Human Development
Editor: D. Kuhn, New York, N.Y.

Reprint
Publisher: S. Karger AG, Basel
Printed in Switzerland

Paper

Human Development 1992;35:321–342

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Shifting Levels of Analysis in the Investigation of Cognitive Aging

Key Words
Age-related
Aging
Cognition
Influences, general
Influences, specific
Methodology
Null hypothesis
Parsimony
Research integration

Abstract
Questions can be raised regarding the progress that has been achieved in accounting for the well-documented negative relations between chronological age during adulthood and fluid or process aspects of cognition. Advances in knowledge may have been limited in part because many researchers have ignored age-related influences that are common to a number of dependent variables. Two procedures are discussed that appear to have the potential to distinguish between general or common age-related influences and unique or specific age-related influences. Adoption of these or similar procedures is recommended to increase the cumulative nature of research and to facilitate integration of results from different research areas.

The explicit goal of this article is to inspire, or possibly to provoke, a reexamination of research practices currently employed in the investigation of cognitive aging phenomena. The focus will be on only one facet of cognitive aging, but it is the one most actively investigated and extensively documented – namely, the decline in fluid or process aspects of cognition associated with advancing chronological age during adulthood.

The Phenomenon

The basic phenomenon can be illustrated with results from two recent projects I have conducted in conjunction with several colleagues. Both projects involved the administration of a variety of cognitive tests to cross-sectional samples of 350 or more healthy adults between about 18 and 80 years of age. In the figures illustrating the results of these projects, performance at each age range is represented in terms of standard deviations of young adults. Converting the original scores to this metric facilitates comparisons across different variables because the conversion

An earlier version of this article was presented as an invited 'New Directions' talk at the 1991 eleventh biennial meeting of the International Society for the Study of Behavioral Development in Minneapolis, Minn. Preparation of the article was supported by NIA Grant R37 AG06826.

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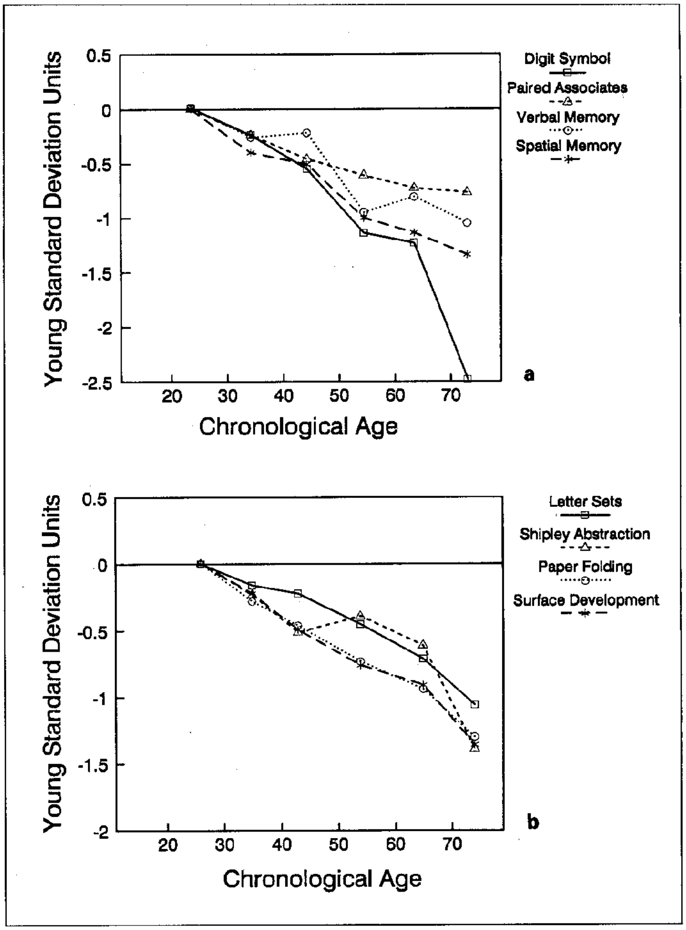


Fig. 1. a Mean performance at each decade of chronological age in four tasks, scaled in standard deviations of young adults. Data from Salthouse et al. [1988]. **b** Mean performance at each decade in four tasks, scaled in standard deviations of young adults. Data from Salthouse and Mitchell [1990].

makes the units of measurement equivalent for all variables. (The distribution of scores for the entire sample could be used as the reference distribution, and doing so has the advantage of increasing the stability of the estimates because of the greater number of observations. However, because the standard deviation of the entire sample includes any variation that is associated with age, it will underestimate the magnitude of age-related effects relative to a standard deviation based on an age-homogeneous sample.)

One project involved a variety of computer-administered tests, including several assessing memory and speed of processing [Salthouse et al., 1988]. Figure 1a illustrates the results for four of the measures. It can be observed that (a) increased age is associated with lower performance for all of the measures; (b) the declines are roughly monotonic, and (c) the level of performance of subjects in their 60s and 70s generally averages about one standard deviation below the level of those in their 20s.

The second research project involved paper-and-pencil tests of reasoning and spatial abilities [Salthouse and Mitchell, 1990]. Results from this project are displayed in figure 1b. The patterns are very similar to those in the top panel. Age trends are roughly monotonic, and performance of adults in their 60s and 70s averages about one standard deviation below performance of adults in their 20s.

The results illustrated in figure 1 are fairly typical of the results from many research projects over the last 50 or 60 years [see Salthouse, 1991a, for a review]. Because the phenomenon of negative relations between age and certain measures of cognition seems to be very well established, the major question at the current time is how those relations are to be explained.

The Problem

Much of the research on adult age differences in cognition has been analytical or decompositional in nature. Although much analytically oriented research has been conducted, I am not completely convinced that it has led to substantial advances in understanding the causes of age-related differences in cognition. One of the reasons for my reservations can be illustrated by reporting the results of a survey of articles published in recent volumes of the two major journals in this area – *Psychology and Aging* and *Journal of Gerontology*. All of the articles published in these journals in the 1990 calendar year were examined. Those reporting statistically significant age differences for the primary performance measure, and for which an explanation or theoretical interpretation could be identified, are summarized in table 1.

The major point I wish to make from this simple survey is not that age-related deficits have been documented for many different cognitive measures, but rather that there appear to be nearly as many explanations or interpretations for those deficits as there are published articles. Although it is encouraging that the research activity has been so vigorous and has been extended in so many different directions, it is nevertheless discouraging to note that explanations for any given result seem to have been developed almost completely independent of the explanations proposed to account for other results.

