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Constraints on theories of cognitive aging

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There is currently little consensus regarding what must be explained by theories of cognitive aging. In the present article, four empirical generalizations that seem to imply certain constraints in theorizing are identified. These generalizations, and their possible implications or constraints, are that (1) age-related differences are found in a wide range of cognitive variables, implying that either a large number of specific factors or a small number of general factors must be contributing to the age-related differences; (2) the age-related influences on different cognitive variables are not independent, and unique age-related influences appear to be few in number and small in magnitude, implying that some fairly general factors need to be postulated to account for the shared age-related influences; (3) only a small proportion of distinct age-related variance occurs late in practice and at long presentation durations, implying that adequate explanations must include factors operating when the individuals are just beginning to perform the task and when the stimuli can first be registered; and (4) measures of how quickly very simple cognitive tasks can be performed share considerable age-related variance with many cognitive variables, implying that factors related to simple processing efficiency need to be incorporated into the explanations.

Research concerned with the relations between adult age and cognitive performance has been increasing dramatically over the last several decades. Despite the rapid expansion of research, however, there is still little consensus regarding the reasons for the negative relations that are typically reported between chronological age and the measures of memory, reasoning, and spatial ability sometimes referred to as comprising Type A (Hebb, 1942) or fluid (Horn & Cattell, 1963) cognition. The primary purpose of this article is to describe several sets of empirical results that appear to place important constraints on theoretical explanations of age-related cognitive decline phenomena.

It is helpful to begin by describing the broad phenomenon in need of explanation by theories of cognitive aging. Consider the distribution of scores on a cognitive test, such as immediate free recall of a list of unrelated words. In a recent experiment (Salthouse, 1993b), a total of 305 adults between 19 and 84 years of age attempted to remember two 12-word lists (presented auditorily at a rate of 1 word every 2 sec), and their average scores across the two lists ranged from near zero to perfect (top panel of Figure 1). Because the sample included people of different ages, the distribution can be disaggregated by age. That is, the individuals can be ordered by their ages, and then the scores plotted by age (as in the bottom panel of Figure 1). This type of disaggregation typically results in considerable variability at each age, but with an average trend that is clearly negative, indicating that increased age is associated with lower performance. For example, in this particular data set, the R^2 value for age in a regression equation was .162, and thus a moderate proportion of the total variance in the free-recall measure was associated with chronological age.

Similar patterns of shared variance with age have been found for many cognitive variables. To illustrate, problems in the Raven's Advanced Progressive Matrices Test consist of a 3×3 matrix of symbols or geometric elements in all but one of the cells of a matrix. The task for the examinee is to use abstract reasoning to identify the pattern that provides the best completion of the missing cell. A recent study involving 221 adults between 20 and 80 years of age (Salthouse, 1993a) found that 32.2% of the variance in the Raven's score was associated with chronological age, and in a similar study (Babcock, 1994) 21.2% of the variance in the Raven's score was found to be related to age.

There is clearly substantial scatter in the data of Figure 1, and the proportions of variance associated with age are always substantially less than 1.0. Because many researchers may not be comfortable thinking in terms of proportions of variance, it is reasonable to question the magnitude of the age-related effects in Type A or fluid measures of cognitive functioning. Fortunately, these values can be placed in context by reference to Cohen (1988), who, in his influential book on power analysis, has suggested that in the behavioral sciences proportions of variance of .01 are small, those of .09 are medium, and those of .25 are large. The effects just described are therefore in the medium-to-large range with respect to behavioral science research.

The phenomenon of age-related cognitive decline in Type A or fluid aspects of cognition is not only moder-

