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The Processing-Speed Theory of Adult Age Differences in Cognition

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A theory is proposed to account for some of the age-related differences reported in measures of Type A or fluid cognition. The central hypothesis in the theory is that increased age in adulthood is associated with a decrease in the speed with which many processing operations can be executed and that this reduction in speed leads to impairments in cognitive functioning because of what are termed the limited time mechanism and the simultaneity mechanism. That is, cognitive performance is degraded when processing is slow because relevant operations cannot be successfully executed (limited time) and because the products of early processing may no longer be available when later processing is complete (simultaneity). Several types of evidence, such as the discovery of considerable shared age-related variance across various measures of speed and large attenuation of the age-related influences on cognitive measures after statistical control of measures of speed, are consistent with this theory.

The purpose of the current article is to describe, and discuss the evidence relevant to, the processing-speed theory of cognitive aging phenomena. The fundamental assumption in the theory is that a major factor contributing to age-related differences in memory and other aspects of cognitive functioning is a reduction with increased age in the speed with which many cognitive operations can be executed (Salthouse, 1985b). In this article, discussion of evidence relevant to the theory is restricted to the adult portion of the life span, but the basic mechanism may be relevant across the entire life span because similar ideas have been proposed by Kail (e.g., 1986, 1991; Kail & Park, 1992) regarding the development of cognitive functioning during childhood.

Because the success of a theory cannot be evaluated if the goal one hopes to achieve is never clearly specified, I begin by briefly describing the phenomenon that the present theory is intended to explain. Some of the best-documented findings in the literature on aging and cognition are the age-related differences in Type A (Hebb, 1942) or fluid (Cattell, 1943; Horn, 1982; Horn & Cattell, 1963) cognition, which include a wide variety of measures of memory, reasoning, and spatial abilities. The relations between age and cognition have been well documented since the earliest mental testing of adults (e.g., Foster & Taylor, 1920; Jones & Conrad, 1933), and they are readily apparent in the results from the standardization data in psychometric and neuropsychological test batteries (e.g., see Salthouse, 1991c, chap. 2, for a review). Because the samples for the standardization data in these test batteries are typically large and representative, and because the performance measures are of established reliability and span a broad range of cognitive abilities, the general phenomenon of negative relations between age and Type A or fluid cognition can be considered quite robust.

Performance on tests of cognitive ability is also a meaningful target or criterion phenomenon because cognitive batteries have proven useful for prediction and assessment outside of the laboratory and in nonacademic settings (e.g., Ghiselli, 1973; Hunter & Hunter, 1984). A focus on cognitive test performance therefore provides a relatively parsimonious linkage to real-world activities. The prediction is not perfect, but significant relations to real-world functioning have been empirically established; thus, if the age-related influences on these measures can be explained, at least some of the age-related effects in extralaboratory activities might also be explainable (Salthouse, 1992c).

Although the range of cognitive measures is extensive, it is important to emphasize that the present goal is not to explain all determinants of cognitive functioning but, rather, to account for the differences in cognitive functioning that are systematically related to adult age. The phenomenon to be explained is thus the age-related variation in behavior, and not the behavior itself (Salthouse, 1991c, 1992d). Ultimately, of course, more comprehensive theories should encompass all dimensions of cognitive phenomena, but an explanation of the relations between adult age and Type A or fluid aspects of cognition is by itself an extremely formidable goal at the present time.

The article is organized in two major sections. The first section summarizes the primary assumptions of the processing-speed theory. Evidence relevant to critical hypotheses of the theory is then described in the second section.

Theoretical Assumptions

One substantive assumption of the current perspective is that performance in many cognitive tasks is limited by relatively general processing constraints, in addition to restrictions of knowledge (declarative, procedural, and strategic), and varia-

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tions in the efficiency or effectiveness of specific processes. Some relevant limitations may be partially overcome by experience, and indeed one view of expertise is that it serves to circumvent processing constraints or limitations (Salthouse, 1991a). Nevertheless, it is assumed that general limitations frequently impose constraints on many types of processing and, hence, that they have consequences for the performance of a large variety of cognitive tasks.

It is sometimes asserted that general mechanisms are not plausible as explanations of adult age differences in cognitive functioning because of evidence presumed to implicate selective or differential age-related effects, such as Age × Treatment statistical interactions. However, the assumption of one or more fairly general age-related factors does not preclude the occurrence of significant interactions because interactions can originate as a result of (a) the existence of specific or local age-related influences in addition to the hypothesized broad or general influences (Salthouse, 1992d), (b) differential reliance of processes or measures on the general or common factor(s) (e.g., Salthouse & Coon, 1994), (c) a multiplicative or proportional influence of the general factor(s) such that the absolute differences between age groups increase with the magnitude of the treatment effect (e.g., Cerella, 1990; Cerella, Poon, & Williams, 1980; Salthouse, 1985a), or (d) a statistical artifact attributable to differential discriminating power (e.g., reliability, power, and region in the measurement range) of the variables (e.g., Salthouse, 1985b, 1991c). Particularly when one does not assert that general factors are the exclusive source of age-related differences in cognition, therefore, the existence of what appear to be selective or differential age-related effects in the form of statistical interactions is not at all inconsistent with the existence of common or general factors.

A second substantive assumption of the processing-speed theory is that speed of processing is a critical processing constraint associated with increased age. From the current perspective, the speed with which an individual performs a cognitive activity is not simply a function of the processes required in that activity but also a reflection of his or her ability to rapidly carry out many different types of processing operations. A slower speed of executing many cognitive operations is not assumed to be the exclusive source of age-related differences, because other age-related influences are also postulated to exist. Nevertheless, a reduction with increased age in the speed with which many cognitive operations can be executed is hypothesized to be a major contributor to the adult age differences in many measures of cognition (Salthouse, 1980, 1985b, 1991b, 1992b, 1994d).[1] Because this is a fundamental aspect of the theory, much of the remainder of the article is devoted to the elaboration and justification of this assumption.

Two distinct mechanisms are postulated to be responsible for the relation between speed and cognition. The limited time mechanism is assumed to operate because relevant cognitive operations are executed too slowly to be successfully completed in the available time, and the simultaneity mechanism is hypothesized to operate because slow processing reduces the amount of simultaneously available information needed for higher level processing. A metaphor for the limited time mechanism is an assembly line because if relevant processing operations are not successfully completed within a particular temporal window, then the quality of the final product is likely to be impaired because later processing operations would be either less effective or only partially completed. Some type of juggling activity might be a metaphor for the simultaneity mechanism because the fundamental principle is that many complex activities require synchronization of the constituent tasks, and synchronization is easier when the relevant processing operations can be executed rapidly.