One way of assessing progress is in terms of the integration of previously distinct and independent phenomena into a coherent scheme with common explanatory principles. The primary expectation is that the number of interpretations should be fewer than the number of observations, and the law of parsimony further dictates that the number should be as few as possible. Viewed against these criteria, one could argue that there has been little progress in explaining cognitive aging phenomena. Observations have certainly accumulated in great quantity, but it is debatable whether there has been progress in integrating and explaining those observations.

In some respects, this state of affairs can be considered an almost inevitable outcome of the analytical emphasis inspired by the information-processing perspective, in which cognition is conceptualized as the product of a series of processing operations that store information and transform input into output. Consider two hypothetical information-processing task analyses, one involving components a, b, and c in task 1, and the other components x, y, and z in task 2. Both analyses might be considered successful in the sense that research evidence is consistent with primary localization of the age differences in a specific information-processing component. That is, results from various investigations might suggest that age-related effects were concentrated in component a in task 1, but had their greatest influence in component y in task 2. The difficulty in this case is that even if we are confident that we now have a reasonable explanation for the existence of age differences in one task, that information may be of little help in accounting for age differences in other tasks. In the present example, we know nothing about the relation between components a and y in tasks 1 and 2, or about age-sensitive components that might exist in other tasks. Components a and y may be highly related, and could even reflect exactly the same construct. However, it is impossible to determine whether such relations exist when different research projects proceed in isolation, and researchers show no awareness of age differences reported in one another's projects.

Complaints about the lack of integrative explanations, and the proliferation of task-specific interpretations, have been expressed before in the form of warnings about the dangers of issue isolationism [Salthouse, 1985] and research sectarianism [Birren and Renner, 1977]. However, the diversity of entries in table 1 reveals that fairly specific interpretations continue to be offered for most research results. A possible reason why earlier objections have been largely ignored is that they were not accompanied by concrete suggestions about how research practices might be altered to remedy the perceived problems. I would like to address this omission in the present article by proposing certain modifications in research methodology that I believe would contribute to greater integration, and hence understanding, of cognitive aging phenomena. In essence, I suggest a shift in the level of analysis, away from an exclusive focus on specific and unique explanations of cognitive aging phenomena, and to a consideration of specific interpretations while simultaneously examining, and possibly controlling for, any more general or common age-related influences that may also be operating.

Distinguishing General and Specific Age-Related Influences

I will discuss two methods, and although each has limitations, both appear to have the potential to lead to more integrated explanations of cognitive aging phenomena than those currently employed by most researchers working within an experimental or analytic perspective. Because a key feature of both

Table 1. Interpretations of age differences in cognition from recent articles in *Journal of Gerontology* and *Psychology and Aging*

Explanation	Measure	Source
Reduced frequency of text-based processing style	prose cell	Adams et al. [1990]
Reduced cognitive flexibility associated with frontal lobe dysfunction or dopamine reduction	proverb interpretation	Albert et al. [1990]
Declines in storage capacity and processing efficiency	working memory	Babcock and Salthouse [1990]
Impairment in classifying targets according to source or in ignoring nontargets	auditory selective attention	Barr and Giambra [1990]

Table 1 (continued)

Explanation	Measure	Source
Decline in tendency to spontaneously organize and integrate information	memory for source information	Dywan and Jacoby [1990]
Elevated blood pressure (?)	categories test	Elias et al.
Decreased ability to alter target strength, qualitatively different search strategy	visual and memory search reaction time	Fisk et al. [1990]
Failure to inhibit personal information	memory for events	Hashtroudi et al. [1990]
Metamemory deficits (?)	word and prose recall	Hertzog et al. [1990]
Declines in verbal speed and working memory	word and prose recall	Hultsch et al. [1990]
Diminished working memory reducing proficiency of effortful memory search	memory for actions	Kausler et al. [1990]
Deficit in relational encoding and bias toward item-specific encoding	word recall	Luszcz et al. [1990]
Deficit in encoding specific information	word recall	McEvoy and Holley [1990]
Generalized slowing and decline in attentional processing	reaction time	Madden [1990]
Decrease in distinctiveness of encoding	word recall	Mantyla and Backman [1990]
Failure to fire recognition units, failure to access semantic information from recognition units, failure to access name from semantic information	face recognition	Maylor [1990]
Cohort differences (?)	memory search time	Menich and Baron [1990]
Deficient episodic memory	picture recognition	Mitchell et al. [1990]
Problems in inhibiting attention and integrating information into single trace; incorrect assessment of task difficulty	memory for prescription information	Morrell et al. [1990]
Integration deficit	picture recall	Park et al.
Impairment in health (?)	block design and digit symbol	Perlmutter and Nyquist [1990]
Failure to encode or retain relevant information	reasoning accuracy	Salthouse et al. [1990]
Impaired encoding and retrieval (?)	picture recognition	Smith et al. [1990]
Limitations in working memory capacity	prose recall	Stine [1990]
Deficits in working memory and possibly spatial processing capacity	prose recall	Stine et al. [1990]
Decreases in spontaneous strategic encoding, resistance to distraction, and impaired retrieval	telephone number recall	West and Crook [1990]
Deficiency in organizational processes	word recall	Witte et al. [1990]

methods is the collection of information on several variables from each participant, the proposed methods do not represent a major shift for researchers working within the psychometric perspective because they have a long tradition of relying upon multivariate assessment. The present discussion is nevertheless relevant to psychometric researchers because they typically have attempted to explain all of the variance in the dependent variables, not merely the age-associated variance. The primary question of interest in the present context is not whether there is a relation between two variables or constructs, but whether there is a relation between the *age-related influences* on these variables. Both methods are based on the assumption that age-related effects on performance in any given task can be conceptualized in terms of the contribution of several types of influences. Again, the concern here is with determinants of age differences in performance, not all factors contributing to a given level of performance. Influences on performance that are unrelated to age are ignored. Some age-related influences can be postulated to be specific to particular tasks, such as mental rotation, formation of associations, abstraction of relations, whereas others, perhaps including effectiveness of encoding, reliance on working memory, speed of executing relevant processing operations, might be assumed to be common to many different tasks. Because some of the influences are common to many performance measures while others are specific to a few particular measures, the age differences in any measure of cognitive performance can be conceptualized in terms of the sum of common (or general) age-related factors and unique (or specific) age-related factors.

General and specific are not well-defined absolute categories, but more like extreme ends of a continuum. To many researchers, neither extreme is particularly interesting since it is very unlikely that a single factor is responsible for all of the age-related differences evident in every possible cognitive task, and a discovery that age-related effects are highly specific to particular samples, methods, and materials is of little concern because the results have virtually no generalizability. Intermediate regions of the continuum are nevertheless meaningful when general and specific are interpreted as relative terms, with specific implying that the age-related influence is restricted to a very small number of highly similar measures, and general indicating that the influence is common to a large number, and wider range, of measures.

