between the hypothesized mediator and the target variable it is presumed to explain, because no mediation is possible if the suspected mediator and the target variable are not related to one another. Third, age-related differences in the target variable should be reduced after statistical control of the mediator, with the magnitude of the reduction serving as an approximate index of the degree of mediation. This last result is critical because mediation is not plausible if the relations of age to the target variable are not at least moderately attenuated when the variability in the hypothesized mediator is eliminated.

A variety of procedures can be used to statistically control the hypothesized mediator, such as partial correlation, semipartial correlation (available from hierarchical regression), analysis of covariance, and so on. In each case, the goal is to eliminate the variance in the target variable that is related to the mediator such that relations between age and the target variable can be examined when differences in the level of the mediator no longer influence the target variable.

The most relevant comparisons from mediational analyses of WM on reasoning are those between the initial age relation on the reasoning variable and the age–reasoning relation after statistical control of the WM measure. A consistent finding across several different types of reasoning tasks has been a substantial reduction in the age-related vari-

ance after statistical control of WM, with reductions of 57% (Salthouse et al., 1989), 88% (Salthouse, 1992b; also see Salthouse, 1991), and 48% (Salthouse, 1992c) in integrative reasoning tasks, 65% in a geometric analogies task (Salthouse, 1992b), and 43% to 84% in matrix reasoning tasks (Salthouse, 1993). Similar findings have been reported by other researchers with matrix reasoning (Babcock, 1994) and syllogistic reasoning (Fisk & Sharp, 2002; Gilinsky & Judd, 1994) tasks. Sizable reductions in the age-related differences after control of WM have been found even with percentage correct measures (Salthouse, 1992b) and on the accuracy of individual items in a matrix reasoning task (Salthouse, 1993). A significant relation of WM on two-premise and three-premise integrative reasoning problems also has been found after control of the influence of one-premise problems (Salthouse, 1992b, 1996b), which implies that WM specifically contributes to the maintenance of information needed in more complex problems.

This pattern of results clearly is consistent with the hypothesized influence of WM on age-related differences in reasoning. However, it is important to recognize that comparable, and sometimes even larger, reductions in the age-related effects in reasoning have been found after statistical control of other theoretical constructs, such as perceptual speed (e.g., Salthouse, 1991, 1993, 1994, 1996a). Because most cognitive variables are positively correlated with one another, some attenuation of the age-related effects on one cognitive variable likely would be expected after statistical control of almost any other cognitive variable. A discovery of attenuated age-related variance after statistical control of a hypothesized mediator therefore should be considered only necessary, but not sufficient, evidence for the validity of mediational hypotheses.

## Componential Models

Componential models are more complex than mediational models because they postulate that nearly every cognitive task involves multiple processes or components,

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and that performance of the task is influenced by the efficiency or effectiveness of each component. Componential models have been investigated by relying upon the pattern of correlations among measures of the components and a measure of performance on the target reasoning task to determine the relative contribution of each hypothesized component. For example, a researcher might postulate that components A, B, and C are required to perform a particular task, administer tasks to obtain variables that reflect A, B, and C as directly as possible, and then examine correlations among the variables based on the reasoning tasks and the component tasks. Componential models can be applied to research on aging by determining the degree to which age-related effects on the target reasoning task are altered when variability in measures of the components is statistically controlled.

Componential models of the matrix reasoning and analytical reasoning tasks were investigated by Salthouse (2001), and a somewhat different componential analysis of age differences in matrix reasoning was reported by Babcock (1994). Salthouse hypothesized three components were involved in each of the tasks: rule identification, rule application, and information integration in the matrix reasoning task; and simple comprehension, information integration, and condition verification in the analytical reasoning task. Primarily on the basis of intuition and judgments of face validity, two variables were selected to represent each hypothesized component. To illustrate, the rule identification component was assessed by a Figure Classification test, in which examinees determine the basis by which different figures are related to one another, and by a Location test, in which examinees determine the rule governing the position of a set of Xs in each row of a matrix. The rule application component was assessed with two tasks (i.e., Pattern Transformation and Geometric Transformation) in which the examinee views an initial line pattern or geometric figure, carries out a specified transformation (such as rotation, subtraction, or addition), and then decides whether the transforma-

tion applied to the initial figure would match a comparison figure.

