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Resource-Reduction Interpretations of Cognitive Aging

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It is reliably found in samples of adults of varying ages that increased age is associated with poorer performance on many cognitive tasks involving reasoning, memory, and spatial abilities. The assumptions underlying three process-oriented interpretations (i.e., inefficient components, less effective strategies, and diminished processing resources) of this phenomenon are critically examined, and the logic of the experimental procedures used to investigate each category of interpretation is reviewed. The interpretation postulating that an age-related reduction in some type of general-purpose processing resources contributes to impaired cognitive performance appears to be the only explanation with sufficient generality to account for the age differences observed acrosss a variety of cognitive tasks, and thus it warrants serious consideration despite ambiguity currently inherent in the resources construct. Three techniques used to investigate the role of processing resources in cognitive aging are reviewed, together with a discussion of the limitations of each. Finally, it is suggested that better understanding of the contribution of processing resources to age-related individual differences in cognitive functioning might emerge from (a) a theoretically guided search for relevant physiological mechanisms with properties presumed to be characteristic of processing resources, and (b) the examination of the consequences of limitations of resource-like parameters in simple abstract systems. © 1988 Academic Press, Inc.

One of the fundamental questions in the area of cognitive aging at the current time is "Why does the effectiveness of certain types of cognitive functioning decline with increased age in adulthood?" This question is addressed in the present article by considering alternative classes of explanation for the phenomenon of age-related cognitive decline, evaluating evidence relevant to one interpretation of the phenomenon, and then discussing what appear to be promising directions for future research on this topic. The organization of the article is as follows: (a) documentation of age-related effects on selected aspects of cognition reported in cross-sectional samples of adults; (b) critical review of the logic and assumptions underlying alternative approaches that have been adopted to explain this phenomenon; (c) detailed examination of the rationale behind, and limitations of, procedures designed to investigate the processing resource category of explanation, including a brief survey of major results from these procedures; and (d) consideration of new ways of conceptualizing the processing resources construct, and its role as a possible mediator of age differences in cognitive functioning.

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DOCUMENTING THE EFFECTS OF AGE ON COGNITION

Despite an overwhelming body of evidence accumulated over a period of more than 50 years, there is still some controversy about whether increased age in adulthood is associated with poorer performance on measures of cognitive functioning. However, much of this controversy seems attributable to a failure to distinguish between different types of cognitive abilities, and to a premature acceptance of the hypothesis that age trends are fundamentally different when examined longitudinally rather than cross-sectionally. Space limitations preclude an extensive review of the relevant literature in this context, but the issues are briefly discussed to justify restricting the scope of the current efforts to what might be considered a rather narrow aspect of adult cognitive functioning. That is, unlike most previous review or theoretical articles in which a broad variety of topics concerned with adult cognition have been addressed, the focus in the current article is restricted to examination of possible explanations for age-related differences in fluid-ability measures of cognitive functioning.

From the time of the earliest systematic investigations of the effects of aging on cognitive functioning it has been reported that different measures of cognition exhibit varying degrees of sensitivity to increased age (e.g., Beeson, 1920; Foster & Taylor, 1920; Jones & Conrad, 1933; Miles, 1933; Sorenson, 1938; Weisenburg, Roe, & McBride, 1936; Willoughby, 1927). Research of this type has led to a distinction between fluid and crystallized abilities (cf. Cattell, 1963, 1971; Horn, 1970, 1982; Horn & Cattell, 1967; Horn & Donaldson, 1976, 1980; also see Hebb's (1942, 1949) very similar distinction between Type A and Type B intelligence), with the former presumed to decline substantially with increased age, and the latter to decline much less, or perhaps even to improve, across many of the adult years. Fluid abilities include processes of memory, reasoning, and spatial cognition—all of which are presumed to be relatively independent of specific cultural experiences. In contrast, crystallized abilities are postulated to reflect one's experiential history, and are assessed by tests of vocabulary, general information, and nearly all types of acquired knowledge.

Although a comprehensive appraisal of the cognitive capacities of older adults must obviously include an account of both fluid and crystallized aspects of cognition, studies of crystallized abilities may be of limited value for theoretical purposes because performance on such tests can be considered to represent a confounding of age and experience. That is, because the level of crystallized abilities is presumed to be at least partially dependent upon the individual's experiences with his or her culture, assessing cognitive functioning with measures of crystallized ability may result in older adults having an unfair advantage over young adults because of their many more years of exposure opportunity to new or additional experiences.

The boundaries between fluid and crystallized cognitive abilities are not precise, and consequently it is sometimes difficult to determine whether a specific ability should be classified as fluid or crystallized. Nevertheless, the possibility that some aspects of cognitive functioning primarily reflect the cumulative products of prior processing and past interactions with one's environment, while other aspects are more representative of the efficiency of current processing, suggests that some distinction of this type should be made. Moreover, the fact that age and total experience are likely to be positively correlated with one another dictates that researchers should be very cautious in attempting to interpret results involving measures of crystallized ability as truly indicative of the effects of increased age on cognitive functioning. For this reason, the focus in the current article will be on age effects in fluid cognitive abilities, with consideration of age effects on crystallized abilities deferred until better understanding is reached of both the (primarily negative?) effects associated with increased age and the (primarily positive?) effects associated with increased experience.

Concerns about the possibility of design-specific aging effects originated from early reports of longitudinal studies revealing much smaller influences of aging on cognitive functioning than those typically reported in cross-sectional studies. However, later examination of this literature (e.g., Botwinick, 1977; Horn & Donaldson, 1976, 1980; Salthouse, 1982) indicated that the two types of studies were not comparable with respect to the types of abilities assessed (i.e., the early longitudinal studies often included only crystallized measures of cognition) or to the range of ages studied (i.e., several of the early longitudinal studies examined age effects only to the middle 40s).

More recent longitudinal studies have overcome several of these limitations, but they are still not fully comparable with cross-sectional studies in several respects. For example, even the most extensive of the recent longitudinal studies investigating cognitive processes span ranges of from only 16 to 21 years (e.g., Arenberg, 1982, 1983; Schaie, 1983), compared to the 40- or 50-year span typically investigated in cross-sectional studies. The range of abilities assessed in longitudinal studies is also quite limited relative to that found in cross-sectional studies. To illustrate, although an enormous variety of cognitive tasks have been investigated in cross-sectional studies, the primary assessment instruments in the Seattle Longitudinal Study (e.g., Schaie, 1983) are highly speeded psychometric intelligence tests originally developed in 1948 for the assessment of children and adolescents ranging from 11 to 17 years of age.

When these procedural differences are taken into account, several reviewers (e.g., Botwinick, 1977; Horn & Donaldson, 1976, 1980; Salthouse, 1982) have concluded that the basic results from longitudinal and cross-sectional studies do not differ markedly and what differences do exist seem more quantitative rather than qualitative in nature. Moreover, even the quantitative differences are sometimes quite negligible as Arenberg (1982, 1983) has reported very similar age trends in cross-sectional and longitudinal analyses of measures of paired-associate learning, serial learning, and memory for designs. The question of the comparability of results from cross-sectional and longitudinal studies is still quite controversial (e.g., Baltes & Schaie, 1974; Schaie, 1974), and it is possible that systematic and substantial discrepancies between cross-sectional and longitudinal trends may be convincingly demonstrated that will require explanation. At the present time, however, there appear to be some doubts about the robustness and size of purported discrepancies, and there is an immediate need to explain the very extensive and consistent body of cross-sectional results indicating that increased age is associated with progressive declines in the efficiency of several types of cognitive functioning.