This distinction between general and specific age-related influences is important because there are several reasons for arguing that a primary goal in cognitive aging research should be to identify, and account for, any broad or general factors involved in the relations between age and cognitive functioning. One reason is that it is easier to determine the distal causes of a small number of relatively general influences than of a large number of highly specific influences. From a purely pragmatic perspective, therefore, it may be more efficient to try to identify the factors responsible for any broad or general age-related influences that might exist before trying to investigate the causes of a large number of more circumscribed or specific age-related effects. A second reason for emphasizing general age-related influences is that more precise estimates of specific age-related influences can be obtained if the general influence is first removed. That is, without controlling for the influence of general age-related factors, estimates of specific effects may be contaminated by, and perhaps merely another manifestation of, general factors that may exist. Finally, research will become more cumulative if one can establish that results are not attributable to a general influence that has already been discovered. In other words, unless a more systematic approach to investigating both general and specific age-related influences is adopted, we may continue to rediscover different consequences of the same causal factors and may never dispel the lingering ambiguity about if, and when, specific interpretations of age-related effects are really necessary.

Less-than-Optimal Methods

How can a general age-related influence be detected? Before describing two possible methods, I will first briefly mention three methods that have either been proposed or implied and that I believe are inappropriate, or at least suboptimal. One such method consists of comparing the absolute magnitude of age trends across various measures, based on the expectation that the existence of a general factor will lead to identical age-related effects for all measures. This method is unsatisfactory as a means of investigating general age-related influences because measures can vary in terms of their age relations due to differential dependence on the general factor, as well as because of differences in measurement sensitivity and/or reliability. Moreover, this method completely ignores the contribution of specific age-related influences that can be expected to vary from one measure to another.

Comparison of patterns of correlations at different ages [Birren et al., 1962] is also undesirable as a method of detecting the existence of a general age-related factor. At least three potential problems with this approach can be identified. First, important variables could be neglected because age-sensitive dimensions may not be adequately represented in age-homogenous samples. This point can be elaborated by an analogy from the field of real estate. Suppose one were trying to identify the factors responsible for variations in real estate prices by determining the predictors of housing prices within each of two randomly sampled neighborhoods. Variables such as lot and building size, quality of construction, type of materials, and number of amenities would probably be identified as important predictors of house prices within each neighborhood. However, analyses of each neighborhood separately are likely to omit what may be the most important factor – location – because the range of that variable will be greatly restricted within each neighborhood. Similarly, in developmental research, relevant dimensions of change may be salient only in cross-age comparisons. Researchers should thus be quite cautious in interpreting correlational results from age-homogeneous analyses.

A second, related problem with trying to investigate the existence of a general aging factor by separate analyses within each age-group is that it may be the wrong variance that is being analyzed. That is, the goal is not necessarily to identify or understand all of the performance determinants at a given age, but rather to understand the relations between age and cognitive performance. Stated somewhat differently, the variance of primary interest to a developmental researcher is not the total variance, but merely that portion systematically related to age. Only if age is incorporated into the analysis can one distinguish age-related variance from total variance.

The third problem with relying on analyses of data from age-homogeneous samples to investigate a general age-related influence is that it is based on the questionable assumption that a general factor can be detected by the presence of higher correlations among variables in samples of older adults than in samples of young adults. However, higher intercorrelations among variables are neither necessary, nor sufficient, to infer the existence of a general factor. They are not necessary because correlations may not differ across age groups if individual differences in rates of developmental change in the general factor are relatively small. Higher correlations are not sufficient to infer the existence of a general factor because correlations could increase from one group to another for many reasons unrelated to the presence or absence of a general age-related factor.

Another possible strategy in attempting to distinguish between general and specific age-related influences is factor analysis of the simple correlations among a set of variables [Dirken, 1972; Jalavisto, 1965]. Age either could be one of the variables included in the analysis, or its correlation with the extracted factors could be determined. The problem with both of these procedures is that the factors are determined by the total variance in each variable, not just by the age-related variance. This distinction is potentially important because the interest in the present context is not in the variables that are related because they share *some* common variance, but instead in the variables that are similar because they share *age-related* variance. A procedure is discussed later in which factor analyses might be used to reveal clustering of variables with respect to the amount of age-related variance they have in common. Unless some such procedure is employed, results of factor analyses may not be directly relevant to distinguishing general and specific influences associated with age.

Overview of Proposed Methods

I now turn to methods that seem more promising for distinguishing between general and specific age-related influences. Fundamental to both methods is the general measurement assumption that the variance of a variable is equal to the sum of the variance of common, specific, and error influences. That is,

$$\text{Var(X)} = \text{var(common)} + \text{var(specific)} + \text{var(error)}.$$

This assumption is extended in the case of age-related comparisons by specifying that the age-related variance in a variable is attributable to common and specific age-related influences. In other words, it is assumed that:

$$\text{Var(age-related differences in X)} = \text{var(common age-related influences)} + \text{var(specific age-related influences)} + \text{var(error)}.$$

Because difference scores obtained from longitudinal comparisons are the simplest type of age-related differences, it is useful to begin description of the two proposed methods by assuming that the variables of interest are the differences across two measurement occasions on a number of variables for the same individuals. If the sample of individuals with scores on all variables at both occasions is relatively large, one method is a factor analysis of the difference scores. The interrelations of longitudinal difference scores, which by definition represent age-related influences, are examined to identify common and specific groupings of variables.

The second method does not necessarily require large samples, but it does require that the variables are all measured on the same scale. This method involves examining the scores on the variables across the two measurement occasions (and consequently the two ages) to determine whether there is a systematic relation between the two sets of scores. The existence of a systematic relation can be interpreted as a reflection of the common influence, and deviations from the systematic relation can be attributed either to specific influences or to error. The key to both methods is the availability of measures of several variables for the same individuals, to allow common and specific age-related influences to be distinguished. A common influence is inferred if there is a pattern among the age-associated effects on the variables, such that the age differences on some variables are not independent of those on other variables. In contrast, a specific influence is inferred if the age differences on a given variable are unrelated to the age differences on other variables.

I turn now to a more detailed description of each method, beginning with the latter method of assessing systematic relations between scores across measurement occasions.