A critical prerequisite for a componential analysis is that the pattern of correlations and, specifically, the results from a confirmatory factor analysis, should provide evidence for distinct constructs. That is, only if there is evidence that the variables represent separate constructs is it meaningful to examine their relative contributions to the age differences in the performance of the criterion reasoning task. The results of the two studies reported by Salthouse (2001) were not consistent with the existence of three separate factors because all of the variables had similar correlations with one another. To illustrate, the correlation between the two-rule identification variables was 0.50, and their correlations with variables hypothesized to reflect the rule application component ranged from 0.48 to 0.62. Because there was no evidence that the hypothesized components represented distinct dimensions of individual differences (i.e., exhibited construct validity), it was impossible in these studies to decompose the age differences in the target tasks into discrete components.

There are at least three possible interpretations of results such as those just described. First, the theoretical models may not have been valid because the designated components are not actually required to perform the tasks. Second, the models could have been valid and the components might have been relevant to performance on the target task, but the components were not accurately assessed with the selected tasks. And third, the models may not have been valid because the hypothesized components do not actually exist as distinct entities. Unfortunately, the available data do not allow these alternatives to be distinguished. However, it is worth considering whether a similar situation may exist in componential models of other cognitive tasks but has not been recognized because there have seldom been any attempts to investigate the construct validity of the hypothesized processes or components. Results of the Salthouse (2001) project therefore suggest that it is important to obtain empirical evidence of the construct

validity of hypothesized components before investigating their role in cognitive tasks.

## Correlated Factor Models

The variables included in mediational and componential models typically have been selected because of their presumed relevance to the target variable one is trying to explain. An alternative approach based on correlational data would be to consider the interrelations among a broad variety of cognitive variables in terms of some organizational structure and then examine relations of age to the target variable within the context of that structure.

The simplest organizational structure is one in which the variables are grouped into several first-order factors or abilities, with the factors allowed to correlate with one another. Age-related effects on specific reasoning variables can be investigated in this type of correlated-factors structure by determining the degree to which the age-related effects on the target reasoning variable are direct or are indirect and operate through one or more cognitive abilities.

The ideal data set for analyses involving cognitive abilities would involve a wide variety of cognitive variables, and as large and diverse a sample of participants as possible. No single study is likely to possess all of these characteristics, but an approximation to this ideal can be obtained by aggregating data across different studies involving different combinations of variables. Aggregation of the data in this way essentially treats the individuals as though they were participants in a single large study but with missing values for the variables that were not collected in the particular study in which an individual participated. Although data with a large proportion of missing values can be complicated to analyze, meaningful analyses can be conducted by relying on an algorithm such as the full information maximum likelihood procedure (e.g., Enders & Bandalos, 2001) to take advantage of all available information.

A combined data set of this type was created by aggregating data across 33 separate studies from my laboratory involving a to-

tal of 6,828 individuals. The major variables included in the aggregate data set are listed in Table 24.1 together with the respective sample sizes and age correlations. Entries in the right-most columns in Table 24.1 are the factor loadings from a confirmatory factor analysis in which factors corresponding to reasoning, spatial visualization, episodic memory, perceptual speed, and vocabulary abilities were postulated. As expected, the loadings of the variables on the factors all were high, with only four below 0.7, and the factors were moderately correlated with one another. A second model examined relations between age and each of the ability factors. These (standardized) relations were −0.49 for reasoning, −0.41 for space, −0.48 for episodic memory, 0.63 for speed, and 0.25 for vocabulary.