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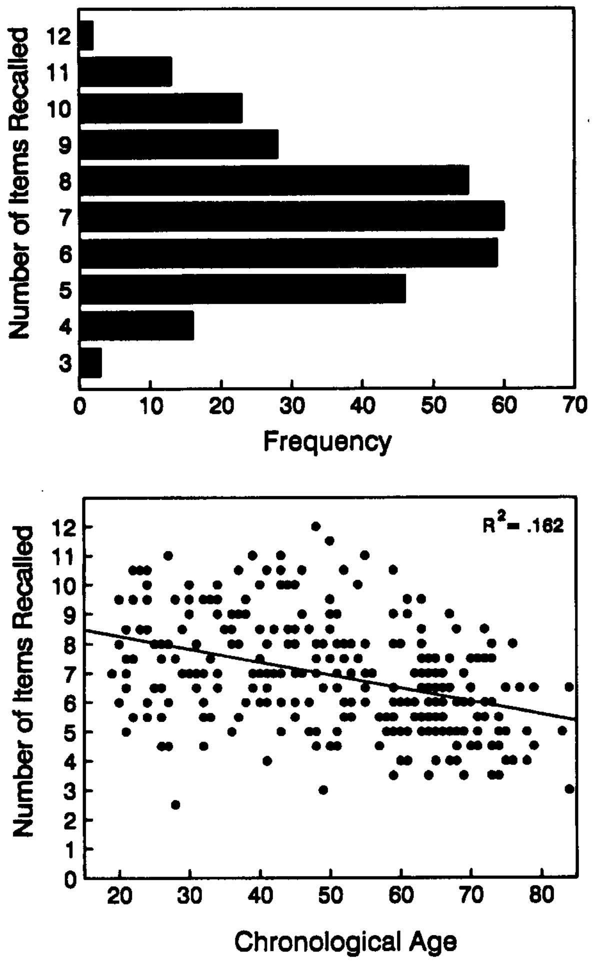

Figure 1. Distribution of scores in a 12-word free-recall task in a sample of 305 adults. Data from Salthouse (1993b).

ately large but also robust, because it has been documented since at least 1920 and has been replicated with many different types of tests, with both cross-sectional and longitudinal data-collection procedures, in several different cultures, and in a variety of species (e.g., for reviews, see Birren & Schaie, 1996, Craik & Salthouse, 1992, and Salthouse, 1991). One of the major questions in the field at the current time is: how can these negative age relations be explained? That is, what is responsible for the lower levels of cognitive performance often associated with increased age?

The goal in this article is not to describe a specific theory or explanation, but instead to identify several broad constraints that presumably must be satisfied by any plausible theory of the age-related cognitive decline phenomenon. The rationale for this approach is the assumption that it may be easier to reach a consensus on theoretical explanations if, first, there is agreement on the broad constraints that plausible theories must satisfy.

To qualify as true constraints, the relevant results should be robust, with numerous replications across different measures, procedures, and samples of participants. The emphasis will therefore be on patterns of results obtained from several independent studies and different methodological procedures rather than on results from a single study or analytical method.

EMPIRICALLY BASED CONSTRAINTS

Although many researchers, and especially those trained in experimental rather than multivariate traditions, tend to focus on single dependent variables, the age-related cognitive decline phenomenon is actually quite broad, because a great many cognitive variables have been found to exhibit age-related differences. The breadth of the phenomenon can be assessed by inspecting the contents of major journals in the field (e.g., *Psychology and Aging* and *Journal of Gerontology: Psychological Sciences*) and noting the range of variables in which significant age differences have been reported. To illustrate, in the last 5 years young adults have been reported, in these journals, to perform significantly better than older adults in the following cognitive tasks: memory for words, prose, paired associates, pictures, faces, source, activities, locations, phone numbers, routes, grocery lists, and golf shot information; reasoning with series completion, matrix, analogy, letter sets, and categorization problems; block design, paper folding, object assembly, rotation, and integration spatial tasks; divided, selective, and focused attention; and miscellaneous tasks assessing comprehension, following instructions, and serial learning.