Method of Systematic Relations

The reasoning underlying the method of systematic relations is as follows. (Although the description refers to a contrast between a group of older adults, O, and a group of young adults, Y, the method is applicable to groups distinguished by other age groupings, or to the same group at different times, or to nondevelopmental classifications.) Assume that the age differences on variable 1 are represented as $O_1 - Y_1$, and that the age differences on variable 2 are represented as $O_2 - Y_2$. (For this example, assume that performance is measured in terms of errors or time, such that higher scores indicate poorer performance.) If the age differences on each variable are completely determined by specific age-related influences, i.e., specific_1 and specific_2, and if those specific influences are independent of one another, the age differences on the two variables would also be independent, i.e., $O_1 - Y_1$ would be independent of $O_2 - Y_2$. However, if the age differences are determined by a combination of general and specific age-related influences, and if the same general influence contributes to both variables, the age differences on the two variables would be related because of the common influence. Expressed in equation form, we assume:

$$O_1 - Y_1 = f(\text{general} + \text{specific}_1).$$
$$O_2 - Y_2 = f(\text{general} + \text{specific}_2).$$

Because the general influence is common to both equations,

$$O_2 - Y_2 = f\{[(O_1 - Y_1) - \text{specific}_1] + \text{specific}_2\}.$$

Rearranging the equation yields

$$O_2 = f(Y_2 + [O_1 - Y_1] + [\text{specific}_2 - \text{specific}_1]).$$

This last expression implies that the performance of older adults on variable 2 should be a function of the performance of young adults on variable 2, and of the difference between the young and old adults on variable 1, plus the difference between the specific influences on the two variables.

The preceding equations are obviously only crude approximations, but the basic argument is quite simple. If the age differences on two variables are largely a consequence of different specific influences, no relation would be expected between the age differences on the two variables. However, if a common or general influence contributes to the age-related variance on each variable, the age difference on one variable should be related to the age differences on other variables. Furthermore, it should be possible to predict the performance of older adults on a given variable from (a) the performance of young adults on that variable, and (b) knowledge of the relation between the two groups on one or more other variables.

It is this last implication that leads to a possible means of distinguishing between general and specific age-related influences. The key to the proposed method is an examination of the performance of older adults on a set of variables as a function of the performance of young adults on the same variables. To the extent that there is a systematic relation between the measures of performance in the two age groups, and the two groups differ in average level of performance, a common age-related influence might be inferred. That is, only if at least some of the age-related effects on each variable were determined by a factor common to other relevant variables does it seem reasonable to expect age differences on one variable to be related to age differences on other variables. 'General' or 'common' in this context thus implies lack of independence, in the sense that knowing the magnitude of the age differences on one variable provides information about the magnitude of the age differences on other variables.

Application of the method can be illustrated by an example involving body dimensions at two ages in childhood. Imagine that a number of body measurements are obtained from a child at age 5 and again from the same child at age 10, and that the two sets of measures are plotted against one another, as illustrated in figure 2. Three important types of information are available from analyses of this type. First, the magnitude of the correlation indicates the extent to which there is a systematic relation between the measures at different ages. For these particular data, the correlation is quite high, indicating that there is a high degree of 'structural stability', in the sense that the measures with high values at one age also have high values at a later age. Second, the intercept and the slope of the linear regression equation characterize the nature of the relation between the measures at the two ages. For the data illustrated in figure 2, it can be seen that the intercept is close to 0 and the slope is 1.24. This pattern indicates that the variables at age 10 were about 24% greater than they were at age 5. (In fact, the average of the percentage differences shown in the legend at the right of figure 2 is 24.8%.) Finally, functions like that portrayed in figure 2 are informative about the exceptions or deviations from the general pattern. In the illustrated data it appears that the values for the variable of head circumference do not exhibit the same pattern as the other variables, in that the percentage increase for this variable is only 3.3%.

The hypothesis that some of the data points deviate from the general trend can be investigated by conducting additional analyses to evaluate the statistical significance of potential exceptions. As an example, outlier tests on the residuals from the prediction equation can be conducted to determine the probability that a data point represents an exception to the general pattern. Alternatively, the possibility that the data are better characterized by two or more distinct regression equations can be investigated by classifying the variables into categories and then examining the significance of predictor variable-by-classification interactions in a regression analysis. In the data illustrated in figure 2, the data point corresponding to head circumference has a residual 2.8 times larger than its standard error, indicating that it is a significant exception to the overall pattern. On the basis of this result, one could infer that the head circumference variable exhibited a different pattern of age-related growth than the other variables examined. A regression analysis including major body dimensions (variables 1 through 7, coded as 1) and hand and foot dimensions (variables 8 through 12, coded as 0) as a body-part classification reveals that neither the main effect of body-part classification nor the product of age-5-by-body-part classification is significant. As discussed by Pedhazur [1982, chapter 12], findings of this type imply that the same regression equation applies to both sets of variables. (Of course, a finding of no difference means that one is accepting the null hypothesis and hence one must be sensitive to the possibility that the failure to detect a difference as significant may be attributable to low power of the statistical test.)

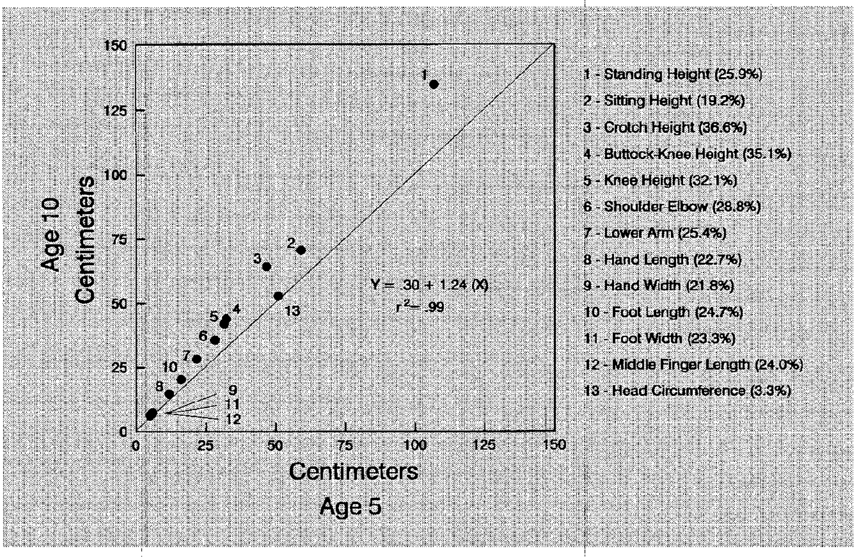


Fig. 2. Measurements of bodily dimensions at age 10 as a function of the same variables at age 5. Data from Snyder et al. [1975].