One of the simplest ways of illustrating the effects of aging on cognitive functioning is to display plots, for a variety of cognitive tasks, of the percentage of the maximum score across all age groups achieved by individuals of different ages. This has been done in Fig. 1, which is based on the normative data from subtests in two psychometric intelligence batteries—the Wechsler Adult Intelligence Scale—Revised, WAIS-R,

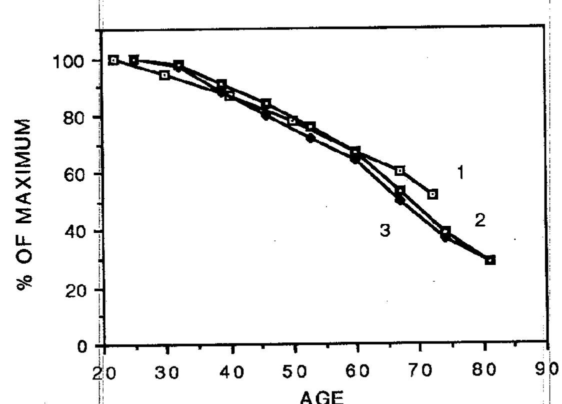

FIG. 1. Percentage of the maximum score as a function of age for (1) the Block Design subtest from the WAIS-R (Wechsler, 1981); (2) the Reasoning subtest from the STAMAT (Schaie, 1985); and (3) the Space subtest from the STAMAT (Schaie, 1985).

(Wechsler, 1981) and the Schaie–Thurstone Adult Mental Abilities Test, STAMAT, (Schaie, 1985). Expressing age trends in terms of the percentage of the maximum score is rather crude, but the results illustrated in Fig. 1 leave little doubt that increased age is often associated with poorer performance on certain commonly used tests of cognitive functioning.

Another means of summarizing the effects of age on cognitive functioning is to report the correlations between age and performance on cognitive tasks in samples of adults ranging from about 20 to 80 years of age. A total of 54 such correlations from studies involving tasks of memory, reasoning, and spatial ability were abstracted from the published literature and tabulated in Salthouse (1985, Tables 11.1, 12.1, and 13.1). The distribution of these correlations, which had an overall median of −.36, is illustrated in Fig. 2.

Correlations are not as meaningful in extreme-group designs involving only young and old samples, however, and thus another means of summarizing aging effects is to report the performance of the older sample in standard deviation units of the performance of the younger sample. One hundred-eleven values of this type from studies of memory, reasoning, and spatial ability were abstracted from the published literature by Salthouse (1985, Tables 11.1, 12.1, and 13.1). A histogram portraying the frequency distribution of these values is illustrated in Fig. 3. The median standard deviation value was −1.36, indicating that the performance of the average older adult (typically between 60 and 80 years old) was at about the ninth percentile of the distribution of performance of young adults (typically between 18 and 30 years old).

These three types of analyses, based on data representative of the

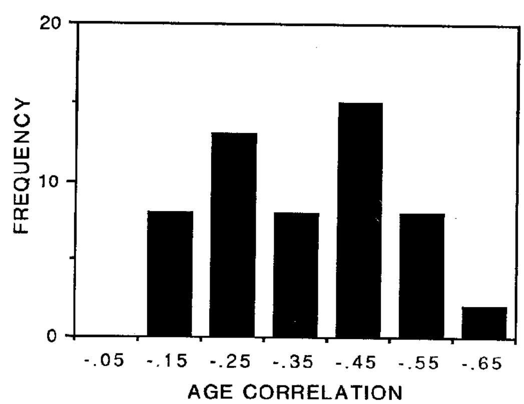

FIG. 2. Frequency distribution of correlations between age and measures of cognitive performance from studies of memory, reasoning, and spatial ability.

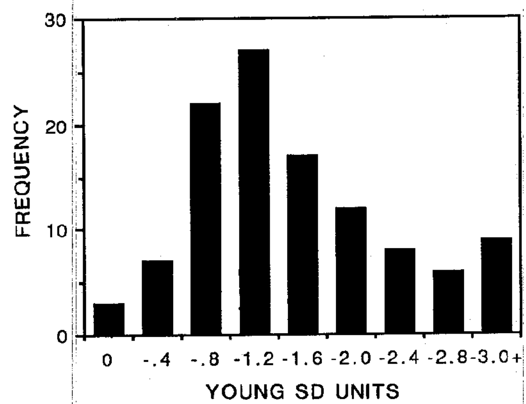

FIG. 3. Frequency distribution of performance of older adults in standard deviations of the performance of young adults from studies of memory, reasoning, and spatial ability.

findings of literally hundreds of studies in the research literature, clearly indicate that increased age is frequently associated with poorer performance in fluid-ability tests of cognitive functioning. The major challenge in light of these data is how are the results to be explained? That is, what is responsible for the effects of aging on fluid aspects of cognitive functioning?

CATEGORIES OF EXPLANATION FOR AGE DIFFERENCES IN COGNITION

Because the information-processing framework has dominated cognitive psychology for the last 20 years, most researchers in cognitive aging have relied upon this perspective in seeking explanations for the age differences observed in measures of cognitive functioning. Although concern with sources of individual differences has not been a major focus of the information-processing perspective, several theorists have postulated that individual differences in cognitive functioning might be attributable to variations in the efficiency of different types of processing. Before examining the application of these process-oriented categories of explanation to the phenomena of age-related differences in cognition, however, it is first important to consider the possibility that many cognitive aging phenomena are caused by fundamental alterations in the structure of the information-processing system.

Very few techniques are apparently available that can provide direct evidence for the role of structural differences in cognition, and consequently this type of explanation is likely to be invoked only after a researcher has concluded that alternative process-based interpretations are not sufficient to account for the observed phenomena. Although that stage might eventually be reached in the area of cognitive aging, a number of findings suggest that age differences in at least the processing of verbal information are probably not attributable to qualitative differences in the relevant cognitive structures. For example, young and old adults have been found to exhibit similar patterns of word associations (e.g., Burke & Peters, 1986; Howard, 1980; Lovelace & Cooley, 1982; Scialfa & Margolis, 1986), qualitatively similar priming effects in word recognition (e.g., Bowles & Poon, 1985; Burke, White, & Diaz, 1987; Burke & Yee, 1984; Cerella & Fozard, 1984; Chiarello, Church, & Hoyer, 1985; Howard, 1983; Howard, Lasaga, & McAndrews, 1980; Howard, McAndrews, & Lasaga, 1981; Howard, Shaw, & Heisey, 1986; Madden, 1986a), and comparable patterns of reaction time differences across variations in probe type (e.g., Mueller, Kausler, & Faherty, 1980; Petros, Zehr, & Chabot, 1983), word frequency (e.g., Bowles & Poon, 1981; Poon & Fozard, 1980; Thomas, Fozard & Waugh, 1977), or category typicality (e.g., Byrd, 1984; Eysenck, 1975; Mueller, Kausler, Faherty, & Olivieri, 1980).

Results of this type seem to indicate that adults of different ages have similar semantic memory structures, and that age differences in the performance of fluid-like tasks involving verbal material are not attributable to fundamentally different cognitive organizations of the relevant information. Evidence from tasks with other types of material is not yet as extensive, but there seems to be little indication that the basic structure of the information processing system is substantially altered with increased age, at least among relatively healthy individuals between about 20 to 70 years of age.

The various types of process limitations have received different labels and have been defined in somewhat different ways by different researchers (e.g., Butterfield, 1981; Calfee & Hedges, 1980; Carroll & Maxwell, 1979; Chi & Glaser, 1980; Hunt, 1978, 1983; Keating & Bobbitt, 1978; Salthouse, 1985; Simon, 1976; Snow, 1979, 1981; Sternberg, 1977, 1978, 1980). However, most of the taxonomic systems include categories concerned with differences in the efficiency or effectiveness of individual components, differences in the strategy or sequence of components, and differences in the quantity of some form of resources presumed necessary for many types of information processing.