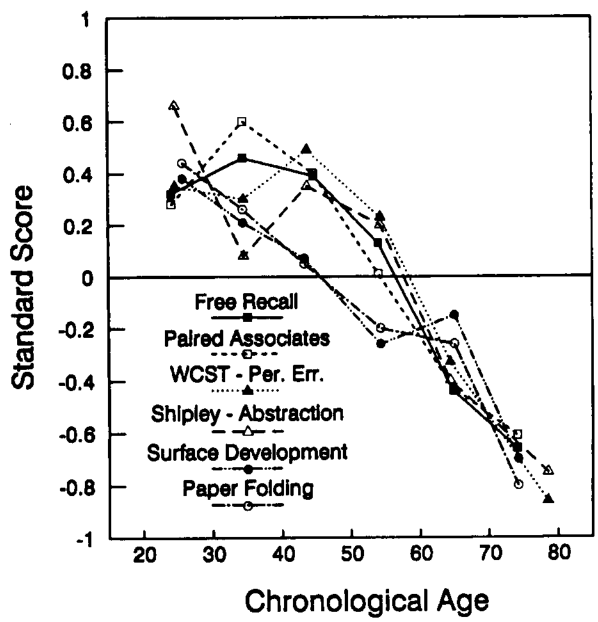

Figure 2. Mean standard scores by age decade for six cognitive measures. Data for the free-recall and paired associates tasks are from Salthouse (1993b), data for the Wisconsin Card Sorting and Shipley Abstraction tasks are from Salthouse, Fristoe, and Rhee (in press), and data for the Surface Development and Paper Folding tasks are from Salthouse and Mitchell (1990).

The scope of the phenomenon can also be appreciated by examining the age trends for different variables in moderately large samples of adults from a wide range of ages. For example, Figure 2 illustrates the age relations for six different variables (i.e., number correct in free recall of two lists of 12 words each, number correct in paired associates memory of 6 word pairs, percent perseverative errors in the Wisconsin Card Sorting Test, and number of correct responses in the Shipley Abstraction Test, in the Surface Development Test, and in the Paper Folding Test) from three separate studies. The original scores on each of the various tests were first converted to *z* scores to produce units on a comparable scale, and then the means were plotted by decade. Note that the age trends are very similar for measures of memory ability (paired associate and free recall), reasoning ability (Shipley Abstraction and Wisconsin Card Sorting), and spatial ability (paper folding and surface development). For each of these abilities there is a difference of approximately 1 *SD* between people in their 20s and people in their 70s. Similar age trends in an age-heterogeneous sample of 1,628 adults across 17 different cognitive measures have also recently been reported by Schaie and Willis (1993).

The existence of statistically significant, and often roughly comparable, age-related differences across such a wide variety of cognitive measures leads to the first constraint on theorizing about cognitive aging phenomena.

Constraint 1

Either a small number of fairly broad and general mechanisms or a large number of specific mechanisms are needed to account for the age-related differences found across a wide range of cognitive variables—

that is, because the phenomenon of age-related cognitive decline encompasses such a large number of cognitive variables, explanations of the phenomenon must either incorporate a large number of factors with highly specific effects or a relatively small number of factors with broad-reaching consequences. Theories postulating deficits in a few processes specific to a limited number of cognitive tasks will therefore not suffice to provide a complete account of the age-related cognitive decline phenomenon.

In light of the wide range of variables exhibiting significant age relations, and of the apparent similarity of the age patterns across different variables in moderately large samples, the question arises as to the extent to which age-related effects on different variables are independent. The issue of independence is also relevant to the number of distinct mechanisms necessary to account for cognitive aging phenomena, because many separate mechanisms would presumably be needed if most of the age-related effects were found to be independent. In contrast, a common or general age-related factor would probably be implicated if large proportions of the age-related effects were found to be shared.

In the past there has been a tendency among many cognitive researchers to assume that all age-related effects were attributable to specific deficits, with these deficits possibly even localizable in discrete processing stages or components. Because the focus was often on single dependent variables, such as an index of performance on a particular type of memory task, the issue of shared age-related influences was never seriously evaluated since there was no means of separating common (or shared) and specific (or unique) age-related effects. Broader interpretations have sometimes been considered, but they were often dismissed because of results (e.g., the existence of age × condition interactions) interpreted as suggesting that a general factor was not sufficient to account for all of the observed effects. For a variety of reasons (e.g., failure to consider the role of differential reliability of factors with a multiplicative influence, of processes that might vary in their reliance on a general factor, and of the possibility that both general and specific influences might operate simultaneously), these analyses may not have been optimal (Salthouse, 1991, pp. 291–300; Salthouse & Coon, 1994). In any case, however, it seems more productive to evaluate the relative contribution of different types of influences rather than to attempt to distinguish between extreme all-or-none interpretations (such as *only specific* or *only general*).