The advantage of the type of analysis just described is that the simultaneous examination of many variables allows the researcher to determine whether the age-related results observed for one variable are similar to those observed for other variables. Doing so in turn enables the investigator to place his or her results in a larger context, and in particular, to determine the extent to which the age-related influences on a particular variable are common or specific. Based on the data illustrated in figure 2, it seems reasonable to infer that a researcher studying developmental growth of the middle finger is probably investigating many of the same basic processes as researchers studying developmental growth of the lower arm or the length and width of the foot. The only exception among the variables represented in the figure is head circumference, because this variable does not exhibit the same pattern of age-related change as the other variables.

Application of the method of systematic relations to cross-sectional data is straightforward. One need only substitute the means of an age group for the scores at each age. In other words, instead of using the scores from the same individual at age 5 and at age 10, the data can consist of the means of a sample of individuals at age 5 and the means of another sample of individuals at age 10. (In fact, the values in figure 2 were derived from samples of 300 or more 5-year-olds and 200 or more 10-year-olds, as reported in Snyder et al., 1975.) The primary limitation of this method is that the variables must all be on the same scale. The method is also sensitive to all of the factors that affect the precision and accuracy of correlation and regression procedures, including reliability and stability of the measures, the number of paired observations, and the range of values in each group [Pedhazur, 1982].

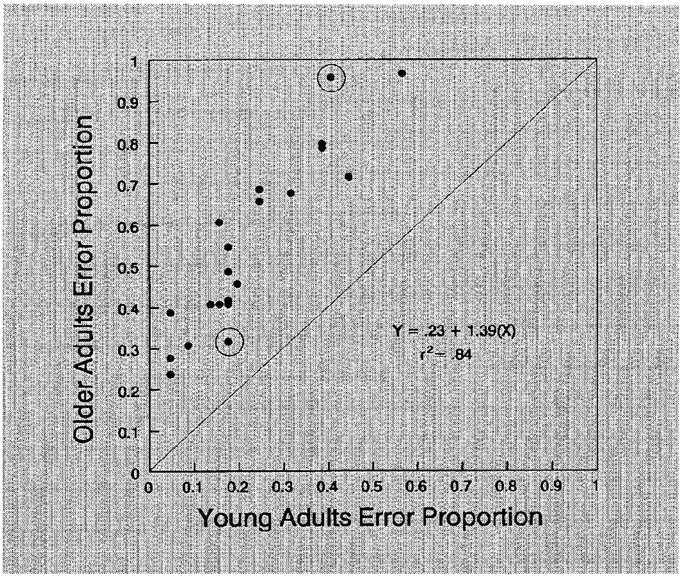


Fig. 3. Error proportions on individual items of the Raven's Progressive Matrices Test for older adults (age >59 years) as a function of the error proportions on those same items for young adults (age < 31 years). Circled items are outliers with residuals greater than twice their standard errors. Data from Salthouse [1991b, study 1].

It should be emphasized that the distinction between general and specific influences in the method of systematic relations is based both on the extent to which the data can be accounted for by a linear equation, i.e., the coefficient of determination, or r^2, and on tests for outliers or moderators of the regression equation. Once again the data in figure 2 can be used to illustrate this point. The very high r^2 implies that there is a large systematic, and potentially general, influence across most variables. However, one variable was still found to deviate significantly from this overall trend, and hence it can be considered an exception to the general pattern. Both tests for generality and tests for specificity or uniqueness should therefore be conducted before reaching conclusions about the existence of general and specific age-related influences.

The variables used in analyses of systematic relations can be derived from performance on individual items within a single task, or from measures of average performance across different tasks. Individual items have been used as the units of analysis in studies of memory by Rubin [1978, 1985] and by Stine and Wingfield [1988, 1990]. The method is applicable to many types of tasks, however, as illustrated by the data figure 3. This figure represents performance on individual items from the Raven's Progressive Matrices Test. (Data were derived from samples of adults 30 years and younger and adults 60 years and over in Study 1 by Salthouse, 1991b.) Notice that there is a systematic relation between the performance of young and old adults, as evidenced by the r^2 value of 0.84. Furthermore, an analysis of the residuals revealed that only the two circled data points had residuals greater than twice their standard errors. These results therefore suggest that, across different items on this test, there is a relatively general pattern of poorer performance by older adults relative to young adults.

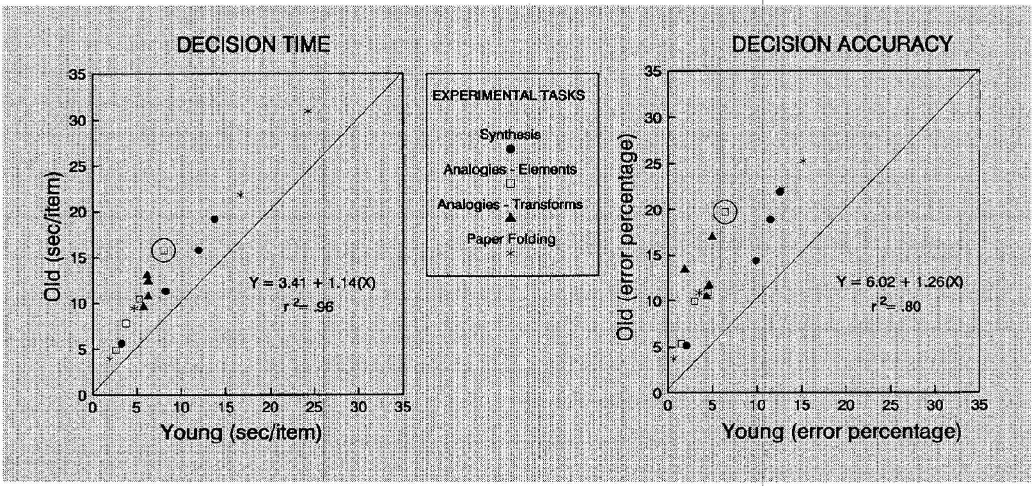


Fig. 4. Time and accuracy of older adults as a function of the time and accuracy of young adults in the same conditions. Circled items are outliers with residuals greater than twice their standard errors. Data from Salthouse [1988, experiment 1].