The remainder of this section consists of a discussion of the logic and assumptions underlying the application (actual or potential) of each of these explanatory categories to account for age-related differences in cognition. No attempt is made to conduct an exhaustive review or evaluation of the empirical evidence relevant to these categories of explanation, but instead the focus is on the rationale behind the techniques that have been (or could be) used to investigate these different categories of explanation for the effects of aging on cognition. Moreover, because the wide usage of these techniques suggests that their advantages are well recognized, the discussion will emphasize weaknesses or limitations of the procedures that might restrict their usefulness in research on age-related individual differences.

Component efficiency. A category that has received considerable attention in recent research in cognitive aging is that in which age differences are hypothesized to originate because of limitations in either the efficiency or the effectiveness of one or more specific hypothesized processing components. For example, a researcher might postulate that successful performance on a particular task requires several distinct processing operations or components. By devising procedures to obtain independent assessments of each component, and then administering those procedures to adults of different ages, it has been assumed that one could determine which of the presumed components is primarily responsible for the observed age deficits in cognitive functioning.

The popularity of this componential approach is not surprising because it seems to provide a means of specifying the precise nature of the age-related impairments, and consequently of "localizing the loss" to certain critical components of processing. Even granting that localization may be a very limited form of explanation (cf. Salthouse, 1985, pp. 29–33), it is indisputable that, when successful, this approach provides a much more refined description of the nature of the age-related performance differences on a given cognitive task than that available from typical assessments.

However, there are a number of limitations of the component localization approach in accounting for age differences in cognitive functioning. One major weakness is that the approach, because of its focus on isolating the impairment to discrete components, provides little basis for developing an integrated explanation of the age differences found in different tasks. That is, the research summarized earlier indicates that age differences have been found in a great variety of fluid cognitive tasks, and yet explanations based on hypothesized inefficiencies in single components are necessarily specific to the tasks in which those components are presumed to play a role.

A second limitation of the component localization approach is that serious questions still remain as to the validity of many of the processing models used to identify the hypothesized components in a given task.

Advocates of a particular processing model often argue that validity is established by the impressively high R^2 values in multiple regression equations predicting the total time to perform the task from estimated duration parameters assumed to correspond to the hypothesized components. However, these demonstrations have largely been confined to measures of speed of performance in relatively simple tasks, and have not yet been widely applied to measures of quality or accuracy of performance in more complex tasks. Furthermore, it is frequently found that a substantial proportion of the predictability in these models is associated with intercept parameters that are essentially a reflection of all processes other than those directly specified in the model. In this respect, therefore, the high percentages of variance accounted for may be somewhat misleading because they are at least partially due to unanalyzed processes incorporated in the intercept parameter in regression-based models.

Another potentially serious criticism of the validity of process models is that very few of the hypothesized components have been examined for construct validity outside of a single task. Keating and his colleagues (e.g., 1984; Keating, List, & Merriman, 1985) have argued that in order to make a compelling case for the existence of hypothesized components, it must be demonstrated that very similar parameters are obtained when the components are assessed in different tasks. Because Keating et al. (1985) failed to find high correlations between the parameter estimates of what were postulated to be the same component in different tasks, these authors have suggested that the very existence of processing components may be questioned. This suggestion may be somewhat overstated on the basis of results from a single experiment, but there does seem to be a dearth of evidence for the cross-task construct validity, or context independence (Neisser, 1983), of most hypothesized processing components.

Still another apparent limitation of the component localization approach is that the procedure yields reasonable inferences about sources of age differences in cognition only if it can be assumed that the components have been exhaustively investigated and that the assessment was of equivalent sensitivity for all components. Claims that the age differences have been localized cannot be taken very seriously if only a few relevant components are examined because it is possible that age differences might also have been found in additional components that were not investigated. Of course, if age differences are discovered in every component investigated it may not be necessary to conduct an exhaustive analysis, but because such a finding would imply that the age differences are not localized, it would represent a failure for the component localization approach. It is also essential that the tests of possible differences in hypothesized components have comparable statistical power because incorrect inferences about localization would be reached if the conditions of measurement made it easier to detect differences in some components than in others. Because neither of these issues has received much attention by cognitive aging researchers using the component localization approach, prior conclusions about the purported localization of age differences in cognition should probably be viewed with some skepticism.

Inefficient strategies. A second approach to the investigation of age differences in cognition is to attribute those differences to the use by older adults of less effective strategies, or sequences of processing components, compared to those employed by young adults. The basic assumption in this perspective is that aging does not necessarily impair the efficiency of basic cognitive processes, but instead leads to an alteration in the strategies used to perform certain tasks. This view has probably been appealing to many researchers because a difference in the manner in which a task is performed is seemingly more amenable to remedial intervention than are alternative categories of explanation for the effects of aging on cognitive functioning. That is, a discovery that age differences in cognition were attributable to differential use of effective strategies would lead to much more optimistic implications concerning the possible remediation of cognitive aging effects than would support for other categories of explanation.

Unfortunately, this strategic variation approach shares one of the major limitations of the component localization approach in that to the extent that strategies are truly task-specific, the explanations that result will have little generality to other tasks. Of course, the data may eventually dictate that separate and independent explanations are needed for each age-related cognitive phenomenon, but premature focus on explanations of very limited generality may blind researchers to broader interpretations of greater potential significance.

A second disadvantage of the strategy differences approach is that it is not clear exactly what would constitute evidence for this category of explanation. A discovery that there were age differences in the strategy used to perform a given task has no special significance unless it is demonstrated that the strategic variation had a causal relation to the age differences observed in the performance of that task. An obvious method of investigating this latter issue is to attempt to induce a change in the strategies used by either young or old adults, and then to determine whether the manipulation results in an alteration in the direction or magnitude of the effects of aging on the relevant measures of cognitive performance. However, consideration of the possible outcomes that might result from this procedure suggests that few would be very convincing.

For example, if it proves impossible to induce a change in the participants' strategies, then what was thought to be a strategy may not actually be one because it is not amenable to modification or change. That is, strategies connote an optional form of processing, and if it is discovered that research participants cannot easily adopt an alternative mode of performing the task then it is probably inappropriate to characterize the performance differences between groups of individuals as being attributable to differences in strategies. It may be that because of prolonged use certain strategies become difficult to modify, but the resistance to modification suggests that they no longer possess what seems to be the defining characteristic of strategies. Therefore what might be considered a strategy in one individual may not be one in a different individual if the mode of processing has become so entrenched that it no longer possesses the property of modifiability essential for strategies.

Now consider the possible interpretations if the researcher is successful in inducing an identifiable change in the participants' strategies for performing a given task. If the age differences in performance are not substantially altered, then the probable conclusion would be that strategy variations contribute little to the observed age differences. In other words, strategy differences are unlikely to be responsible for the effects of age on cognition if the strategies can be changed and the aging effects remain the same.

A finding that the direction or magnitude of the age differences is dramatically modified by changing the strategies used to perform the task would seemingly provide positive evidence for the differential strategy interpretation. However, this is not a very satisfying explanation unless an account is also provided for the origin of the apparent differences in strategy. That is, because strategies are essentially a form of behavior, it is questionable whether it is sufficient to attribute performance differences (one aspect of behavior) to the use of different strategies (another aspect of behavior) without also providing an explanation of the reasons for those strategy differences. Particularly important in this regard is ruling out the possibility that the strategy differences emerged as a consequence of differences in a potentially more fundamental characteristic of processing such as inefficient components or a diminished supply of processing resources. Another way of expressing this point is to emphasize that while it is useful to know *whether* people of different ages are performing a task in a different manner, ultimately the more interesting question is *why* those strategic differences occur.

Of the three possible outcomes of attempts to manipulate the strategies used by research participants to perform a task, therefore, only one—successful alteration of strategy accompanied by elimination of the age differences in performance—would be consistent with the differential strategy interpretation. However, it is suggested that this outcome is probably best characterized as more refined description rather than actual explanation unless an account is also provided of the reasons for the observed strategy differences.