Inspection of the coefficients in the reasoning column reveals that the matrix reasoning and analytical reasoning variables both had high loadings on the reasoning factor and therefore can be considered prototypical reasoning tasks. The contributions of the five abilities to these two variables therefore were examined by modifying the analysis to specify relations of each of the five abilities to these variables. In effect, these analyses are asking what abilities contribute, and by how much, to the individual differences in performance of these tests. The top panel of Table 24.2 summarizes results of these analyses, where it can be seen that, as expected, the strongest relation of each variable was with the reasoning factor. However, it is important to note that each variable also had significant relations with factors representing other cognitive abilities. Both the matrix reasoning and the analytical reasoning variables were positively related to spatial visualization ability and negatively related to vocabulary ability. This latter relation is rather puzzling because it suggests that, when other relations are taken into consideration, people with higher levels of vocabulary tend to perform somewhat worse on these reasoning tasks than people with lower levels of vocabulary.

This simple structure can be used to estimate the indirect effects of age on reasoning

Table 24.1. Results of a Confirmatory Factor Analysis on Data Aggregated across Multiple Studies

| | | | Factor Loading | | | | |
|---|---|---|---|---|---|---|---|
| Variable | N | Age r | Rea | Spc | Mem | Spd | Voc |
| Matrix reasoning | 1976 | −.50 | .87 | | | | |
| Analytical reasoning | 1160 | −.46 | .76 | | | | |
| Shipley abstraction | 1283 | −.29 | .87 | | | | |
| Integrative reasoning | 985 | −.35 | .62 | | | | |
| Figure classification | 458 | −.60 | .74 | | | | |
| Cattell matrices | 420 | −.48 | .82 | | | | |
| Letter sets | 1179 | −.26 | .80 | | | | |
| Geometric analogies | 756 | −.36 | .78 | | | | |
| PMA reasoning | 305 | −.41 | .86 | | | | |
| Grammatical reasoning | 229 | −.35 | .80 | | | | |
| Series completion | 150 | −.37 | .80 | | | | |
| Analysis synthesis | 204 | −.36 | .79 | | | | |
| Power letter series | 150 | −.47 | .93 | | | | |
| WCST number of categories | 711 | −.28 | .56 | | | | |
| Diagramming relations | 449 | −.40 | .76 | | | | |
| Locations | 449 | −.41 | .60 | | | | |
| Spatial relations | 1154 | −.34 | | .91 | | | |
| Paper folding | 994 | −.43 | | .81 | | | |
| Form boards | 847 | −.38 | | .80 | | | |
| Surface development | 639 | −.32 | | .72 | | | |
| PMA space | 305 | −.39 | | .76 | | | |
| Block design | 463 | −.39 | | .89 | | | |
| Object assembly | 259 | −.41 | | .81 | | | |
| Cube assembly | 1272 | −.17 | | .60 | | | |
| Paired associates | 1769 | −.38 | | | .72 | | |
| Free recall | 1764 | −.42 | | | .84 | | |
| Logical memory | 793 | −.24 | | | .72 | | |
| Free recall of transfer list | 1054 | −.35 | | | .77 | | |
| Digit symbol | 2041 | −.57 | | | | .78 | |
| Letter comparison | 6082 | −.43 | | | | .79 | |
| Pattern comparison | 6082 | −.52 | | | | .82 | |
| Cross out | 204 | −.71 | | | | .92 | |
| Digit symbol reaction time | 2417 | −.56 | | | | .77 | |
| WAIS vocabulary | 795 | .13 | | | | | .86 |
| WJ picture vocabulary | 795 | .30 | | | | | .80 |
| Antonym vocabulary | 3509 | .18 | | | | | .90 |
| Synonym vocabulary | 3511 | .27 | | | | | .89 |
| Shipley vocabulary | 259 | .22 | | | | | .93 |
| Factor correlations | | | | | | | |
| Reasoning (Rea) | | | — | .88 | .73 | .79 | .47 |
| Space (Spc) | | | | — | .65 | .67 | .46 |
| Memory (Mem) | | | | | — | .70 | .42 |
| Speed (Spd) | | | | | | — | .28 |
| Vocabulary (Voc) | | | | | | | — |

Notes: N = number, Age r = , Rea = reasoning, Spc = space, Mem = memory, Spd = speed, Voc = vocabulary, PMA = Primary Mental Abilities, WCST = Wisconsin Card Sorting Test, WAIS = Wechsler Adult Intelligence Scale, WJ = Woodcock–Johnson.