Analyses of systematic relations are probably most interesting when the measures represent average performance in different tasks, because 'specific' then refers to characteristics of the entire task rather than to properties of individual items within the task. Figure 4 contains examples of data analyzed in this manner from a recent study [Salthouse, 1988, experiment 1], in which all participants performed four tasks, each at four levels of complexity. Results of this study are fairly typical of those reported in the literature. The correlations between measures of the average performance of young and old adults are commonly 0.9 or higher. Systematic relations are not as easily detected with measures of quality or accuracy of performance as with measures of speed of performance because (a) the performance measures from different tasks are not always comparable; (b) the measurement scales are more likely to have floor or ceiling restrictions, and (c) the means are less precise when each observation is discrete (i.e., correct or incorrect) rather than continuous (i.e., time). Despite these difficulties, orderly patterns can be detected in accuracy measures, as is apparent in the right panel of the figure, and in articles by Brinley [1965], Campbell and Charness [1990], and Salthouse [1987].

The data in each panel of figure 4 were subjected to two separate regression analyses, one ignoring the distinctions among the tasks and one including task (coded as a dummy variable), and the product of task and the continuous variable (mean performance of young adults), as additional predictors. The initial analyses yielded the parameters presented in the figure and indicated that the circled data points had residuals greater than twice their standard errors. The analyses including task as a predictor variable were designed to determine whether the regression equation for the Analogies-Transforms task differed significantly from that for the remaining tasks. Neither the main effect of task nor the task-by-young product term was significant, and thus there is no evidence that the relation between the performance of young and old adults varied across these particular tasks.

The method of examining relations among variables does not indicate the identity of age-related influences that might be common to a set of variables. It merely suggests that something more general than the characteristics of a particular task probably contribute to the age differences in each variable. That is, the fact that a systematic relation may exist between age differences on measures of speed of performance does not imply that the common factor is an age-related speed reduction, for the same reason that the existence of a systematic relation between age differences on measures of accuracy would not necessarily imply that the common factor is an age-related accuracy reduction. When details of the functional relation are available, it may be informative about how the general factor exerts its influence (e.g., additively or multiplicatively) across a particular combination of variables, but other methods are needed to determine the nature or identity of the general factor(s) responsible for the systematic relations among the age differences on assorted variables.

An important point to be noted about the results in figure 3 and 4 is that systematic relations are often evident between the performance of young and old adults across a range of dependent variables. The fact that 80% or more of the variance in the group means is accounted for by this relation can be interpreted as suggesting that some type of general or common factor may be a major determinant of the age differences on these variables. That is, the systematic pattern among the variables can be considered a manifestation of the general factor, and specific influences can be inferred to be operative whenever data points deviate appreciably from the overall pattern. Exceptions can be either greater or less than the predicted value, but as long as accepted statistical techniques are used to establish that the deviations from the general pattern are significantly greater than that expected by chance, one can infer that a specific age-related influence is operating, above and beyond any more general age-related influence that may exist.

The method of systematic relations therefore allows the results for a particular task to be viewed in the broader context of results for other tasks or results for other conditions within the same task. It thus becomes possible to distinguish whether the results observed for that variable are consistent with the pattern evident for other variables, in which case they may simply be another consequence of a more general phenomenon, or whether they represent an exception to the overall trend and might require a specific interpretation. The key feature of this method is that identification of the overall pattern of age differences across a set of variables provides a basis for determining the extent to which the results obtained for a given variable are truly unique and independent of the age-related differences observed for other variables.

Factor Analysis of Age-Related Differences

The goal of factor analysis is to identify groupings or clusterings of variables that share similar variance. Common or general influences are represented by the fctors extracted early in the analysis that are responsible for the largest proportions of variance, and specific influences are represented either by factors extracted later, and associated with smaller proportions of variance, or by high uniqueness values in one or more variables (with uniqueness defined as 1 minus the communality, and communality referring to the

Table 2. Factor analysis of illustrative variable set

Variable	Correlation matrix 1	2	3	4	5	6
1	–	0.674	0.702	0.627	0.402	0.478
2		–	0.872	0.810	0.587	0.668
3			–	0.958	0.792	0.821
4				–	0.778	0.834
5					–	0.984
6						–

Factor	Proportion of variance associated with each factor 1	2	3	4	5	6
	0.784	0.132	0.052	0.026	0.007	–0.000

Variable	Communality (and uniqueness) estimates: One-factor solution	Two-factor solution
1	0.513 (0.487)	0.863 (0.137)
2	0.756 (0.244)	0.837 (0.163)
3	0.949 (0.051)	0.955 (0.045)
4	0.904 (0.096)	0.904 (0.096)
5	0.750 (0.250)	0.967 (0.033)
6	0.828 (0.172)	0.969 (0.031)

proportion of variance in the variable associated with the extracted factors). Uniqueness as the term is used here includes both the variance specific to the variable and the error variance. These two sources of variance can be separated if the reliability of the variable is known, but for the present purposes it is the distinction between common and other influences that is most important.

Two steps are involved in the identification of general or common influences on age-related differences using factor analytic procedures. The first step is to determine the proportion of total variance associated with each factor, because the higher the proportion, the broader or more general the influence of the factor. The second step is to determine the uniqueness of each variable, that is, the proportion of variance in the variable not shared with the extracted factors. This value provides an upper estimate of the proportion of the variable's variance that is available for partitioning either into secondary factors or into unique influences. It is an upper estimate because it includes unsystematic variance or measurement error in addition to the systematic variance unique to that variable.

Consider the data summarized in the correlation matrix in the top portion of table 2. A factor analysis conducted on these data revealed that the first factor was associated with 78.4% of the total variance in the variables and the second factor with 13.2% of the variance. These results therefore indicate that there is a considerable degree of common variance among the variables, because over

78% of the total variance can be accounted for by a single factor and two factors can account for almost 92% of the variance in the six variables. Results in the lower portion of table 2 indicate that some variables still have appreciable unique or nonshared variance after removing the variance associated with the first factor. However, removing the variance associated with the second factor reduces these residual, or unshared, components of variance considerably, to 16.3% or less for each variable.