Limited Time Mechanism

The basis for the limited time mechanism is simply that the time to perform later operations is greatly restricted when a large proportion of the available time is occupied by the execution of early operations. This mechanism is primarily relevant when there are external time limits or other restrictions on the time available for processing, such as the presence of concurrent demands on processing.

Some cognitive tasks (or tests) have a relatively low level of difficulty, such that the primary determinant of individual differences in performance is likely to be the speed of performing relevant operations. For these types of tasks no special explanation appears to be needed to account for the relation between speed and measures of very simple cognition because performance on the cognitive measure could merely be another manifestation of slow processing.

The limited time mechanism may also operate in more complicated cognitive tasks in which the quality or accuracy of performance is affected by the number of operations (e.g., associations, elaborations, and rehearsals) that can be carried out in the available time (Salthouse, 1980, 1982; Salthouse & Kail, 1983). If complex operations are dependent on the products of simpler operations, and fewer of those products are available because of a slower execution speed, the effects of slow processing can be expected to be most pronounced on the speed and accuracy of complex operations. A mechanism of this type may therefore account for what is sometimes referred to as the complexity effect, or the positive relation between task complexity and the magnitude of age differences in both speed and accuracy measures of task performance (Salthouse, 1982, 1985b, 1991c; Salthouse & Kail, 1983).

Because a gradual reduction in the speed of basic processes with increased age is likely to be accompanied by numerous adaptations, the consequences of slower processing are not always easy to predict (Salthouse, 1985b). This point can be illustrated by considering what may be an analogous situation in reverse, in the form of the evolutions of computer programs that have occurred as successive generations of computers have become progressively faster and more powerful. The enormous increases in performance have not simply been attributable to increases in the speed of executing the same programs, because major modifications in the nature of the programs have also

[1] Note that not all cognitive operations are assumed to be necessarily affected by slower processing and that a role for nonspeed influences is explicitly acknowledged. The theory described here is thus not accurately characterized by claims such as the following: "Slowing of information processing . . . is a single master factor underlying involutional changes in all cognitive skills" (Nettelbeck & Rabbitt, 1992, p. 191).

occurred to capitalize on the faster speed (and larger memories) of newer computers. Similar types of adaptations in the form of alterations in strategy, reliance on prestored solutions instead of novel problem solving, and so forth could also occur in the human processing system as it becomes progressively slower and less efficient with increased age. Despite the complications associated with identifying all of the consequences of a slower rate of processing, however, the basic principle underlying the limited time mechanism is quite simple; namely, more processing frequently results in higher levels of performance, and the opportunity to accomplish a larger amount of processing is greater when the speed of processing is faster.

Simultaneity Mechanism

The second hypothesized mechanism for the relation between processing speed and quality of cognitive performance is based on the idea that the products of early processing may be lost by the time that later processing is completed. To the extent that this is the case, relevant information may no longer be available when it is needed. Processing deficits could therefore emerge because of discrepancies between the time course of loss of information and the speed with which critical operations such as encoding, elaboration, search, rehearsal, retrieval, integration, or abstraction can be executed (Salthouse, 1982, 1985b, 1988a, 1992b).

A key assumption of the simultaneity mechanism is that information decreases in availability (i.e., quantity or quality) over time as a function of either decay or displacement. Moreover, under rapidly changing conditions, the information could also become obsolete in that it may no longer be accurate or pertinent by the time it becomes available. In either case, when the rate of executing operations is slow, relevant information is less likely to be useful because it is more impoverished or degraded by the time that preceding operations are finally completed. Moreover, this will occur regardless of the amount of time allowed for processing because the critical limitations are based on internal dynamics rather than on the relation between internal (i.e., processing speed) and external (e.g., stimulus presentation time) factors.

Performance on tasks assumed to assess working memory capacity might be postulated to reflect functioning of the simultaneity mechanism because working memory is sometimes conceptualized as consisting of information that is currently available for storage or processing, or both. However, it is important to distinguish the amount of simultaneously available information, which may be indexed by measures of working memory, from possible causes of age-related reductions in that amount. A critical hypothesis in the processing-speed theory is that an age-related decrease in speed is one of the major causes of the variations in working memory associated with increased age (e.g., Salthouse, 1992a; Salthouse & Babcock, 1991). As discussed later, there is considerable evidence in support of this hypothesis because statistical control of measures of processing speed has been found to greatly reduce the amount of age-related variance in measures of working memory (see also Salthouse, 1994b).

From the perspective of the processing-speed theory, it is the slower speed of activating or processing information rather than the rate of information loss or decay that is primarily responsible for age-related consequences of the simultaneity mechanism (Salthouse, 1992a, 1994b; Salthouse & Babcock, 1991). In fact, research with tasks such as continuous recognition or continuous paired-associates memory suggests that forgetting functions are very similar across the adult age range (see Salthouse, 1992a, for a review). However, it should be noted that simultaneous availability of information can also be reduced because of disruptions in the synchronization of neural signals or patterns of activation, and not only because of changes in the rates of decay or information loss. For example, alterations in the variability of timing at elementary levels might also lead to decreases in the quantity or quality of information based on multiple interacting inputs. The simultaneity mechanism should therefore not simply be viewed as attributable to forgetting because any factor that affects the synchronization of relevant inputs also has the potential to alter the amount (and quality) of simultaneously available information.

The importance of simultaneous availability of relevant information is not a novel idea, because it has been mentioned in one form or another for at least 60 years. For example, the concept is similar to speculations by Eysenck (1987), Jensen (e.g., 1982, 1987), and Vernon (1983, 1987). The idea of a trade-off between loss of information and speed of relevant processing is also fundamental to the notion of an articulatory loop in Baddeley's (e.g., 1986) model of working memory. Analogous arguments in discussions related to aging have been made by Birren (e.g., 1965, 1974) and Jones (1956). To illustrate, Jones (1956, p. 138) suggested that problem-solving effectiveness is impaired when lower level operations are too slow and earlier steps are lost before the relevant information can be integrated.