Table 24.2. Loadings of Matrix Reasoning and Analytical Reasoning Variables on Five Cognitive Abilities

|  | Rea | Spc | Mem | Spd | Voc |
|---|---|---|---|---|---|
| **All** |  |  |  |  |  |
|   Matrix reasoning | .86* | .25 | −.06 | −.07 | −.20* |
|   Analytical reasoning | .76* | .25 | −.04 | −.13 | −.17* |
| **Matrix reasoning** |  |  |  |  |  |
|   Under age 50 | .97* | .18 | −.11 | −.08 | −.20* |
|   Age 50 and over | .79* | .30* | −.02 | −.02 | −.21* |
| **Analytical reasoning** |  |  |  |  |  |
|   Under age 50 | .91* | .01 | −.04 | −.04 | −.10 |
|   Age 50 and over | .50* | .46* | −.04 | −.09 | −.17 |

*p < .01

*Note:* None of the coefficients for the under-age-fifty group and the age-fifty-and-over group was significantly different from one another.

Rea = reasoning, Spc = space, Mem = memory, Spd = speed, Voc = vocabulary.

variables by incorporating information about the relations between age and each ability. To illustrate, because the standardized coefficient for the relation from age to the reasoning ability factor was −0.49, and that for the relation between the reasoning factor and the matrix reasoning variable was 0.87, it can be inferred that −0.43 (i.e., −0.49 × 0.87) of the total −0.50 age effect on matrix reasoning (cf. Table 24.1) is associated with influences through the reasoning ability factor.

The correlated-factors structure can also be used to investigate whether the variables represent the same constructs to the same degree at different ages (i.e., the issue of measurement equivalence). The preceding analyses therefore were repeated in samples of adults under and over the age of 50, with the results summarized in the bottom panels of Table 24.2. Inspection of the entries indicates that the pattern of ability relations for the matrix reasoning variable was very similar in the two age groups, consisting of a large positive relation with the reasoning factor, a small positive relation with the spatial visualization factor, and a small negative relation with the vocabulary factor. Although the pattern appears somewhat different across the two age groups for the analytical reasoning variable, a direct test in which the parameters were constrained to be equal in the two samples to determine if there was

a significant loss of fit to the data indicated that the group differences were not statistically significant. It therefore appears from these results that the two reasoning variables represent nearly the same combination of abilities at different ages. These particular results should be replicated before reaching any strong conclusions, but they serve to illustrate how correlational results can be informative about the possibility of qualitative differences in performance at different ages.

## Hierarchical Structure Models

The correlated-factors model can be considered relatively simple because, although the factors are allowed to correlate with one another, there is no attempt to explain the basis for those correlations in the context of the model. A somewhat more complicated model involves a hierarchical structure in which one or more higher-order factors are postulated to be responsible for the relations among the first-order factors (Carroll, 1993). An advantage of hierarchical models for the investigation of age-related effects is that they allow broad (on the higher-order common factor) and narrow (on the first-order ability factors) age-related influences to be examined simultaneously.

A hierarchical analysis was conducted on the combined data summarized in Table 24.1 by examining the relations of age

Age

.68    -.50    -.13

Common

-.30

.86    .66

.97

.86    .71

Voc    Space    Reas    Mem    Spd
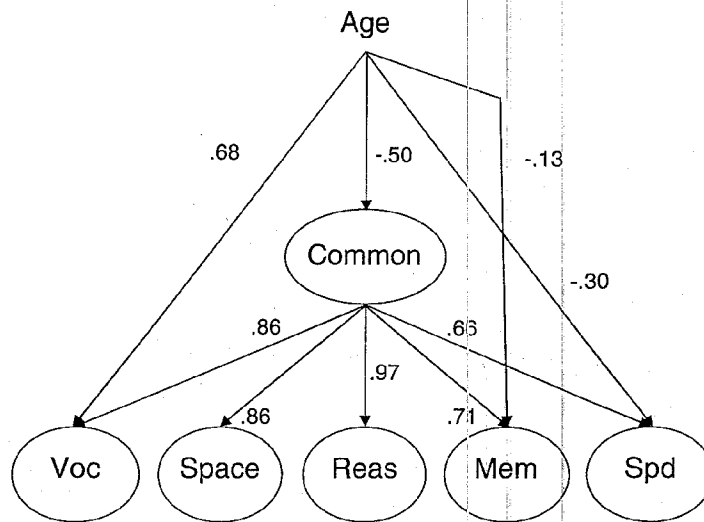
| | | | | | |
|---|---|---|---|---|---|
| Predicted: | .25 | -.43 | -.49 | -.49 | -.63 |
| Observed | .25 | -.41 | -.49 | -.48 | -.63 |