Reduced resources. The third category of explanation that has been used to account for age differences in cognitive functioning attributes the age differences to an age-related reduction in the quantity of some essential processing resource. The nature of this processing resource has seldom been explicitly specified, but as long as it is needed for many different types of information-processing operations, a reduction in its quantity has been presumed to be a plausible source of the age differences observed in numerous cognitive tasks.

Processing resources might be either unitary or multiple, but unless they are relevant to a variety of different tasks they are not differentiable from explanations attributing age differences to task-specific components or strategies. As Wickens (1980) pointed out, the processing resources construct ". . . can rapidly lose its predictive and explanatory value as the number of proposed reservoirs begins to approach the number of different tasks and task elements" (p. 242). In this respect, therefore, the primary distinguishing feature of the processing resources category of explanation of cognitive age differences is that resources have a relatively general influence, applicable to many different types of tasks, rather than being specific to only a few highly related tasks. It should be noted that according to this criterion, interpretations postulating the existence of metacomponents or general-purpose strategies relevant to more than one type of task would be classified within the resource category because there is apparently no operational basis for distinguishing among these purportedly different concepts.

It is probably the general-purpose characteristic of processing resources that is responsible for the prevalence in the cognitive aging literature of interpretations invoking processing resource concepts such as attentional capacity, working-memory capacity, and speed of processing. Although seldom explicitly acknowledged, it is easy to document the status of resource-based interpretations of cognitive age differences by examining how age differences in cognitive functioning have been interpreted by authors of articles in the first volume of the new journal, *Psychology and Aging*. Twelve articles published in 1986 seemed to have a primary focus on measures of cognitive functioning, and of these, five referred to resource constructs in speculating about the causes of the observed results. For example, Plude and Hoyer (1986) attributed age differences in visual search to "an age-related divided-attention deficit" (p. 9), Hartley (1986) attempted to investigate the influence on age differences in discourse recall of "speed of cognitive processing . . . (and) . . . working memory-capacity" (p. 151), Hess and Slaughter (1986) suggested that performance of elderly adults in prototype abstraction tasks "may be limited by age-related capacity variations" (p. 206), and Stine, Wingfield, and Poon (1986) concluded that at least part of the elderly adult's difficulty in comprehending and remembering spoken passages is due to "a processing rate deficit" (p. 310). In fact, the notion of processing resources seems so ingrained in the thinking of many researchers that Park, Puglisi, and Smith (1986) apparently felt compelled to offer a resource interpretation of a finding of no age differences in memory for pictorial information; that is, "It may be that picture memory requires very little capacity so that even with the divided attention task, there is still ample capacity left for each age group" (p. 16).

The dominance of resource interpretations in cognitive aging is probably even greater than that implied by these overt references because five of the remaining articles in this sample reported negative results in attempts to investigate alternative types of explanations. That is, Burke and Peters (1986) found that the age differences in word associations were very slight, thus suggesting that young and old adults did not differ with respect to the organization of semantic information. Other investigators concluded that "the locus of the age sensitivity . . . in memory for performed activities . . . remains unresolved" (Kausler, Lichty, Hakami, & Freund, 1986, p. 81), that "it seems unlikely that storage is the locus of the age decrement in memory for input mode" (Lehman & Mellinger, 1986, p. 179), and that age differences in memory are not attributable to age-related differences in "participation in student activities" (Parks, Mitchell, & Perlmutter, 1986, p. 253), or to age-related differences in "spontaneous self-referencing" (Mueller, Wonderlich, & Dugan, 1986, p. 299). Somewhat more positive, but nevertheless qualified, speculations were offered in the other two cognitively oriented articles in that Sinnott (1986) suggested that age-related effects in the performance of everyday memory tasks "might be understood as motivational effects or as stylistic compensatory processing differences" (p. 114), and Coyne, Allen, and Wickens (1986) proposed that in a memory search task, "older adults may adopt a different response strategy than do younger adults" (p. 194).

Despite the de facto acceptance by many researchers of the processing resource category of explanation for age differences in cognition,[1] it has been very difficult to adequately test this proposal because the nature of the hypothesized resource has never been precisely specified or independently measured. In fact, past usages of the resources concept have frequently been distinctly circular in that age differences in the performance

[1] See Salthouse (in press-a) for further documentation of the prevalence of resource interpretations in cognitive aging. It should also be noted that research efforts concerned with age differences or lack of age differences in automatic processing are implicitly based on the processing resources notion because the term automatic is only meaningful in the context of independence from a limited-capacity processing resource.

of certain cognitive tasks have been attributed to a reduction in the quantity of processing resources, but the reduction in resource quantity has also been inferred on the basis of the same observed age differences in performance.

The preceding discussion indicates that none of the available categories of explanation for age-related differences in cognitive functioning is without potentially critical conceptual problems and that each represents a compromise in certain respects. Moreover, until some degree of consensus is reached regarding the resolution of these seemingly fundamental problems, it appears unlikely that the validity of different approaches to explanation can be evaluated simply by examination of the existing empirical evidence.

While it is probably not yet possible to distinguish among the explanatory categories on empirical grounds, preferences among the categories can be established on the basis of one's assessment of the relative importance of different characteristics or criteria. Because the field of cognitive aging is currently very fragmented and chaotic, and composed of numerous sets of largely isolated phenomena, it can be argued that the ability to provide a coherent and integrated interpretation should be the paramount consideration in assessing the heuristic value of various categories of explanation. The processing resources category appears to be the only class of explanation that can be evaluated very highly in this respect, and therefore the greatest progress may result from efforts directed toward the elaboration and investigation of this category of explanation for age differences in cognitive functioning.

PARALLELS BETWEEN PROCESSING RESOURCES AND INTELLECTUAL *g*

Before discussing how the processing resources interpretation might be investigated in the area of cognitive aging, it is useful to briefly consider the background and status of the construct of processing resources in the field of cognitive psychology. (Also see Allport, 1980, Navon, 1984; and Wickens, 1984) for additional discussions of this topic from somewhat different perspectives.) In many respects the notion of processing resources in cognitive psychology is analogous to the concept of *g* in psychometric intelligence. That is, the concepts were originally proposed for similar reasons, they have been modified and extended in parallel ways, and despite being subjected to the same types of criticism, both concepts have exhibited remarkable persistence in the scientific literature. Moreover, the resemblance is probably not merely fortuitous because both concepts can be traced to Spearman (1927), who originated the notion of *g*, and also used resource-like terminology in characterizing the force behind *g* as some type of mental energy or power.

Both *g* and processing resources were initially postulated to account for commonalities of performance in what appeared to be quite distinct types of cognitive tasks. Positive correlations among performance measures from different intellectual tasks provided the evidence for commonality leading to *g*, while reciprocities in the performance of two concurrent tasks stimulated interest in a common pool of shared processing resources. These initially simple concepts were then elaborated by subsequent theorists who, among other things, postulated multiple, rather than unitary, entities and hierarchical organizations of the multiple entities. In both cases there were also theorists who argued that the purportedly common factors were actually quite specific. In the domain of psychometric intelligence this phenomenon is clearly exemplified in Guilford's model of well over 100 different types of intelligence. Examples within the domain of attention are the claim of Navon and Gopher (1980) that vertical and horizontal axes in manual tracking each require a different type of perceptual–computational resource, and the recent conclusion by Hirst and Kalmar (1987) that decisions involving semantic categories such as animals and body parts make demands upon separate types of processing resources.

The constructs of intellectual *g* and processing resources have also been subjected to similar types of criticism. The most frequent objection is that because these terms are so vague, it is very difficult to determine exactly how propositions that include these concepts might be tested. In fact, it is sometimes suggested that the usage of these terms is merely self-reinforcing, rather than based on rigorous empirical investigation. Skeptics have also questioned whether concepts such as *g* or processing resources are actually necessary because plausible alternative explanations of the relevant phenomena can apparently be formulated that do not include these concepts.