Contemporary research concerned with aging and cognition can be characterized as consisting of a surplus of sensitivity evidence but a shortage of specificity evidence. Claims of sensitivity are based on evidence that the variable or theoretical process is significantly related to age. As noted above, there are many reports of significant age relations across a wide range of cognitive variables, and thus age sensitivity has been convincingly demonstrated for many variables. The term *specificity* in this context can be used to refer to evidence that the age-related influences on one variable are distinct from, and independent of, the age-related influences on other variables. Because of the dominance of research based on small-sample, extreme-group designs focusing on a single dependent variable, very little research relevant to the issue of specificity is currently available in the field of cognitive aging. This is unfortunate because convincing evidence of specificity is needed before interpretations based on separate and distinct age-related influences can be considered plausible. That is, if a large proportion of the age-related effects on different cognitive variables is found to be shared, or in common, then attempts to identify mechanisms specific to one of the variables may merely be describing symptoms of a much broader phenomenon. Moreover, even if only some of the age-related influences are shared, the magnitude of the unique age-related effects that remain to be explained by task-specific mechanisms will depend on how much of the total effects are attributable to more general factors.

Independence is often assessed with correlational procedures, because the square of the correlation indicates the proportion of variance in two variables that is shared. However, because the current interest is in shared *age-related* influences, the relevant variance is not the total amount of variance; instead, it corresponds only to the amount of age-related variance that is shared. For example, if the proportion of age-related variance is .162, then the question of interest in the present context is how much of this variance is shared with other variables. The relevant proportions of variance can be estimated with correlation/regression procedures because prediction of the criterion variable when age is the only predictor variable in the regression equation indicates the total age-related variance, and the increment in variance associated with age after partialling out the effects of another control variable indicates the unique age-related variance. Subtraction of the unique age-related variance from the total age-related variance and division by the total age-related variance therefore yields the proportion of age-related variance in the criterion variable that is shared, or in common, with the other variable. (See Salthouse, 1992, 1994b, in press–a, for further discussion of these procedures.)

If only a small proportion of the age-related variance in a given variable is shared with another variable, then most of the age-related influences on that variable can be inferred to be independent, distinct, and potentially specific. However, if the ratio of shared (or common) age-related variance to total age-related variance is high, then one can infer that most of the age-related effects on the two variables are shared.

To ensure maximum generalizability, it is important to examine these proportions across many combinations of variables. Among the criteria desirable in data sets to be used for this purpose are: (1) multiple variables should be available from the same individuals or else no independence analyses are possible; (2) the variables should have at least moderate reliability to ensure that there is sufficient systematic variance to be shared with other variables; (3) the sample should have a wide age range, and preferably consist of a continuous distribution of ages, to ensure accurate assessments of the age-related influences; and (4) the samples should be large enough to ensure reasonably precise estimates of the relevant proportions of variance. Several studies from my laboratory have the requisite characteristics, and thus data from those studies can be examined to estimate proportions of age-related variance shared across different cognitive variables.

It is useful to illustrate these procedures with an example of the relevant computations. In a recent study (Salthouse, Fristoe, & Rhee, in press), 259 adults between 18 and 94 years of age performed tasks of inductive reasoning (i.e., Shipley Abstraction) and verbal memory (i.e., paired associates) that are usually assumed to represent distinct cognitive abilities. An initial regression analysis on the abstraction measure revealed that the R^2 associated with age was .199, indicating that 19.9% of the variance in this measure was related to age. A hierarchical regression equation in which the paired associates memory measure was controlled before the effects of age on the abstraction measure were examined revealed that the increment in R^2 associated with age was .062. An estimate of the shared age-related variance can be derived by subtraction of this value, which represents the unique age-related variance, from the total age-related variance of .199 to yield a value of .137. In this particular case, then, 68.8% (i.e., .137/.199) of the age-related variance in the abstraction measure can be inferred to have been shared with the age-related variance in the paired associate memory measure. Because the amount of age-related variance is not necessarily identical for the two variables, the estimates of unique and shared proportions need not be equivalent. In fact, the percentage of age-related variance for the paired associates memory measure estimated to have been shared with that in the abstraction measure was 58.9% (i.e., .142/.241).