Figure 24.4. Hierarchical structural model of age relations on different cognitive abilities based on the data summarized in Table 24.1. Numbers adjacent to the arrows are standardized regression coefficients, and numbers in the bottom two rows are correlations between age and the latent construct directly above.

to a second-order factor representing variance common to the first-order factors and to each first-order factor, and then deleting all relations from age that were not significantly different from zero. Because the aggregation of data from samples with different combinations of variables results in a very high proportion of missing values for most variables, conventional measures of fit are not readily available in analyses with this type of data. However, the observed age-factor correlations can be compared with those predicted from the parameters of the model, and inspection of the entries at the bottom of Figure 24.4 indicates that the predicted age correlations were very close to the observed age correlations, implying that the model is plausible.

The coefficients provided from the hierarchical structure analysis on these data are portrayed in Figure 24.4, where it can be seen that four statistically independent age-related influences were identified. There was a large negative influence of age on the

highest-order factor, a moderate positive influence on the vocabulary factor, and small to moderate negative influences on factors corresponding to speed and memory abilities. A very similar pattern recently was found by Salthouse and Ferrer-Caja (2003) in analyses of three separate data sets, so these results apparently are robust.

The hierarchical structure represented in Figure 24.4, together with the factor loadings presented in Table 24.1, can be used to estimate age-related influences on individual variables. Because the product of the standardized path coefficients provides an estimate of the expected correlation between the variables, the product of the age-common, common-reasoning, and reasoning-variable coefficients can be compared with the observed age-variable correlation to determine how accurately the model and its estimated parameters reproduce the actual relations in the data. The predicted age correlation for the matrix reasoning variable was −0.42, the observed

correlation was −0.50, and corresponding predicted and observed values for the analytical reasoning variable were −0.37 and −0.46, respectively. With these particular variables, therefore, the age relations are underestimated by the model, which implies that additional paths, such as a direct negative relation from age to the variable, may be necessary to provide more accurate estimates of the true covariations in the data.

One of the most interesting results in Figure 24.4, which was also apparent in the analyses reported by Salthouse and Ferrer-Caja (2003), is that the reasoning factor was the first-order factor with the strongest relation to what is common to all variables. In fact, the standardized coefficient of 0.97 in Figure 24.4 indicates that there was almost complete overlap of the individual differences in the reasoning factor with the individual differences in what is common to several different cognitive abilities. This finding is intriguing because it suggests that an explanation of the age differences in reasoning likely also will explain much of the age-related influences on other cognitive abilities, and vice versa.

## Conclusions and Future Directions

Large age differences have been found in many measures of reasoning, and in some cases the differences are as large as those found in measures of other cognitive abilities such as memory. There still is no convincing explanation of the causes of age-related effects on reasoning, although the available evidence suggests that aspects of WM likely contribute to at least some of these effects. Results of correlational analyses suggest that reasoning variables are central to what is common across a wide variety of cognitive abilities and to the age differences in different cognitive abilities. It therefore seems reasonable to expect that an understanding of age-related effects on reasoning may help explain much of the age-related differences in a broad variety of cognitive variables. Finally, because of the centrality of reasoning to the individual differences in much of cognitive

functioning, future research likely will benefit from a broader, more multivariate, perspective than that typically employed in contemporary research and by considering the effects of aging on what is common to many different types of cognitive variables instead of focusing exclusively on the determinants of age-related differences in one particular task.

## Acknowledgments

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