Although many of these criticisms have been valid, it is remarkable how pervasive references to the concepts of intellectual *g* and processing resources are in the contemporary psychological literature. The continued usage of these terms despite their recognized weaknesses suggests that many researchers believe that there are common determinants of performance across different cognitive tasks even if it is not yet possible to specify exactly what those determinants are. Unless there is some means of subjecting these concepts to investigation, however, there is a risk that they may degenerate into metaphysical entities with little or no scientific value. The next section of this article is therefore devoted to examining the attempts that have been made to investigate the processing resources construct in the area of cognitive aging.

INVESTIGATION OF PROCESSING RESOURCE INTERPRETATIONS OF COGNITIVE AGING

Although most cognitive aging researchers have relied upon the notion of processing resources as an explanatory construct rather than as the direct subject of investigation, there appear to be at least three ways in which the processing resources interpretation of age differences in cognitive functioning can be investigated.[2] These are: (a) the use of secondary task procedures to obtain estimates of the reserve processing capacity, or residual resources, available to adults of different ages; (b) examination of the relationship between hypothesized resource demands and task performance in different age groups; and (c) use of statistical techniques to examine the effects of controlling an index of resource quantity on the magnitude of age differences in cognitive performance. The first two approaches will be briefly described, but their potential contribution appears limited because they primarily address the issue of whether resource quantity declines with age, and not whether a reduced availability of processing resources mediates the age-related impairments in cognitive performance. This latter issue is the explicit focus of the third approach, and thus it will receive the most extensive treatment in this discussion.

Secondary task procedures. The secondary task technique is based on the assumption that when two tasks are performed together they compete for processing resources from the same limited pool, and consequently performance on a secondary task can be interpreted as reflecting the resources remaining after those needed for the primary task have been expended. The reasoning is therefore that if older adults have a smaller quantity of processing resources than young adults, then they should exhibit poorer performance on the secondary task because they have fewer residual resources while performing the primary task. This expectation has been confirmed in a number of studies utilizing simple or choice reaction time as the secondary task with either perceptual–motor or memory primary tasks (e.g., Craik, 1986; Duchek, 1984; Macht & Buschke, 1983; Madden, 1986b; McDowd, 1986; Salthouse & Saults, 1987; Salthouse & Somberg, 1982).

Although the pattern of greater impairment of secondary task perfor-

[2] Actually, two other techniques for investigating single-factor interpretations of cognitive aging phenomena such as reduced processing resources have been proposed. These involve examining age differences across a variety of dependent measures under the assumption that a single factor should result in differences of a similar magnitude, and comparing the pattern of across-variable correlations in different age groups because of an expectation that the correlations should increase with age. However, both techniques depend upon the questionable assumption that the primary determinant of performance in each task is the quantity of processing resources available to the individual (cf. Salthouse, 1985, p. 197), and thus they seem unlikely to yield reasonable inferences.

mance with increased age has been interpreted as indicating that the quantity of processing resources declines with increased age, this interpretation is dependent upon a number of important, but as yet unsubstantiated, assumptions (cf. Salthouse, 1985, pp. 68–70, for further discussion of these issues). One critical assumption is that the quantity of processing resources remains invariant for a given individual across a variety of experimental situations. Very misleading inferences about resource quantity would obviously result if that quantity did not remain constant, and instead varied with level of motivation or degree of arousal, as has been postulated by some theorists (e.g., Kahneman, 1973).

The inferences would also be suspect if adults of different ages used different policies of allocating resources to the two tasks (e.g., 100% of the required resources to the primary task and the remainder to the secondary task vs 50% of the required amounts to each task), or if the concurrence costs of managing the performance of two simultaneous tasks were greater in one group than in another (e.g., an "overhead" rate for each additional task of 5% vs 10% of the required or available resources). Also unknown, but of critical importance for the success of the secondary task procedure, is whether adults of different ages have equivalent relations between resource quantity and performance of each task. For example, a unit increase in resources might result in a 5% increase in task performance in one group of individuals but in only a 3% increase in another group. To the extent that disparities of this type exist, it would be unreasonable to expect meaningful inferences about resource quantity from examination of task performance without taking this differential relation into account.

There are also two practical problems that have been discovered in previous attempts to implement the secondary task procedure. One difficulty is that changing from the single to the dual-task condition often results in altered performance on the primary task, as well as the expected variations in performance on the secondary task. Because this suggests that the allocation of resources to the primary task did not remain constant from the single to the dual-task situation, it greatly complicates interpretation of the results. The second problem is that there are frequently substantial age differences in both tasks when they are performed alone, and thus age differences in the dual-task situation might be expected even if there were no differences in resource quantity. Performance-operating characteristics and the use of relative as well as absolute assessments of divided attention costs (e.g., Salthouse, Rogan, & Prill, 1984; Somberg & Salthouse, 1982) serve to address these issues, but the problems have not yet been completely resolved and thus interpretations of cognitive aging studies employing secondary task procedures are often ambiguous.

Although this large number of unverified assumptions should make one cautious about conclusions based on results from the secondary task procedure, it is still a valuable technique for investigating possible age differences in processing resources because there are few alternatives to the concept of processing resources that can account for the interference observed between what are seemingly quite different tasks. However, there are limits on the usefulness of this procedure in the field of cognitive aging because even in the best of circumstances it is only informative about the possibility of age-related reductions in the quantity of available processing resources, and it does not address the issue of whether that resource reduction is responsible for the observed age differences in cognitive functioning.

Systematically varied resource demands. The second procedure for investigating the influence of processing resources in cognitive aging consists of examining the magnitude of age differences in performance across conditions presumed to vary in their resource requirements. The reasoning in this strategy is that experimental conditions can be created that vary primarily in terms of their required processing resources and that inspection of the relation between performance and the presumed resource requirements will be informative about the quantity of processing resources available to different groups. In fact, by assuming that the resource demands and the resource–performance relations are invariant across age groups, it is even possible to use this procedure to derive quantitative estimates of the amount of resources available to older adults relative to that available to young adults (cf. Salthouse, 1987, in press-a).

This technique has only been explicitly applied in a few studies (Salthouse, 1987, in press-a), but the results have generally been consistent with the processing resource expectations in that the performance differences between age groups have been found to increase as the presumed resource requirements of the tasks increased.[3] That is, in several different types of tasks older adults exhibited greater increments in decision time and error rate than young adults as the number of hypothesized processing operations increased, suggesting that the former may have had smaller amounts of a relevant processing resource than the latter. Moreover, in the Salthouse (in press-a) studies it was found that the magnitude of performance change associated with an increase in task complexity

[3] It is important to point out that this basic phenomenon is well established in the cognitive aging literature in the context of the complexity effect (cf. Salthouse, 1985, p. 183–190 for a review and discussion). However, in none of the earlier studies where this phenomenon was demonstrated was there an attempt to derive predictions about relative quantities of processing resources by ensuring that the complexity variations were introduced by quantitative, rather than qualitative, manipulations.

exhibited in one task was significantly correlated with that evident in other tasks, suggesting that all tasks may have relied upon a common processing resource.

As with the secondary task procedure, however, there are limitations of this approach for the purpose of investigating processing-resource interpretations in cognitive aging. For example, inferences from the technique of systematically varied resource requirements would be erroneous: (a) if resource quantity does not remain constant within an individual, but instead varies across experimental conditions; (b) if the conditions presumed to differ only in resource requirements also differ with respect to other factors that influence performance; and (c) if either the resource demands or the relation between task performance and resource quantity varies across age groups. Moreover, because the procedure is designed to investigate the effects of aging on resource quantity, it does not provide a means of investigating the question of whether a reduction in processing resources mediates the effects of aging on cognitive performance.