A recent article by Salthouse (1994b) reported results of analyses similar to these, conducted on 855 pairs of variables obtained from 13 separate studies. The variables were derived from a wide variety of tasks, ranging from reaction time to number of items correct on the Raven's Progressive Matrices Test, and ranging from accuracy in paired associates memory tasks to accuracy in paper folding spatial tasks. The mean of these 855 values was .500 (median of .520), indicating that an average of about 50% of the age-related variance in many cognitive variables is shared, or in common. Because an average of only 19% of the total variance for these same variables was shared, it can be concluded that the simple correlation between two variables is not sufficient to determine the extent to which those variables share age-related variance.

The frequency distribution for the proportions of shared variance among 16 variables (120 pairs) in the Salthouse, Fristoe, and Rhee (in press) study is portrayed in Figure 3. Notice that the pattern was nearly identical to that found in the Salthouse (1994b) analyses in that an average of over 50% of the age-related variance in pairs of variables was shared. The similarity in outcomes is particularly noteworthy because the variables in the Salthouse, Fristoe, and Rhee (in press) study were derived from neuropsychological tests often postulated to be sensitive to functioning in different regions of the brain. For

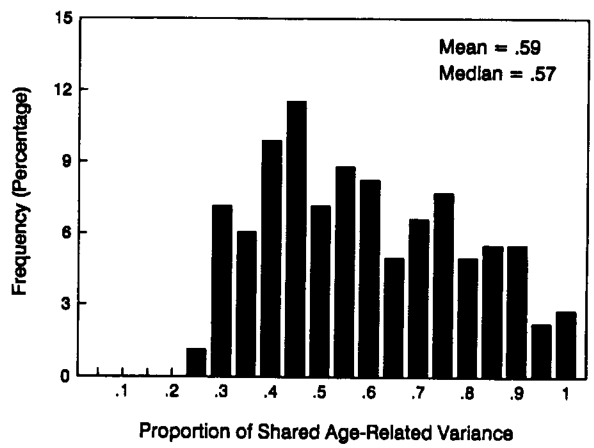

Figure 3. Distribution of proportions of shared age-related variance from 120 pairs of variables in Salthouse, Fristoe, and Rhee's (in press) study.

example, the Wisconsin Card Sorting Test and the FAS fluency test have been hypothesized to be sensitive to frontal lobe damage, visual–spatial tests such as the WAIS-R Block Design and Object Assembly tests have been hypothesized to be sensitive to right parietal lobe damage, and damage to the medial temporal lobe has been postulated to affect performance on verbal learning and memory tests such as paired associates and free recall.

The results just described indicate that the age-related effects on what appear to be quite different variables are not independent. That is, an average of approximately half of the age-related influences on a given cognitive variable appear to be shared with other cognitive variables, even when those variables have little or no resemblance to one another and when they are usually interpreted as representing distinct cognitive abilities or reflecting functioning in different brain regions.

Another analytical procedure that can be used to generate estimates of common and unique age-related influences is one proposed by Kliegl and Mayr (1992) based on a structural equation model with a single common factor. Within this model, both general (i.e., mediated through the common factor) and specific (i.e., unmediated, or direct) age-related effects are postulated to exist. Furthermore, the relative contributions of each type of influence can be estimated from standardized path coefficients derived from the structural model. That is, within this framework, the general influence is estimated by the product of the path coefficients between age and the common factor and between the common factor and the individual variable, and the estimate of the specific influence corresponds to the coefficient between age and the individual variable.

Because the common factor in this type of model is defined by the variables with significant loadings, it can be interpreted as representing what all of the variables have in common. The interesting question in the present context concerns the magnitude of the relations between age and the individual variables after the relation between age and an estimate of what all of the variables have in common has been taken into consideration. If those distinct age relations are large relative to the total age-related effects on the variable, then substantial unique or specific age-related influences can be inferred to exist. However, if the distinct (or direct) relation between age and the variable is very small, then there would be little evidence for specific age-related influences above and beyond the age-related influences shared among all of the variables.