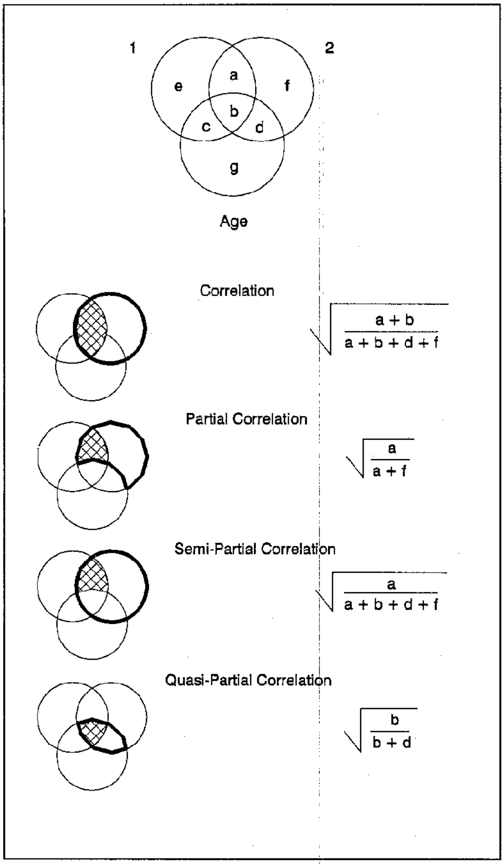
If the variables represented in table 2 were longitudinal difference scores, it would be reasonable to infer that two primary age-related influences were operating. One influence could be assumed to be major, because it was responsible for over 78% of the total age-related variance, and the other could be postulated to be relatively minor because it was associated with a little more than 13% of the age-related variance. These results, together with the fact that the uniqueness values were small for all variables, would lead to the inference that two influences were responsible for most of the age-related variance in this set of variables.

Extension of factor analytical techniques to cross-sectional research designs is somewhat more complicated than in the case of the method of systematic relations because of the need to focus on age-related variance. That is, the correlations in the original matrix should only reflect *age-related variance* in each variable, not the total variance in the variable. The distinction between the total variance in a variable and the variance in the variable that is systematically related to age may be clarified by reference to figure 5.

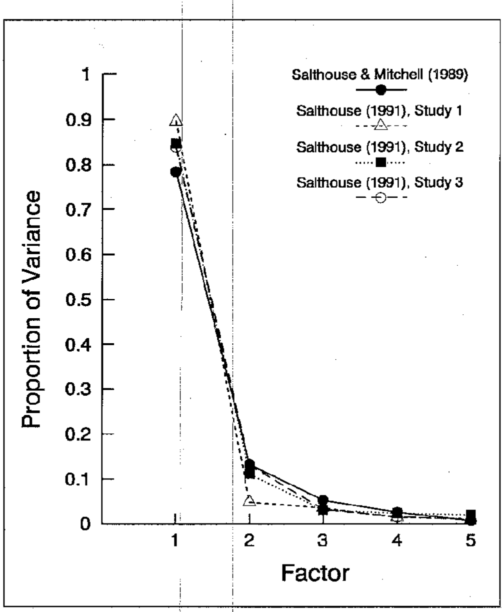
Traditional factor analysis is based on simple correlations in which the variance common to two variables is assessed relative to the total variance in each variable. Several other types of correlations can be computed, however, with partial and semipartial correlations the most common. I have been unable to find a reference to the fourth correlation illustrated in figure 5, and consequently I have labeled it a quasi-partial correlation. Notice that unlike partial correlations, quasi-partial correlations do not remove the age-related variance, but instead remove the variance that is *not* related to age. Of the correlations represented in figure 5, quasi-partial correlations appear most comparable to correlations between longitudinal difference scores because they reflect the magnitude of the relation between two variables relative to the age-related variance in each variable.

A possible method of examining relations within the age-related variance in a set of variables obtained from a cross-sectional design is factor analysis of quasi-partial correlations instead of simple correlations.[1] In fact, the data contained in table 2 are based on quasi-partial correlations derived from a study reported by Salthouse and Mitchell [1990] involving 383 adults between 20 and 83 years of age. The variables were designed to assess three distinct constructs, corresponding to perceptual

[1] There is a complication associated with the use of other types of correlations in factor analyses because unlike simple correlations, correlations in which another variable has been partialled are not necessarily equivalent for the two variables. That is, the square of a simple correlation indicates the proportion of variance in one variable shared with the other variable, and this proportion is equivalent for both variables involved in the correlation. However, this property of symmetry does not necessarily hold for the other types of correlations. In terms of figure 5, the circles represent the total variance in the variable, and thus (a + b + d + f) is equal to (a + b + c + c), but (b + d) is not necessarily equal to (b + c). A possible means of dealing with this potential problem is to compute quasi-partial correlations for both variables and then conduct the factor analyses on the average (determined with the Fisher r-to-z transformation) of the quasi-partial correlations for the two variables.



5



6

Fig. 5. Schematic illustration of four types of correlations between two variables, 1 and 2, with and without adjustment for the influence of age.

Fig. 6. Proportion of variance associated with successive factors in factor analyses of quasi-partial correlations from four data sets.

speed (variable 1 for Finding As and 2 for Number Comparison), inductive reasoning (variable 3 for Letter Sets and 4 for Shipley Abstraction), and spatial visualization (variable 5 for Paper Folding and 6 for Surface Development). To the extent that quasi-partial correlations provide meaningful estimates of the magnitude of the relation between the age-related variance in two variables, the interpretation of the factor-analytic results is the same as if the correlations were based on longitudinal difference scores. In both cases it seems reasonable to infer that there is a substantial general or common influence contributing to the age-related variance in this set of variables.

The results summarized in table 2 are not atypical. Similar patterns have been obtained in analyses of other sets of cross-sectional data. For example, figure 6 illustrates the proportions of variance associated with successive factors in three additional studies involving at least 220 adults and between seven and nine variables each. In each case the first factor was associated with a very large proportion of the age-related variance. The communality estimates after extraction of a single factor were also quite high, with a mean of

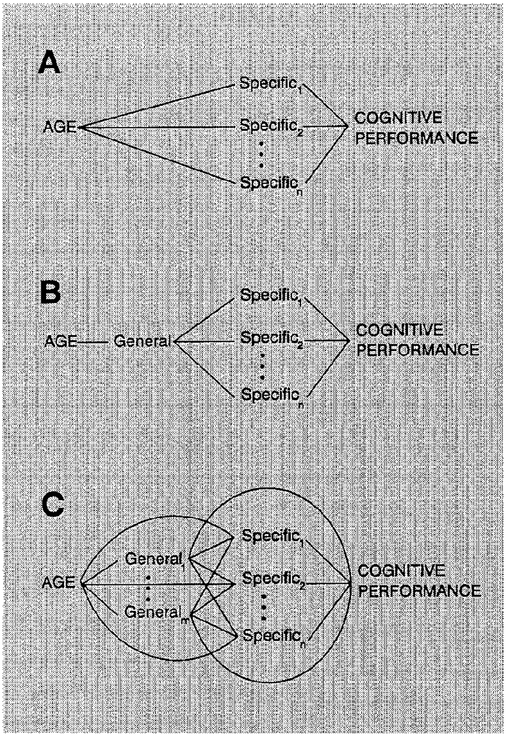


Fig. 7. Schematic representation of three alternative approaches to the analysis and interpretation of age differences in cognition.