Statistical control of resources. The third resource-investigation technique, involving the statistical control of an index of resource quantity, can best be described by considering three alternative interpretations of the interrelationships of age, processing resources, and cognitive performance. An illustration of these interpretations is portrayed in Fig. 4.

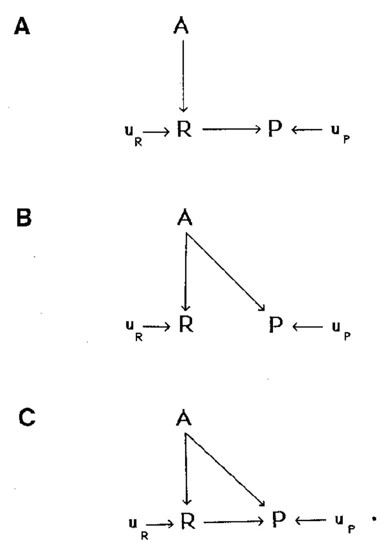

FIG. 4. Three alternative models of the structural relationships among age (A), processing resources (R), and cognitive performance (P). The subscripted u terms refer to unmeasured determinants of the targeted variable.

The strongest view of the role of processing resources in age differences in cognition is that all of the effects of age on the performance of a cognitive task are mediated through a reduced quantity of processing resources. This view is represented in Fig. 4A, which indicates that there are proposed to be direct effects of age on processing resources and direct effects of processing resources on cognitive performance, but no direct (i.e., not resource-mediated) effects of age on cognitive performance.

A diametrically opposed view of the role of processing resources in cognitive aging, one that completely rejects any resource-mediated effects of age on cognitive performance, is illustrated in Fig. 4B. According to this interpretation, measures assumed to index the quantity of processing resources are simply reflections of certain aspects of cognitive functioning, and are in no way responsible for the effects of age on other aspects of cognitive functioning. From this perspective, therefore, all aging effects are direct in the sense that they are not mediated through a construct such as processing resources.

A third interpretation, which is essentially a compromise between the first two positions, is that there are both direct and indirect (or resource-mediated) effects of age on cognitive performance. This view is illustrated in Fig. 4C.

Although the three illustrations in Fig. 4 are very simple, and consequently may omit important variables or relations, they are nevertheless useful because they lead to quite distinct, and hence testable, implications. In this respect, therefore, the various panels of Fig. 4 can be viewed as alternative first-approximation models of the role of processing resources in cognitive aging. Moreover, representation of the alternatives in this structural form suggests that the models might be distinguishable by means of causal modeling procedures such as path analysis or analysis of latent construct structural equations.

The reasoning involved in these analytical procedures can be illustrated by concentrating on the model portrayed in Fig. 4C because, as noted above, it is essentially a composite of the other two models. A key aspect of causal modeling techniques is that they provide a means for determining whether an hypothesized linkage between two variables is statistically significant after the level of other potentially relevant variables has been taken into account. Expressed in the concepts illustrated in Fig. 4, these procedures allow an investigator to determine if there is evidence of a significant relation between age and a measure of cognitive performance after the level of processing resources is taken into account, or if there is evidence of a significant relation between the level of processing resources and a measure of cognitive performance after age is taken into account. Notice that this is precisely the type of information necessary to distinguish among the alternatives portrayed in Fig. 4. That is, the former outcome would rule out the model illustrated in Fig. 4A (i.e., a discovery of a direct connection between age and cognitive performance is inconsistent with the view that all effects of age on cognitive performance are mediated through processing resources), and the latter outcome would rule out the model illustrated in Fig. 4B (i.e., a discovery of a direct connection between processing resources and cognitive performance is incompatible with the view that these are separate and independent correlates of age).

The results to be discussed later will be based upon path analysis procedures, but it should be emphasized that a number of ostensibly different procedures are logically equivalent in their implications. For example, methods of partial correlation, hierarchical multiple regression, and even analysis of covariance are similar in that the goal of each of these procedures is to determine the relationship between two variables after the influence of other variables has been removed by statistical means.

How are resources to be measured? Regardless of the specific technique employed, a critical requirement for conducting these types of analyses is the identification of a suitable index (or indices) reflecting the quantity of processing resources available to an individual. This can be a major obstacle in efforts of this nature because the lack of consensus on the nature of processing resources has precluded identification of variables to assess the quantity of processing resources, and yet those variables are essential for the investigation of structural models incorporating the construct of processing resources.

The absence of widely accepted indices of resource quantity is clearly a difficult problem, but it is important that it be addressed because the technique of examining age effects in cognition after statistically controlling an index of resource quantity seems to provide the best available means of investigating the hypothesized mediational role of processing resources in cognitive aging. The approach I have pursued in attempting to solve this problem has been to identify the different ways in which the construct of processing resources has been used in the research literature, and then to employ various rational and empirical criteria to guide the selection of variables reflecting the various resource conceptualizations. After examining much of the relevant literature, I (Salthouse, 1985; in press-a, in press-b) recently concluded that the bulk of the references to the concept of processing resources could be encompassed within three categories organized around the metaphors of space, energy, and time.[4]

[4] There is, of course, some degree of arbitrariness in this selection of metaphors, and it is interesting to note that other writers have used somewhat different metaphors for characterizing the resources construct. For example, Anderson (1985, p. 41) proposed that attentional or processing resources can be understood in terms of metaphors of energy, space, and animate processing agents or demons, and Hirst and Kalmar (1987) have suggested that the concepts of fuel, structure, and skills can be used as metaphors for attentional resources.

The space metaphor is based on the idea that there is a finite working-memory capacity that determines the amount of short-term storage or computation that is simultaneously possible. To the extent that this cognitive workspace is restricted, performance of tasks requiring access to it for carrying out information transformations or storing temporary products can be expected to be impaired. The metaphor of resources as energy is reflected in references characterizing processing resources as some type of attentional capacity that functions as a general-purpose "fuel" for information processing. As with various forms of physical energy, short supplies of mental energy would presumably reduce the scope of what can be accomplished, or impair the efficiency or effectiveness of what actually is accomplished. The conceptualization of time as a processing resource is somewhat novel, and based on the idea that the quicker or faster cognitive operations are executed the more likely it is that other operations can be initiated, and that processing dependent upon multiple operations will be accurately completed.

Obviously these basic metaphors must be subjected to theoretically guided elaboration before they will prove useful for the selection of variables suitable as indices of the quantity of the relevant processing resources. As an example of this type of effort, I will briefly describe the reasoning I have followed in attempting to select a measure of the speed or time resource. First, I (Salthouse, 1985) have argued that the processing resource of time or speed of processing should ideally be related to the rate of performing cognitive operations. However, it is important that the task chosen to assess rate of processing be of the appropriate level of complexity. On the one hand, performance in very complex tasks, or tasks involving a particular type of stimulus material, may reflect factors such as efficiency of executing specific cognitive operations or the ease of encoding or manipulating certain types of information more than the speed of elementary cognitive operations. On the other hand, performance in very simple tasks such as simple or choice reaction time may reflect the speed of perceptual and motor processes as much or more than the speed of cognitive operations. More satisfactory measures might be those derived from several reaction time tasks, such as the difference in reaction time between two experimental conditions or the slopes of regression equations relating reaction time to a relevant dimension of the task. Unfortunately, a practical problem with derived measures of this type is that they frequently have low reliabilities that limit their usefulness in many situations. An alternative procedure, and one which I have adopted in a number of studies, is to attempt to assess rate of processing with paper-and-pencil tests in which the measures of performance might be interpreted as primarily reflecting the quickness with which one carries out simple cognitive operations.