Perhaps the first discussion of the simultaneity mechanism was in the following passage by Lemmon (1927):

> It is possible that the *quality* of intelligence may depend upon the number of connections, but also upon the *speed* with which those connections are formed. Nerve centers (e.g., association centers) cannot remain excited indefinitely at maximum intensity; consequently in the case of the person who forms connections slowly it is possible that the excitation of the first association centers to be affected will have diminished and disappeared before the latter centers come into play. Thus only a limited number of centers are cooperating at any one time. The person who forms connections quickly, however, is apt to have more association centers interacting at once, since the later centers are aroused before the earlier ones had a chance to lose their effectiveness. But the most intelligent response is, in general, the one in which the determination of which the greatest number of factors have been taken into consideration. In neural terms this may well mean the response in the determination of which the greatest number of association centers have cooperated, and the number of simultaneously active centers may in turn depend to some extent upon the speed with which nervous impulses are conducted from center to center and through synapses within the centers. (p. 35)

Another early description of the simultaneity mechanism was provided by Travis and Hunter (1928):

> Intelligence is probably best defined as the ability to see relationships and meanings by having access to as many alternatives or judgments as possible at approximately the same instant of time. This would necessitate the reaction patterns which subserve the

> judgments to be active within an extremely short interval of time. The "feeble-minded" individual has relatively speaking, such a slow conduction rate that one reaction pattern becomes inactive by the time another becomes active, thus doing away with the very factor, relative simultaneity of activity, which makes possible the seeing of a relationship between ideational elements. (p. 352)

An important implication of the simultaneity mechanism is that the dynamic capacity of processing "structures" or "systems" such as working memory will be affected, with likely impairments of higher order processes such as abstraction, elaboration, or integration, because not all of the relevant information will be available in a usable form when it is needed (Salthouse, 1992b). Furthermore, degradation of these processes will lead either to increased errors or to time-consuming repetitions of critical processing operations (cf. Mayr & Kliegl, 1993). Speed effects on cognitive functioning thus may be indirect because they alter the effectiveness of a process (such as abstraction, elaboration, or integration) that directly affects cognitive performance. Because the simultaneity mechanism is so fundamental, it could have an impact on many aspects of cognition, including performance in tasks without external time constraints. From the current perspective, therefore, Peak and Boring (1926) were correct in suggesting that power tests are not necessarily those that do not involve speed but may simply be those that do not take speed into account.

Some evidence of the sufficiency of the simultaneity mechanism can be obtained from computational models incorporating variations in the speed of propagation of activation or in the speed of firing productions (e.g., Salthouse, 1985b, 1988a; see also MacKay & Burke, 1990, for additional discussion of a very similar mechanism). Prediction of the specific consequences of a processing-speed limitation requires a detailed understanding of, or a willingness to make many assumptions about, the processes involved in a particular task. It may also be difficult to distinguish the contribution of other aspects of the model from the speed parameter being manipulated for the particular consequences that are predicted. That is, the consequences could vary according to the type of processing algorithm or representation system used, even when the method of manipulating the critical variable, in this case processing speed, is identical (cf. Salthouse, 1988a).

Despite these limitations, the absolute differences in various indexes of performance between fast and slow processing systems are often larger when the amount of processing increases (Salthouse, 1988a). Furthermore, if there are external time limits on the usefulness (i.e., accuracy or relevance) of the information or decreases in its availability because of displacement or decay, then qualitative impairments in certain types of processing can also be expected. It is also noteworthy that an important characteristic of a reduction in processing speed exhibited by computational models is graceful degradation of performance (Salthouse, 1985b, 1988a). That is, reductions in the speed of processing seldom result in the total or catastrophic loss of a particular kind of processing but, instead, tend to lead to a broad or diffuse reduction in the efficiency of many types of processing. At least in a relatively general manner, therefore, analyses of speed manipulations in computational models are consistent with the assumptions of the processing-speed theory.

In summary, two mechanisms have been postulated to account for the speed–cognition relation. The principle underlying the limited time mechanism is that necessary operations may not be completed if the processing is slow. The simultaneity mechanism is based on the idea that if the processing is too slow, then not all relevant information will be available when needed, leading to impairments of critical operations that could result in either a high rate of errors or time-consuming repetitions of critical operations.

Evidence

Empirical evidence relevant to the processing speed theory is discussed in the context of three major hypotheses: (a) Age-related slowing is not exclusively determined by specific and independent deficits; (b) processing speed functions as a mediator of some of the relations between age and measures of cognitive functioning; and (c) the limited time and simultaneity mechanisms are primarily responsible for the relations between speed and cognitive functioning. However, before discussing these hypotheses, I briefly summarize the age-related slowing phenomenon, and describe the method by which processing speed has been assessed.

Slowing with age is often considered one of the best-documented and least controversial behavioral phenomena of aging. One illustration of the slowing phenomenon is the median correlation of .45 between age and measures of speed across a very wide range of behavioral activities reported by Salthouse (1985a). The age-related slowing phenomenon is also evident in analyses of the age trends from perceptual speed tests in psychometric test batteries such as the Digit Symbol Substitution Test from the Wechsler Adult Intelligence Scale–Revised (see Salthouse, 1992e) and the Visual Matching and Cross Out Tests from the Woodcock–Johnson Cognitive Ability Tests (see Kail & Salthouse, 1994). Performance in the Finding A's and Identical Pictures tests (Ekstrom, French, Harman, & Dermen, 1976) has also been found to be negatively related to age in both cross-sectional and longitudinal comparison, by Schaie (1989) and Schaie and Willis (1993). Not only have these researchers reported pronounced age trends in each type of comparison, but Schaie (1989) has suggested that, in contrast to the situation with many cognitive variables, the age-related declines are actually greater in longitudinal comparisons than in cross-sectional comparisons.

Figure 1 illustrates the age-related slowing phenomenon with data from a sample of 221 adults between 20 and 80 years of age (Salthouse, 1993b, Study 1) on two paper-and-pencil perceptual speed tasks (i.e., Letter Comparison and Pattern Comparison, described subsequently). The vertical axis in this figure is the average of the two perceptual speed measures expressed in standard deviation units, with higher scores representing faster performance. These results are typical of many in the literature in that a strong systematic relation is usually found in which increased age is associated with a largely monotonic, and approximately linear, decrease in speed of performance.