0.857 and a minimum of 0.665. These results suggest that, at least for the variables in these studies, a very large proportion of the age-related variance in each variable is shared with the other variables. The original set of variables can therefore be reduced to a much smaller set that still captures most of the reliable age-related variance within the variables.

This pattern of results from factor analyses of quasi-partial correlations helps to explain why statistical control of some variables (i.e., measures of perceptual speed) greatly attenuated the age-related variance in other variables (i.e., measures of working memory or various types of cognitive functioning) in the studies reported by Salthouse [1991b]. If the variables load on the same factor, or if they each have high loadings on factors that are moderately correlated with one another, it is reasonable to expect that removing the influence of one variable will also tend to reduce the age relation in variables with which it shares common age-related variance. Statistical control procedures therefore provide another means of determining whether variables share age-related variance. General age-related influences can be inferred to be operating whenever statistical control of one variable greatly attenuates the variance associated with age in other variables. Conversely, the age-related influences can be inferred to be specific if there is little attenuation of the age-associated variance when other variables are controlled by procedures such as hierarchical regression or partial or semipartial correlation.

Conclusions

Neither of the approaches that has been described implies that search for specific age-related determinants of performance should be abandoned. Instead, they merely suggest that this search proceed with some awareness on researchers' part of the results from other research. This position can be clarified by contrasting it with two alternative approaches to the interpretation of age differences in cognition, as portrayed in figure 7. Followers of approach A only consider specific influences, whereas followers of approach B consider the general factor sufficient to account for all age differences, with the specific level of interpretation largely viewed as superfluous. Followers of approach C, which I am advocating, explicitly acknowledge the possibility of one or more general factors, as well as the potential for direct or unmediated effects between age and a variety of specific determinants.

Examples of the first two approaches are represented in articles in a recent issue of the *Journal of Experimental Psychology: General.* Fisk and Rogers [1991] proposed quite specific interpretaitons of age differences in reaction time by suggesting that age differences vary as a function of type of search (visual or memory), type of stimulus-response mapping (consistent or varied), and stage in practice (early or late). Cerella [1991], in a commentary on the Fisk and Rogers [1991] article, claimed that nearly all of their results were consistent with the existence of a single, general age-related factor. Because the age differences in any given condition could be predicted with reasonable accuracy from one equation (i.e., the method of systematic relations described earlier), Cerella argued that there was no need for specific or local interpretations of these age differences.

In my view, neither of these positions is satisfactory. Fisk and Rogers [1991] can be criticized for failing to consider possible influences of general age-related factors before proposing highly specific interpretations. Cerella [1991] can be criticized for rejecting specific influences associated with age without conducting statistical tests of deviations from the general pattern. Admittedly, such tests would probably have had low power in this particular situation because the number of observations was limited and the confidence intervals around each data point were probably large due to the fact that only 9 young adults and 9 older adults contributed to each relevant observation. It is nevertheless premature to conclude that no specific factors are operating if small samples and weak statistical power do not allow a sensitive evaluation of deviations from the general pattern.

It is important to emphasize that the methods proposed in this article neither presume the existence of one or more general age-related factors, nor do they imply that age differences would be explained if they were found be consistent with a general factor. With respect to the first point, both the method of examining relations among variables and the method based on factor analysis have possible outcomes that would be clearly inconsistent with the existence of a general age-related influence. In the case of the method of systematic relations, such an outcome would be the discovery of little or no relation between the age differences on one variable and the age differences on other variables. In the factor analysis method, results inconsistent with a general factor would be evident in the form of small proportions of variance associated with the factors and/or low communalities (high values of uniqueness) of the variables (in addition to little or no attenuation of the age differences on one or more variables after statistical control of an index of the hypothesized general factor).

It is also incorrect to claim that discovery of evidence for the existence of a general or common factor contributing to age differences on a number of different variables means that those age differences have been fully or adequately explained. Even if there were absolutely no evidence for any specific age-related influences, we would still need to know how, and why, the general factor operates. In a very real sense, therefore, a discovery that general factors are involved in the age differences on many cognitive variables represents a starting point, rather than a termination, of truly explanatory research in cognitive aging. There is nothing inherent in either of these methods implying that general age-related influences should be treated as disciplinary primitives, exempt from further attempts at analysis or explanation. To the contrary, general factors should be viewed as candidates for mediators of age differences in cognition. Such mediators must themselves be subjected to thorough investigation.

Whether or not general age-related influences are ultimately determined to be causally responsible for some of the relations between age and fluid or process aspects of cognition, discovery that a limited number of factors affect age differences in many cognitive tasks would be important because it would greatly reduce the number of phenommena in need of explanation. It is in this respect, therefore, that the search for both general and specific influences of aging can be expected to contribute to greater integration of research results and to facilitate progress toward the eventual explanation of those results.

How might research practices change if analytically oriented researchers were to shift their level of analysis to the general-plus-specific approach advocated in this article? First, more measures would be included in each study because distinguishing between general and specific age-related influences requires multivariate data. A minimum of two measures is needed to allow statistical control procedures to be employed, but ideally as many measures for which reliable assessment is practical within the available time constraints should be included. A large number of variables is desirable because the power and sensitivity of both linear regression and factor analytic procedures are directly related to the number of distinct variables (which are equivalent to observations in the proposed application of regression procedures).

Second, sample size would be larger than is currently the case. Larger samples are necessary to provide reasonably accurate estimates of the contribution of general and specific age-related influences and to permit analyses of residual age-associated variance in terms of different types of specific influences. There is no absolute minimum sample size, but total samples in the range of 100 or more are clearly preferable to the 50 or fewer often used in contemporary research. This guideline is particularly important with factor analytic procedures because it has been suggested that a minimum sample size of 100 is needed for a meaningful factor analysis [Gorsuch, 1983]. However, it is also relevant with the method of systematic relations because the precision of the performance estimates in each sample is directly related to the number of individuals in the sample.

Third, a shift in level of analysis means that statistical analyses would become more complex in order to allow general and specific age-related influences to be distinguished. The actual procedures vary according to the method employed, but some means are neeeded (a) for determining whether the age difference on a particular variable deviates from a systematic pattern evident across a number of variables, or (b) for statistically controlling the influence of other variables when examining the relation between age and the variable of primary interest.

Last, but possibly most important, adoption of the proposed methods might well result in a change in the nature of the null hypothesis used in research on cognitive aging. This change would reflect a recognition that considerable research has been conducted in the area of aging and cognition and that age-related differences have been reported for a great many variables. The null hypothesis therefore may no longer be that there are no age differences, but instead that there are no age differences beyond those already established.

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