A variety of structural equation modeling procedures (e.g., EQS, LISREL) can be used to derive the estimates for the relevant path coefficients. Because the prerequisites for these types of analyses are similar to those mentioned earlier (i.e., moderately large samples from a wide age range with several variables available from each participant), the procedures will again be illustrated with data from my laboratory. (But see Lindenberger & Baltes, 1994, and Lindenberger, Mayr, & Kliegl, 1993, for particularly elegant examples of this type of analysis.) Results from four independent data sets are illustrated in Figures 4 and 5. Figure 4A contains data from Salthouse (1993a), with measures of perceptual speed, working memory, and inductive reasoning from 221 adults between 20 and 80 years of age. The second data set, portrayed in Figure 4B, consists of measures of perceptual speed and three sets of verbal and spatial memory measures from 173 adults between 18 and 88 years of age (Salthouse, 1995a). The data set represented in Figure 5A consists of measures from neuropsychological tests from a sample of 259 adults between 18 and 94 years of age (Salthouse, Fristoe, & Rhee, in press). Finally, the data set in Figure 5B consists of measures of concept identification, associative learning, working memory, perceptual comparison speed, and visual acuity from 197 adults between 18 and 92 years of age (Salthouse, Hancock, Meinz, & Hambrick, in press).

The models summarized in Figures 4 and 5 were all generated in the same manner. First the data from the study were converted into a covariance matrix, and then a single common factor model was specified with relations from age to the common factor. Relations between variables sharing similar methods were next examined and included in the model if the coefficients differed from zero by more than 2 standard errors. Successive models were then examined in which direct relations were specified between age and each individual variable, and relations with coefficients differing from zero by more than 2 standard errors were retained in the model. The final models, represented in Figures 4 and 5, therefore portray all of the significant relations between age and the observed variables. Because there was little attempt to represent possible relations among subsets of the variables, the models can be considered relatively crude summaries of the structure of the data.[1] However, the important issue from the current perspective concerns the relative magnitudes of the mediated, or common, and the direct, or specific, age-related influences. Notice that a similar pattern is apparent in each data set in that there is a large common or general influence on all variables, along with small specific age-related influences on a few of the variables.[2] These results suggest that there are relatively few unique relations between age and the individual variables beyond those shared among all variables.

The two analytical methods described above are both quite recent, and consequently their potential limitations have not yet been fully explored. Furthermore, because relatively few studies have been conducted with the requisite data, the results illustrated were all derived from a single investigator's laboratory. Despite these qualifications, the outcomes of both types of analyses are quite consistent in suggesting that the age-related influences on many different cognitive variables are not independent. That is, the moderate-to-large proportions of shared age-related variance and the small-to-nonexistent direct relations between age and individual cognitive variables after taking into account the relation of age to a single common factor both suggest that the age-related effects