Because the processing speed construct is fundamental to the theory, it is important to consider how this construct has been assessed in recent studies. Several criteria have been proposed to guide the selection of measures used to assess processing speed (e.g., Salthouse, 1985b, 1991c, 1992b). For example, one

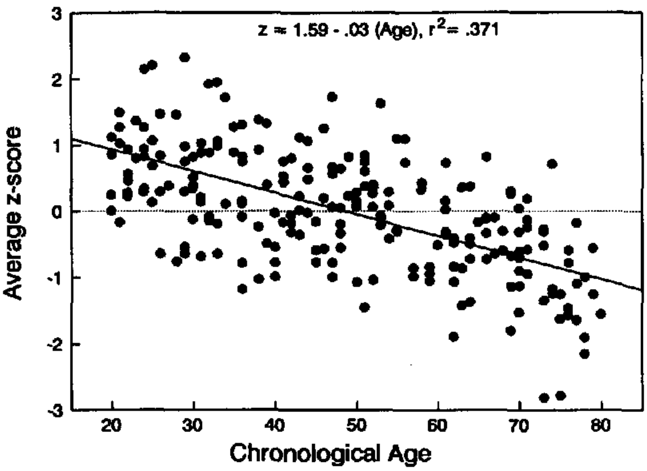

Figure 1. Relation between age and a composite measure of processing speed (data from Salthouse, 1993b, Study 1).

criterion is that the tasks used to assess processing speed should be relatively simple, such that most of the individual differences in performance are attributable to how quickly one can carry out the relevant operations rather than to variations in amount of knowledge or in other cognitive abilities. When more complex measures are used, such as lexical decision speed or reading speed (e.g., Hartley, 1986, 1993; Hultsch, Hertzog, & Dixon, 1990; Hultsch, Hertzog, Small, McDonald-Miszczak, & Dixon, 1992), it is difficult to determine how much of the variation in the measures is due to differences in the speed with which elementary cognitive operations can be executed as opposed to differences in the quality or quantity of semantic knowledge or differences in the level of more general verbal abilities. However, the speed measure should not merely represent input and output processes or sensory and motor processes, or else it may not reflect the duration of relevant cognitive operations. Finally, as with the assessment of any theoretical construct, it is generally desirable that the construct be evaluated with several measures to minimize the specific variance associated with single measures and to emphasize the common, construct-relevant variance. Reliance on multiple measures also has the advantage of increasing the reliability of the assessment because of aggregation (Rushton, Brainerd, & Pressley, 1983).

Much of the research described subsequently has used various combinations of seven measures to assess processing speed. One measure is the score on the Digit Symbol Substitution Test (Wechsler, 1981). This is a paper-and-pencil test consisting of a code table with pairs of digits and symbols and rows of double boxes with a digit in the top box and nothing in the bottom box. The task for the research participant is to refer to the code table to write the symbol in the bottom box that is associated with the digit in the top box. Performance on the test is represented by the number of correct symbols written in 90 s.

Two perceptual speed measures require comparisons of pairs of letters (Letter Comparison) or pairs of line patterns (Pattern Comparison). In each case, the paper-and-pencil test form consists of pairs of items with a horizontal line between the members of the pair. The task for the participant is to write an S (for same) or a D (for different) on the line between the two members of the pair and to complete as many of the items as possible within a specified time (usually 30 s).

Two additional paper-and-pencil tests were designed to involve minimal cognitive operations, but with stimulus and response requirements similar to the perceptual speed tests. One measure (Digit Copying) assesses how quickly individuals can copy digits, and another (Boxes) assesses how quickly they can draw lines in specified locations.

Finally, in several projects processing speed has been assessed with two computer-administered reaction time tasks. These tasks are based on the Digit Symbol Substitution Test in that they consist of a code table at the top of the screen and a probe stimulus in the middle of the screen. In the Digit Symbol version of the task, the code table contains pairs of digits and symbols, and the probe stimulus consists of a single digit–symbol pair. In the Digit Digit version of the task, the code table contains pairs of identical digits, and hence is superfluous, and the probe stimulus consists of a single pair of digits. In both tasks, the research participant is to press one key on the keyboard if the probe stimuli match, either with respect to associational equivalence (Digit Symbol) or in terms of physical identity (Digit Digit), and to press a different key if they do not match.

In addition to exhibiting moderate to large relations with age (see later discussion), all of these measures have been found to have respectable test–retest reliabilities. To illustrate, in a sample of 240 adults between 19 and 82 years of age (Salthouse, 1994a, Study 1), the immediate test–retest correlations were .86 for Boxes, .86 for Digit Copying, .58 for Letter Comparison, .73 for Pattern Comparison, .61 for Digit Digit reaction time, and .93 for Digit Symbol reaction time. Values from a sample of 131 adults between 17 and 79 years of age (Salthouse, Fristoe, Lineweaver, & Coon, 1995, Study 2) were .93 for Boxes, .93 for Digit Copying, .60 for Letter Comparison, .78 for Pattern Comparison, .69 for Digit Digit reaction time, and .89 for Digit Symbol reaction time.

Hypothesis 1: Age-related slowing is a broad phenomenon and is not simply attributable to specific and independent processing deficits.

A key hypothesis of the processing-speed theory is that age-related speed differences of the type just discussed originate at least partially because of a small number of fairly general or common factors rather than exclusively from a large number of specific and local factors. One reason for the assumption of a substantial shared or common influence is that many measures of processing speed have been found to be related to increased age, and not merely those restricted to a few tasks or to a few types of cognitive operations. More important, evidence discussed later indicates that the age-related influences on many speed measures are not independent but, instead, have considerable shared or common variance.

There are two primary implications of the hypothesis that common age-related influences contribute to measures of processing speed. The first is that it should be possible to predict the age differences in particular speed measures from knowledge of the age differences in other speed measures. The second implication is that the age-related effects in different speed measures are not expected to be independent, rather, they are assumed to have a considerable amount of shared age-related variance. Analytical procedures based on the examination of systematic relations and on statistical control techniques can be used to examine these implications.

Analyses of Systematic Relations

In recent years, there has been considerable interest, and controversy, regarding the existence and interpretation of systematic relations between mean levels of performance in different age groups (e.g., Cerella, 1985, 1990, 1991, 1994; Fisk & Fisher, 1994; Fisk, Fisher, & Rogers, 1992; Hale, Lima, & Myerson, 1991; Laver & Burke, 1993; Madden, Pierce, & Allen, 1992, 1993; Mayr & Kliegl, 1993; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; Myerson, Wagstaff, & Hale, 1994; Perfect, 1994). The method of examining age-comparative data in which the task or condition means of one group are plotted against those of another group was originally described by Brinley (1965), who used it to express relations with both accuracy measures and speed measures. Most subsequent researchers using this method have focused on speed measures, and heated debates have arisen concerning the meaning of these relations. One of the major issues of contention is whether the primary contribution of portraying condition means of two groups as a function of one another is to illuminate global age-related influences or to obscure specific age-related effects.