Results with the statistical control procedure. Several studies recently conducted in my laboratory involved variables designed to assess resource quantity, and which yielded data that could be subjected to path analysis causal modeling techniques. One study (Salthouse, in press-a) relied upon the WAIS-R Backward Digit Span measure to represent the space or working-memory conceptualization of processing resources and the WAIS-R Digit Symbol Substitution measure to represent the time or processing-rate conceptualization of processing resources. Although these measures are obviously very crude indices of processing resources and probably also reflect variations in factors unrelated to resource quantity, they do allow an initial assessment of the resource predictions. These two tasks, along with two fluid-ability tasks, were administered to samples of 100 young adults (ages, 18 to 25; mean = 19.1) and 100 older adults (ages, 57 to 67; mean = 62.4). The tasks selected to assess fluid cognitive abilities were a geometric analogies reasoning task and a mental synthesis spatial task presented in a verification format, with performance evaluated by measures of mean accuracy and median decision time per problem.

Median values (across the time and accuracy performance measures) of the standardized path coefficients for the model illustrated in Fig. 4C are displayed in Table 1. Also displayed in this table are the results from a replication study involving 100 young adults (ages, 17 to 26; mean = 18.9) and 40 older adults (ages, 55 to 75; mean = 63.6) with identical cognitive tasks and additional indices of processing resources. It is clear from both sets of results that neither of the simpler models postulating no direct connections between either Age and Performance (Fig. 4A) or between Resources and Performance (Fig. 4B) is consistent with these data. In-

TABLE 1
MEDIAN STANDARDIZED PATH COEFFICIENTS FROM ANALOGIES AND SYNTHESIS TASKS

Resource index	A → R	R → P	Direct A → P	Indirect A → R → P
Study 1				
Digit symbol	−.77	.18	−.40	−.14
Backward digit span	−.35	.24	−.41	−.08
Study 2				
Digit symbol	−.76	.44	−.23	−.33
Coding time	−.53	.45	−.30	−.24
Number comparison	−.43	.28	−.41	−.12
Verbal memory	−.38	.16	−.47	−.06
Spatial memory	−.52	.32	−.37	−.17

Note. All variables have been scaled such that better performance is represented by higher numbers.

stead the existence of substantial coefficients for the Age–Performance and Resource–Performance paths suggests that Fig. 4C provides the best characterization of these results.

A quantitative estimate of the percentage of the total effects of age on cognitive performance mediated by processing resources can be obtained by dividing the average of the indirect effects by the average of the sum of the direct and indirect effects. These computations reveal that the total age effect was −.53, indicating that one standard deviation shift in age was associated with a −.53 standard deviation shift in cognitive performance, and that only −.16, or about 30%, of this effect was attributable to the mediation of processing resources.

Similar analyses were also conducted on data recently collected by Salthouse, Kausler, and Saults (1988) from two slightly different cognitive test batteries administered to samples of 129 and 233 adults ranging from 20 to 79 years of age. The cognitive tasks in this project ranged from paired-associate tests of learning to series-completion tests of reasoning to paper-folding tests of spatial ability. Time and accuracy measures in these tasks served as the cognitive performance variables, with two speed measures and two memory measures functioning as the indices of processing resources. Medians across performance variables of the standardized path coefficients for each resource index are displayed in Table 2. As in the previous studies, these results are most consistent with Fig. 4C. The estimate of the contribution of the total effects of age on cognitive performance mediated by processing resources is 24%. This is similar to the previous estimate of 30%, despite a smaller total age effect (i.e., −.32)

TABLE 2
MEDIAN STANDARDIZED PATH COEFFICIENTS FROM SALTHOUSE ET AL.'S (1988) COGNITIVE TEST BATTERY

Resource index	A → R	R → P	Direct A → P	Indirect A → R → P
Study 1				
Digit symbol	−.54	.24	−.15	−.13
Number comparison	−.50	.02	−.26	−.01
Verbal memory	−.36	.27	−.17	−.10
Spatial memory	−.47	.26	−.16	−.12
Study 2				
Digit symbol	−.56	.16	−.28	−.09
Number comparison	−.30	.07	−.36	−.03
Verbal memory	−.39	.20	−.29	−.08
Spatial memory	−.42	.14	−.30	−.06

Note. All variables have been scaled such that better performance is represented by higher numbers.

undoubtedly attributable to the use of adults from the complete age continuum rather than from only two extreme age groups.

Although seldom reported in the form of path analysis coefficients, results from a number of other studies are generally consistent with these findings. For example, Salthouse (1985) summarized a variety of partial correlation analyses between age and assorted measures of cognitive performance after statistical control of the WAIS-R Digit Symbol index of time-related processing resources. The dominant finding in these analyses was that the partialling procedure attenuated, but did not completely eliminate, the effects of age on the measure of cognitive performance. Other researchers have also reported similar findings with measures of comprehension or retention of verbal material serving as the cognitive performance variables and measures of working-memory capacity or rate-of-processing functioning as the indices of processing resources (e.g., Hartley, 1986; Light & Anderson, 1985).

To summarize, then, considerable research seems to support the intermediate or weak version of the processing resources perspective in which there are postulated to be both indirect (resource-mediated) and direct (not resource-mediated) effects of age on cognitive performance. This is a weak version of the processing resources view because the sizable path coefficients between age and performance indicate that not all of the effects of age on cognition are mediated through a reduction in the quantity of processing resources, at least as the latter has been indexed by the available measures. In fact, the computations of the indirect effects reported above suggest that only between 24 and 30% of the effects of age on measures of cognitive functioning can be attributed to the mediation of a reduced quantity of processing resources. The apparent inference from these results, assuming that the previously employed measures are accepted as valid indices of processing resources, is that nonresource factors, such as variations in component efficiency or strategic effectiveness, contribute to much of the observed age differences in fluid cognitive abilities.

PURSUING RESEARCH ON PROCESSING RESOURCES

The results just described could be viewed as rather discouraging for the processing resources interpretation because they suggest that while there may be a resource-mediated contribution to the effects of aging on cognitive performance, the resource-mediated effects are generally much smaller than the direct or nonmediated effects. On the other hand, accounting for almost one-third of an important phenomenon with a single construct such as a reduced quantity of processing resources could be considered a fairly impressive accomplishment.

Regardless of how past findings are perceived, however, it is desirable that research with the statistical-control-of-resources procedure continue to be pursued. Not only does this appear to be the most powerful investigative technique currently available for examining the influence of processing resources in age differences in cognition, but there are a number of obvious ways in which the research described above could be extended, and most likely improved. For example, one very natural extension is to consider novel measures as indices of processing resources. Alternative indices could be motivated by different metaphorical conceptualizations of processing resources, by a more reductionistic focus emphasizing psychophysiological measures, or simply by dissatisfaction with the measures that have been examined in the past.

Another possibility for extending this type of investigation is to employ latent construct procedures for the measurement of processing resources. This is a promising approach because relying upon multiple indicators to assess a construct has at least three advantages over univariate assessment: (a) the construct can be evaluated with greater breadth; (b) test-specific variance can be removed; and (c) measurement error can be minimized. However, in order for this technique to be successfully applied in the area of cognitive aging there must be a well-specified theoretical justification for the assignment of manifest variables to the theoretical construct of processing resources. Without a clearly articulated theoretical rationale, which presently seems to be lacking, there is a risk of committing the nominalistic fallacy (cf. Cliff, 1983) in which a theoretical construct is assumed to be understood or accurately measured merely because one or more variables are given the label of the construct.

A third direction that could, and probably should, be explored in extending causal modeling procedures to the examination of the role of processing resources in cognitive aging involves the development of more complex models of the interrelations of age, processing resources, and cognitive performance. Future research would almost certainly benefit from more elaborate specification of mediation mechanisms, particularly with respect to how varying quantities of processing resources influence performance on a given task. This elaboration could obviously take many forms, and might consist of the postulation of different resource pools for different cognitive tasks, of the specification of the conditions under which tasks are believed to be independent of processing resources, of the hypothesis of nonlinear or threshold relations between resource quantity and certain measures of performance (e.g., a minimum quantity of resources might be a necessary but not sufficient requirement for a particular level of performance), or of additional constructs inferred to intervene between processing resources and cognitive performance.