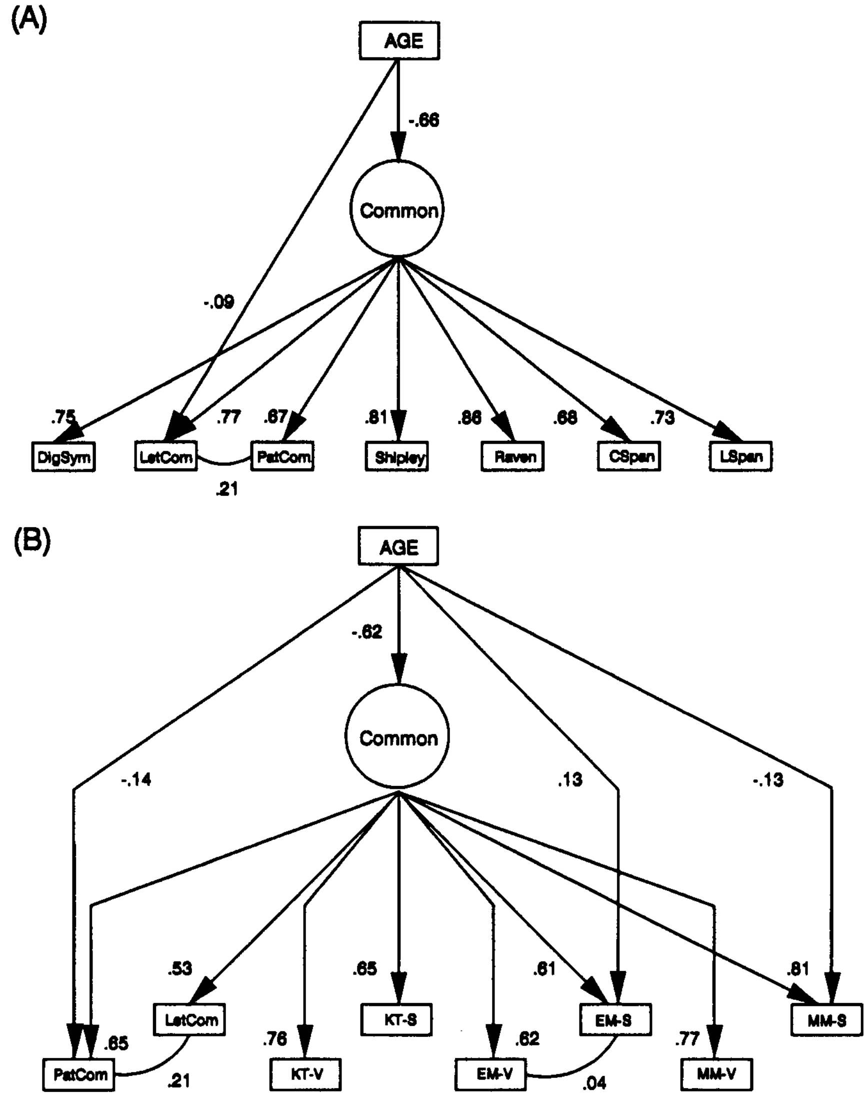

Figure 4. Single common factor structural models for data (A) from Salthouse (1993b) and (B) from Salthouse (1995a). Variables in Panel A are: DigSym = WAIS-R Digit Symbol Substitution score; LetCom = Letter Comparison; PatCom = Pattern Comparison; Shipley = Shipley Abstraction Score; Raven = Raven's Progressive Matrices score; CSpan = computation span working memory score; and LSpan = listening span working memory score. Variables in Panel B are: PatCom = Pattern Comparison; LetCom = Letter Comparison; KT-V = keeping track of verbal information; KT-S = keeping track of spatial information; EM-V = element memory for verbal information; EM-S = element memory for spatial information; MM-V = matrix memory for verbal information; and MM-S = matrix memory for spatial information.

on different cognitive variables are not independent of one another.[3] These results lead to the second important constraint on theories of cognitive aging.

Constraint 2

Some fairly general or broad mechanisms are apparently needed to account for the lack of independence in the age-related influences on cognitive variables—in other words, because a large proportion of the age-related effects on different cognitive variables appears to be shared, theories based exclusively on specific mechanisms will not be sufficient to account for cognitive aging phenomena. Although some specific age-related mechanisms appear to exist, they must be supplemented by broader or more general mechanisms in order to account for the commonality apparent in the age-related effects on different cognitive variables.