From the perspective of the processing-speed theory, systematic relations are interesting primarily because of their potential to generate estimates of the relative contributions of general and specific, or common and unique, age-related influences. That is, given certain assumptions, the relations between the mean levels of performance in two age groups may allow a distinction between common and unique age-related effects (Salthouse, 1992b, 1992d). The rationale has been described as follows:

> Only if at least some of the age-related effects on each variable were determined by a factor common to other relevant variables does it seem reasonable to expect age differences on one variable to be related to age differences on other variables. "General" or "common" in this context thus implies lack of independence, in the sense that knowing the magnitude of the age differences on one variable provides information about the magnitude of the age differences on other variables. (Salthouse, 1992d, p. 330)

One application of systematic relation analyses to distinguish common and unique age-related influences was described by Madden et al. (1992; see also 1993). These investigators used the performance of young adults and the systematic relations from a set of variables to predict the mean values of older adults in a given condition. The method is based on the assumption that the systematic relation reflects the influence of the common or general speed factor for that sample and those variables. If this assumption is valid, then adjusting each score of the members of one age group by the parameters of the function relating the mean scores in the two groups can be interpreted as removing the common or general influence. If the adjustment does in fact eliminate the effects of the common or general factor, then the magnitude of the remaining differences between the original scores in one group and the adjusted scores in the other group provides an estimate of the contribution of unique or specific age-related influences on the target variable (Salthouse, 1991c, 1992b, 1992d).

A similar method was applied in a recent study by Salthouse and Kersten (1993), and it resulted in the elimination of most of the age-related differences across a variety of speed measures. Furthermore, very similar results were obtained even when the adjustment was based on different types of speed tasks (i.e., those derived from paper-and-pencil procedures rather than from reaction time tasks). This outcome not only is consistent with the existence of the hypothesized common speed influence but suggests that, for some measures, nearly all of the age-related influences may be attributable to the common or general factor.

One possible objection to the adjustment of scores by the parameters of the systematic relation is that this method may not be very sensitive to specific age-related effects that are small relative to any general age-related influences that might exist (e.g., Fisk et al., 1992). Although this concern is valid, exceptions to the general pattern were detected in both the Madden et al. (1992) and the Salthouse and Kersten (1993) studies. For example, in the Salthouse and Kersten (1993) study, the time taken by older adults to perform the Digit Symbol reaction time task after an opportunity to learn the associations between digit–symbol pairs was greater than that expected from the systematic relation. According to the reasoning underlying the analytical method, therefore, it can be inferred that specific or unique age-related influences contributed to the age differences on this measure, in addition to the general or common influences that were postulated to be responsible for the systematic relation.

It is important to note that the relations between the mean performance of young and old adults need not be described by a single function to produce moderate to high levels of predictability. That is, although some researchers have relied on the number of distinct quantitative functions relating the performance of young and old adults as the basis for distinguishing between general and specific age-related effects or between single and multiple speed factors (e.g., Kliegl, Mayr, & Krampe, 1994; Lima, Hale, & Myerson, 1991; Mayr & Kliegl, 1993; Myerson et al., 1990), distinctions among alternative functions are only of secondary interest from the current perspective. The question of primary importance in the processing-speed theory is the extent to which the age-related effects in some variables are independent of, or not predictable from, the age-related effects in other variables. If there is considerable independence and lack of predictability, then specific influences would be inferred to predominate over general or common influences. In contrast, if the variables were found to share a large proportion of their age-related variance, and if the age differences in some variables were highly predictable from the age differences in other variables, then general or common influences would be inferred to be of greater relative importance.

This argument can be illustrated with data from two conditions in a speeded verification arithmetic task (Salthouse & Coon, 1994, Study 2). Between zero and seven arithmetic operations were presented in this study in either a sequential condition (e.g., $3 + 2 - 4 = 2$; false) or a hierarchical condition in which temporary preservation of intermediate products was required (e.g., $[(5 - 3) + 4] - 1 = 4$; false).

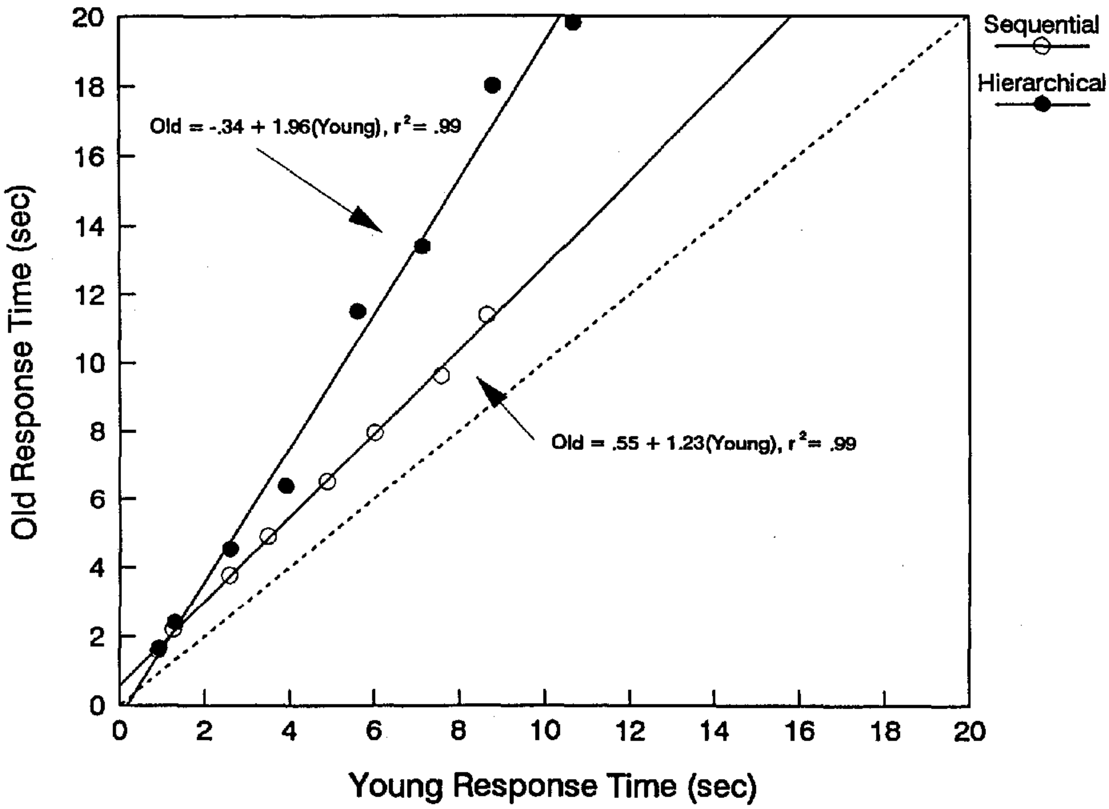

Figure 2. Mean time of older adults as a function of mean time of young adults in sequential and hierarchical arithmetic tasks (data from Salthouse & Coon, 1994, Study 2).