The likely goal with each of these extensions of the approach of statistically controlling the level of processing resources is, at least when viewed from the perspective of adherents of the resources perspective, to discover whether it might eventually be possible to account for all age effects on cognitive performance through the mediation of processing resources. Even if research in these new directions does not prove successful in completely eliminating all direct effects of age on cognitive performance, it should result in more precise estimates of the magnitude of resource-mediated contributions than those currently available. In this respect, therefore, these types of research extensions should certainly be encouraged because they are likely to lead to a better understanding of what, and how much, remains to be explained of the effects of age on cognitive functioning.

However, there are at least two issues that should be considered before fully committing oneself to the pursuit of research of this type. One issue concerns the possibility that the reduced-resource predictions could be supported for artifactual reasons. For example, direct effects of age on cognition might be minimized or even completely eliminated if the range of cognitive performance assessed is very limited, and the resource index is simply another reflection of that same type of cognition. An extreme instance of this situation might be the use of a digit span measure as an indication of the space conceptualization of resources, and the use of a letter span measure as the cognitive performance variable. The obvious similarity between the digit span and letter span measures renders the distinction between processing resources and cognitive performance rather meaningless, and thus in circumstances such as these the only surprising results would be negative ones (i.e., failing to eliminate direct effects of age on letter span performance after statistical control of digit span performance).

A second way in which the processing-resource interpretation of cognitive aging might be artifactually supported is when the resource construct is assessed with multiple indicators which, in the aggregate, encompass nearly all aspects of cognition. The problem here is that if the resource index is a composite of measures of many types of cognition, then there may be little of interest to be explained that is not already incorporated in the resource construct. By increasing the number of variables included within the resource construct, therefore, one may be running the risk of, in effect, demonstrating that the effects of age on cognition can be eliminated by controlling the level of cognition.

Another important issue that should be considered before pursuing further research on processing resource interpretations of cognitive aging concerns the validity of the measures used to index processing resources. As noted earlier, theoretical assumptions are generally used as the basis for assigning some variables as indices of processing resources and interpreting other variables as reflections of cognitive performance. Unfortunately, there are seldom any procedures specified that allow one to assess the validity of the constructs independent of the tests of the hypotheses incorporating those constructs. This is a potentially serious problem in the current context because the debate about the usefulness of processing-resource interpretations of cognitive aging phenomena may be endless if measures are not accepted as valid indicators of the resource construct until the strong predictions of no direct effects of age on cognitive performance are confirmed. It is thus possible that a new circularity may emerge in the resources literature, namely, that the processing resources interpretation cannot be tested until one has valid measures of processing resources, and the measures are not considered valid until one is successful in eliminating all of the direct, or non-resource-mediated, effects of age on cognitive functioning.

Clearly what seems to be necessary is a means of establishing (or at least examining) the validity of the proposed resource indices prior to their use in analyses of the role of processing resources in age differences in cognition. Two avenues that appear promising for achieving the greater understanding of the nature of processing resources needed to address concerns about the validity of proposed resource indices are physiological research and analysis of formal systems. Physiological information could be very helpful in conceptualizing the nature of processing resources by indicating the processes or mechanisms that alter the efficiency of cortical activity. To elaborate, availability of specific neurotransmitters, rate of cerebral blood flow, and degree of glucose metabolism are all potential determinants of processing efficiency that may be related to the processing-resources construct. Establishing a correspondence between the resources construct and reductionistic measures of this type when no such linkage is possible for the cognitive performance measures may therefore be a means of validating the resource construct and distinguishing it from variables assumed to reflect cognitive performance.

An example of physiologically based speculation about processing resources is Beatty's (1982) proposal that the reticular activating system modulates cortical activity and that pupillary dilation can be used as an index of the functioning of the reticular system. In support of his argument, Beatty summarized evidence that task-evoked pupillary response is, as expected for an index of processing resources, sensitive to within-task, between-task, and between-individual variations in processing demands. The pupil dilation measure may not be very useful in studies of aging because of an age-related restriction in the range of pupil dilation for presumably peripheral reasons (cf. Fozard, Wolf, Bell, McFarland, & Podolsky, 1977), but it seems likely that theoretical and empirical efforts of this type will contribute to greater knowledge about the processing-resource construct.

Another approach to the understanding of processing resources is to examine the consequences of limitations in resource-like parameters in relatively simple abstract systems. The fundamental assumption is that once the effects of the various types of resource limitations are well understood in conceptually simple systems, it will be easier to predict how, and when, reduced quantities of processing resources affect various aspects of cognitive functioning. Moreover, the distinction between resource and performance variables will be validated to the extent that manipulation of the former leads to systematic variations in the latter.

Obviously many different types of formal systems could be employed for this purpose. The system I (Salthouse, 1985; 1988) have been exploring is a very simple connectionist associative network in which information processing is conceptualized as the propagation of activation among nodes in the network, and performance is interpreted in terms of properties of activation (e.g., strength, latency) at selected nodes in the network. One of the advantages of the connectionist system is that the three metaphorical conceptualizations of processing resources can each be examined by imposing different types of limitations on processing within the network. That is, space limits can be imposed by restricting the number of nodes that can be simultaneously active. Energy restrictions can be introduced by limiting the total amount of activation that exists within the network at any given time. And finally, restrictions on the resource of time can be implemented by varying the rate at which activation is propagated from one node to another.

Although the initial investigations of the consequences of manipulating these parameters in a computer simulation appear promising (Salthouse, 1985; 1988), it is clear that more concrete and explicit models tailored to specific tasks will be necessary for the potential contributions of the formal analysis of resource constructs to be fully realized. In a similar manner, physiologically based speculations about the nature of processing resources will have to be elaborated and linked to empirically verifiable mechanisms relating physiological processes to cognitive functioning in order for those ideas to have a substantial influence on theories employing the construct of processing resources.

Regardless of how the processing resources construct is elaborated, it is highly desirable that more sensitive and powerful indices of processing resources be identified for use in the statistical-control-of-resources procedure. An ultimate by-product of these elaboration efforts may even be a new technique for investigating the role of processing resources in cognitive aging in which single parameters in a well-specified model are altered to determine whether the resulting performance differences correspond to those observed across adults of varying ages. At the risk of introducing new jargon, this new strategy might be termed "Single Parameter Sufficiency Analysis" in that the goal is to determine whether the alteration of a single parameter in a quantitative formulation of performance on a given task is sufficient to account for the age-related performance differences observed in that task. To the extent that adjustment of the same parameter in either physiological or computational models of different tasks is successful in accounting for age differences in the performance of those tasks, that parameter may be considered to represent the construct of processing resources. Of course the feasibility of this single parameter sufficiency analysis test of the processing resources perspective is still very much an open question, but striving to achieve the knowledge that would allow such a test even to be conducted is a worthy goal independent of the eventual outcome of the test. In this respect, therefore, pursuit of the Single Parameter Sufficiency Analysis strategy appears to have considerable heuristic value for future investigations of the role of processing resources in age differences in cognition.

CONCLUSION

This article has obviously not provided an answer to the fundamental question of why age differences exist in cognitive functioning. Nevertheless, it has demonstrated that the processing-resources interpretation of this phenomenon, which may be the most parsimonious account currently available, can be subjected to empirical investigation. The results available thus far are at least partially consistent with the resources interpretation of cognitive aging phenomena, but past efforts have been limited by (a) lack of knowledge about the invariance of resource quantity across time for a given individual; (b) lack of knowledge about the relationship between resource quantity and cognitive performance; and (c) overly simplistic models, in combination with what may have been inadequate measurement of the resources construct. Most of these problems can be attributed to poor understanding of the exact nature and consequences of processing resources, which might be remedied by greater integration of physiological and psychological processes and by examination of resource-like constructs in abstract systems.

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