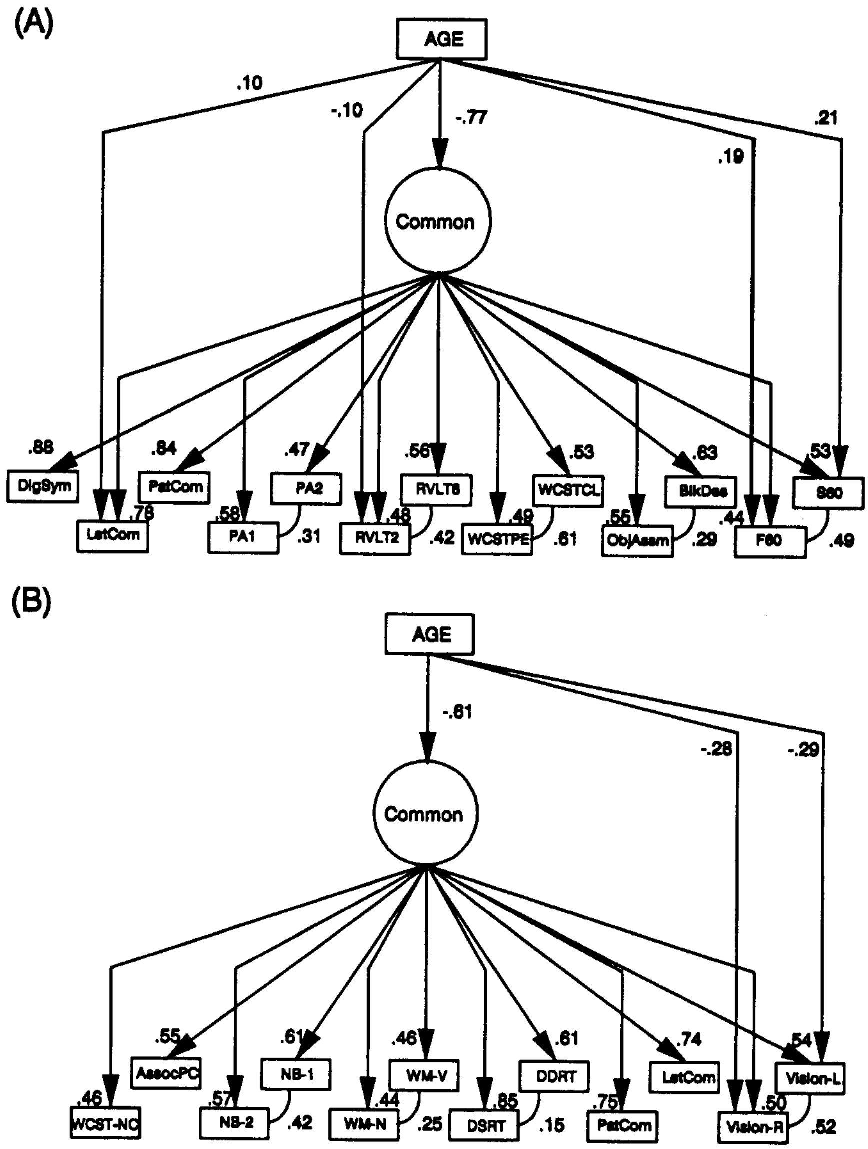

Figure 5. Single common factor structural models for data (A) from Salthouse, Fristoe, and Rhee (in press) and (B) from Salthouse, Hancock, et al. (in press). Variables in Panel A are: DigSym = WAIS-R Digit Symbol Substitution score; LetCom = Letter Comparison; PatCom = Pattern Comparison; PA1 = Trial 1 in Paired Associates Memory; PA2 = Trial 2 in Paired Associates Memory; RVLT2 = Trial 2 in the Rey Auditory Verbal Learning Test; RVLT6 = Trial 6 in the Rey Auditory Verbal Learning Test; WCSTPE = percent perseverative errors in the Wisconsin Card Sorting Test; WCSTCL = percent conceptual level responses in the Wisconsin Card Sorting Test; ObjAssm = WAIS-R Object Assembly score; BlkDes = WAIS-R Block Design score; F60 = number of words beginning with F produced in 60 sec; and S60 = number of words beginning with S produced in 60 sec. Variables in Panel B are: WCST-NC = number of category responses in the Wisconsin Card Sorting Test; AssocPC = percentage correct in associative learning; NB2 = percentage correct in reporting items two-back in a sequence; NB1 = percentage correct in reporting items one-back in a sequence; WM-N = numeric (computation span) working memory score; WM-V = verbal (reading span) working memory score; DSRT = digit symbol reaction time; DDRT = digit digit reaction time; PatCom = pattern comparison; LetCom = letter comparison; Vision-R = visual acuity in the right eye; and Vision-L = visual acuity in the left eye.

An obvious next question, in light of the evidence suggesting that a common or general age-related factor exists, concerns the nature of that factor. One approach to investigating the nature of the general factor involves examining where, in an ordered sequence, independent age-related effects occur (Salthouse, in press–b). The issue of primary interest in these sequential analyses is how much of the age-related variance in later variables