The systematic relation functions for the sequential and hierarchical arithmetic data in this study are portrayed in Figure 2. Separate regression lines are illustrated for the conditions in each task because the interaction of condition (sequential or hierarchical) with time of the young adults was statistically significant (cf. Salthouse, 1985a, 1991c, 1992d, 1992f).

Because all participants in this study also performed two paper-and-pencil perceptual speed tasks (Letter Comparison and Pattern Comparison) and two reaction time tasks (Digit Digit and Digit Symbol), ratios of perceptual speed and reaction time speed measures were computed to serve as additional estimates of the hypothesized general speed factor for these participants. Table 1 summarizes the actual (original) group differences for all speed measures and the differences between actual values and predicted values for older adults after adjustments for the general influence according to each of the equations shown in the notes to the table. The values in the table are *d* units, which correspond to the mean difference between the groups divided by the pooled standard deviation (Cohen, 1988).

Inspection of Table 1 reveals that almost all of the differences involving an adjustment are smaller than the initial differences (i.e., the mean effect size for the original scores was 1.75 units, and the grand means for all other conditions, displayed in the table notes, were between −0.51 and 0.40). The degree of prediction is certainly not perfect, and examination of the measures with consistently large residual differences may be informative about the nature of the specific age-related influences operating in these variables. However, the important point for the current argument is that the magnitude of the age differences in nearly every variable was greatly reduced after adjusting for the estimated contribution of a common speed factor. On average, therefore, there appears to be moderate predictability of the age differences in certain speed measures from knowledge of the pattern of age differences in other speed measures.

Because there were different systematic functions in Figure 2, it is informative to examine the degree to which the age-related variance in the measures from these conditions was independent. That is, even though there are distinct quantitative relations for the sequential and hierarchical measures, it is possible to examine the amount of age-related variance the measures from the two functions have in common. Estimates of the shared age-related variance can be derived by determining the proportion of age-related variance in the measures from the condition with the larger age differences (i.e., hierarchical) that is shared with the measures from the condition with the smaller age differences (i.e., sequential). Moreover, these computations can be carried out both for the mean values across each condition and for pairs of measures with the same number of arithmetic operations. Results of the computations are summarized in Table 2.

Two points should be noted about the entries in this table. First, estimates of the shared age-related variance are moderately high, with an estimate of .871 based on the computations of the mean values and a mean across estimates from different

Table 1
Effect Sizes Before and After Adjustment for the Influence of a General Speed Factor

Condition	0	1	2	3	4	5	6	7	*M*
	Number of arithmetic operations								
Sequential									
Original[a]	2.15*	2.05*	1.59*	1.56*	1.43*	1.28*	1.09*	1.29*	1.56
Equation 1[b]	0.36	0.28	−0.47	−0.66*	−0.95*	−0.92*	−1.06*	−0.88*	−0.54
Equation 2[c]	0.64*	0.57*	−0.18	−0.36	−0.63*	−0.62*	−0.78*	−0.60*	−0.25
Equation 3[d]	−0.25	0.17	0.04	0.04	−0.05	−0.01	−0.13	0.08	−0.01
Equation 4[e]	0.41	0.08	−1.01*	−1.27*	−1.65*	−1.62*	−1.71*	−1.53*	−1.04
Equation 5[f]	1.16*	0.75*	−0.36	−0.64*	−1.01*	−1.03*	−1.18*	−1.02*	−0.42
Hierarchical									
Original[a]	2.24*	2.30*	2.08*	1.76*	1.92*	1.76*	1.82*	1.67*	1.94
Equation 1[b]	0.39	0.54*	0.30	0.04	0.74*	0.49	0.69*	0.43	0.45
Equation 2[c]	0.69*	0.81*	0.56	0.29	0.93*	0.69*	0.86*	0.62*	0.68
Equation 3[d]	−0.19	0.48	0.79*	0.68*	1.29*	1.11*	1.27*	1.08*	0.81
Equation 4[e]	0.40	0.29	−0.19	−0.53	0.24	−0.07	0.18	−0.13	0.02
Equation 5[f]	1.17*	0.97*	0.37	0.01	0.67*	0.38	0.57	0.29	0.55

[a] $M\ d = 1.75$. [b] Ratio of perceptual speed: Old = Young × (1/.62) ($M\ d = 0.05$). [c] Ratio of reaction time speed: Old = Young × 1.51 ($M\ d = 0.22$). [d] Regression equation for sequential condition: Old = (Young × 1.23) + .55 ($M\ d = 0.40$). [e] Regression equation for hierarchical condition: Old = (Young × 1.96) − .34 ($M\ d = -0.51$). [f] Regression equation for both conditions: Old = (Young × 1.72) − .37 ($M\ d = 0.07$).
* $p < .01$.

numbers of operations of .817. Despite the quantitative difference in the functions, therefore, the values representing the two functions shared an average of more than 80% of their age-related variance.[2] Second, the proportions of shared age-related variance tend to decrease as the number of arithmetic operations increases. This decrease may reflect an increased involvement of novel or distinct age-related processes (perhaps related to working memory and the temporary preservation of information while processing other information) when the problems contain four or more operations. Even when it appears that other age-related influences are operating, however, it is important to note that more than 50% of the age-related variance is shared with speed measures that are presumably unaffected by those influences.[3]

The data reported in Figure 2 and in Tables 1 and 2 suggest that the quantitative parameters of the systematic functions are not necessarily informative about the existence, or relative contribution, of a common age-related speed factor. Although those parameters have descriptive value and may be useful for estimating the contribution of the hypothesized general factor(s) on a particular variable, they do not directly indicate the extent to which the age-related influences in different variables are distinct and independent of one another.

In summary, the considerable literature documenting the existence of systematic relations between mean times of young and old adults is viewed as consistent with the hypothesis of a general age-related slowing factor. The current perspective differs from that espoused by other theorists, however, in that analyses of systematic relations are not necessarily assumed to be informative about the number of independent age-related influences; instead, they are postulated to be primarily useful as

Table 2
Estimates of Proportions of Age-Related Variance in the Hierarchical Arithmetic Task

Number of operations	Age-related variance: Alone	Age-related variance: After sequential	Proportion of variance shared
0	.594	.008	.987
1	.613	.013	.979
2	.547	.069	.874
3	.478	.042	.912
4	.503	.131	.740
5	.459	.084	.817
6	.470	.202	.570
7	.417	.142	.659
M	.518	.067	.871

[2] Mayr and Kliegl (1993) reported that slightly more than 6% of the variance in measures from tasks involving coordinative complexity was independent of that in measures from tasks involving sequential complexity. However, because they did not report the total age-related variance in the coordinative complexity measures, estimates of the proportions of shared age-related variance could not be derived from the information in their article. Figure 8 in that article also illustrates results of an adjustment analogous to those reported in Table 2 of this article in which a similar pattern was apparent (i.e., under-prediction of the effects in the complex condition from an adjustment based on results in the simple condition).

[3] A very similar pattern of results was obtained in a contrast of sequential arithmetic performed alone and performed while also remembering four letters (Salthouse et al., 1995). That is, the regression equations for the two sets of variables differed significantly in slope (i.e., Old = 0.47 + 1.11 [Young], $r^2 = .99$, for arithmetic alone, and Old = 0.33 + 1.38 [Young], $r^2 = .99$, for arithmetic with concurrent letter memory), the magnitude of the age difference in d units was greatly reduced after adjustment for the influence of the common factor, and a large proportion of the age-related variance in the concurrent arithmetic measures was shared with the single-task arithmetic measures.

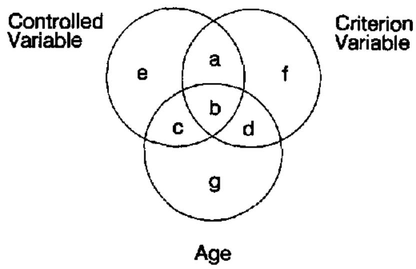

Figure 3. Illustration of regions of variance for age and two variables. The circles represent the total variance in the variables, and the regions of overlap correspond to proportions of shared variance.

a means of identifying variables with potentially specific age-related influences.

Statistical Control Procedures

Because many speed measures have been found to have negative relations with age, a fundamental question within the processing-speed theory concerns the number of separate and distinct age-related influences on speed. That is, are there many independent and unique age-related influences, or are there, instead or in addition, a relatively small number of factors with fairly broad consequences? As noted earlier, a central hypothesis of the processing-speed theory is that some version of the latter interpretation is the most plausible and, hence, that there should be substantial commonality, or overlap, of the age-related influences on many different speed measures. In other words, rather than being completely independent, it is hypothesized that much of the age-related variance in any given speed measure is shared with the age-related variance in other speed measures.

One way of investigating the degree of commonality among speed measures is through use of statistical control methods. The logic of statistical control procedures in the present context can be described by reference to Figure 3 (see also Salthouse, 1992b, 1992d, 1994c, for further discussion of the rationale). This figure represents the total variance, and the regions of shared or overlapping variance, in three variables. Note that the proportion of variance in the criterion variable that is shared with the age variable corresponds to the ratio $(b + d)/(a + f + b + d)$. In a similar manner, the proportion of variance in the criterion variable that is shared with the controlled variable corresponds to the ratio $(a + b)/(a + f + b + d)$. However, it is also apparent in Figure 3 that the proportion of *age-related* variance in the criterion variable that is shared with the controlled variable corresponds to the ratio $b/(b + d)$. It is this latter quantity that is of greatest interest in the current context because the prediction from the processing-speed theory is that the age-related influences on many speed variables are not independent and, hence, that the variables will share a large proportion of their age-related variance. In other words, the ratio $b/(b + d)$ is predicted to be relatively large when the two variables both reflect speed of processing. In contrast, if separate and distinct age-related influences are responsible for the age differences in every speed measure, then most of the age-related variance in the variables will be independent, and the ratio $b/(b + d)$ will be small.

Both correlation and hierarchical regression procedures can be used to derive estimates of the proportions of variance illustrated in Figure 3. That is, the square of the correlation between age and the criterion variable corresponds to the proportion of the criterion variance shared with age (i.e., $[b + d]/[a + f + b + d]$). Hierarchical regression techniques, in which the variance in the controlled variable is removed before the relation of age to the criterion variable is examined, can be used to derive the square of the semipartial correlation (i.e., $d/[a + f + b + d]$). Finally, subtracting the second quantity from the first, and then dividing by the first, yields an estimate of the proportion of age-related variance in the criterion variable that is shared with the controlled variable (i.e., $b/[b + d]$).

These analyses can be illustrated with an example reported in Salthouse (1994c). The primary data in that report were from a large ($N = 910$) sample of adults across a wide age range. The two speed measures were the Digit Symbol Substitution Test and a composite perceptual speed measure formed by averaging *z* scores from the Letter Comparison and Pattern Comparison tasks. The correlation between the Digit Symbol Substitution Test and composite perceptual speed variables was .73, indicating that 54% (i.e., $.73^2$) of the total variance in each variable was shared. The R^2 value associated with age in the Digit Symbol Substitution Test was .289, but the increment in R^2 associated with age after control of the perceptual speed measure was only .008. It can therefore be inferred that 97.2%—$[.289 - .008)/.289] \times 100$—of the age-related variance in the Digit Symbol Substitution Test was shared with the composite perceptual speed measure.

Because the proportions of total age-related variance in the variables need not be identical (i.e., $b + d$ is not necessarily equal to $b + c$), estimates of the proportion of shared age-related variance in two variables are not necessarily symmetric. In fact, when the analyses in the data set just described were reversed, the age-associated R^2 value in the perceptual speed measure was .412, but the increment in R^2 associated with age after control of the Digit Symbol Substitution Test was .086. This leads to an estimate that 79.1%—$[.412 - .086)/.412] \times 100$—of the age-related variance in the composite perceptual speed measure was shared with the age-related variance in the Digit Symbol Substitution Test.

A very similar pattern of shared age-related variance was found in the data from an independent sample of 305 adults reported in the Salthouse (1994c) article. That is, in this sample 92.3% of the age-related variance in the Digit Symbol Substitution Test was shared with the perceptual speed measure, and 77.3% of the age-related variance in the perceptual speed measure was shared with the Digit Symbol Substitution Test. In contrast, because the correlation between the two measures was .68, only 46% of the total variance in each measure was shared with the other measure. The results from these two data sets therefore indicate that a very large percentage of the age-related variance in at least these particular speed measures was shared, and hence relatively little was independent or unique to each measure.

Procedures similar to those just described have also been conducted on a variety of different speed measures from two sepa-

Table 3
Proportions of Shared Age-Related Variance in Speed Measures: Salthouse (1993d; N = 305)

Controlled variable	Criterion variable 1	2	3	4	5	6	7	8	9	10	11	Age *r*
1. Horizontal Marking	—	.975	.873	.763	.468	.467	.942	.745	.449	.462	.590	−.38
2. Vertical Marking	.993	—	.879	.780	.535	.511	.981	.855	.492	.512	.617	−.40
3. Digit Copying	.926	.894	—	.919	.588	.583	.999	.909	.625	.587	.705	−.41
4. Letter Copying	.980	.969	.994	—	.738	.793	.942	.999	.781	.728	.870	−.49
5. Digit Comparison	.838	.875	.915	.877	—	.989	.731	.909	.898	.858	.943	−.55
6. Letter Comparison	.791	.806	.867	.881	.963	—	.865	.964	.852	.789	.908	−.53
7. Digit Transformation	.439	.456	.503	.428	.399	.395	—	.855	.422	.332	.433	−.23
8. Letter Transformation	.318	.369	.388	.398	.369	.380	.885	—	.363	.301	.379	−.24
9. Letter Comparison	.723	.731	.861	.826	.807	.808	.904	.982	—	.827	.820	−.51
10. Pattern Comparison	.912	.925	.976	.941	.930	.913	.808	.964	.973	—	.885	−.59
11. Digit Symbol	.892	.881	.939	.919	.870	.877	.846	.982	.828	.720	—	−.51

rate data sets; results are summarized in Tables 3 and 4. Table 3 contains results from 11 speed measures obtained from the 305 adults reported in the Salthouse (1993d) article. All measures from that study were derived from paper-and-pencil tests. Table 4 contains results from 4 paper-and-pencil tests and 2 reaction time tests from a total of 744 adults who had participated in one of three recent studies (i.e., Salthouse, 1994d, Studies 1 and 2; Salthouse, 1994a, Study 1).

In all cases, the entries in Tables 3 and 4 correspond to proportions of shared age-related variance computed by subtracting the increment in R^2 associated with age after eliminating the variance in the controlled variable from the total R^2 associated with age and then dividing this difference by the total R^2 associated with age. As in the examples described earlier, these values indicate how much of the age-related variance in one variable (represented in the columns) is shared, or in common with, the age-related variance in another variable (represented in the rows).

The median for the values in Table 3 was .842, and that for the values in Table 4 was .628. Only the values obtained after the control for Digit Transformation and Letter Transformation measures were consistently lower than .5, and this may reflect the fact that these two variables had relatively low correlations with age (i.e., −.23 and −.24, respectively, as compared with a range of −.38 to −.59 for all other variables). The amount of age-related variance that can be shared between two variables is obviously limited by the total age-related variance in each variable.

Because all of the measures in Tables 3 and 4 are single variables, the age-related variance is not easily partitioned into that attributable to the hypothesized construct, in this case a common speed factor, and that specific to the particular methods, materials, and measures. Nevertheless, the results summarized in the two tables reveal that there is substantial overlap of the age-related variance in the individual measures of processing speed, with an average of nearly 75% of the age-related variance in these variables shared with other variables. Very similar results have also been reported in two recent studies. Salthouse and Meinz (1995) found that an average of 86.3% of the age-related variance was shared across 2 reaction time, 2 paper-and-pencil, and 10 vocal speed measures. And Salthouse (1996) found that an average of approximately 62% of the age-related variance in 19 different speed measures involving vocal, written, and reaction time responses was shared.

A second method that can be used to investigate the degree of commonality of age-related variance in measures of speed is based on a structural equation model with a single latent speed construct related to all speed measures and with relations from age to the latent speed construct and to each individual speed measure. Within a model of this type, estimates of the common age-related influence on each speed measure can be obtained from the product of the path coefficients from age to the com-

Table 4
Proportions of Shared Age-Related Variance in Speed Measures: Earles and Salthouse (1995; N = 744)

Controlled variable	Criterion variable 1	2	3	4	5	6	Age *r*
1. Boxes	—	.808	.573	.521	.456	.430	−.42
2. Digit Copying	.904	—	.766	.590	.574	.554	−.46
3. Letter Comparison	.551	.648	—	.568	.544	.573	−.41
4. Pattern Comparison	.831	.812	.901	—	.769	.747	−.56
5. Digit Digit reaction time	.500	.531	.608	.511	—	.756	.44
6. Digit Symbol reaction time	.719	.770	.906	.749	.985	—	.56

mon speed factor and from the common factor to the individual speed measures. The direct path coefficients from age to the individual speed measures serve as estimates of the specific or unique age-related influences on the measures.

Salthouse (1996) recently applied this method to four independent data sets and, in all cases, found very similar results. For every variable, the estimate of the common or shared age-related influence was much larger than the estimate of the unique or specific age-related influence. Moreover, the unique age-related influence was significantly greater than zero for only 18 of the 53 variables across the four data sets.

It is important to point out that a general or common age-related influence is also likely to be operating with measures often postulated to reflect the duration of discrete and specific cognitive processes. In fact, results from several analyses suggest that 50% or more of the age-related variance in measures of purportedly specific information-processing components is attributable to a common or general speed factor. Analyses leading to this conclusion can be illustrated with data from an article by Salthouse and Prill (1987) involving a series completion task. In the condition of greatest interest in the present context, each element in the problem was presented successively, and the time taken by the participant in examining each element was monitored by a computer. Two different types of problems were distinguished on the basis of the abstractness of the relations among elements. Problems with first-order relations among elements consisted of a simple continuation sequence (e.g., 2-4-6-8-10-??). In contrast, problems with second-order relations had the invariance or constancy at the second level of abstraction, in the difference among differences (e.g., 2-3-5-8-12-??). A measure of abstraction time can be derived from the difference in inspection or processing time in the two types of problems, particularly at the third element in the sequence, where the problems are first distinguishable. Mean inspection times for correct trials for young and old adults in the two types of problems are illustrated in Figure 4.

It is apparent in Figure 4 that older adults were slower than young adults across every item in the sequence for both types of problems. Of particular interest are the much longer times in the third, fourth, and fifth elements in the second-order problems because these durations presumably reflect the time needed to infer or abstract relations among items. Because these durations are longer for older adults than for young adults, some of the lower accuracy of older adults on the second-order problems (i.e., 35.8% correct, as compared with 68.6% correct for young adults) may be attributable to a greater probability of forgetting early items in the sequence during the longer period needed to identify the relations among elements.

The first two rows in Table 5 contain the values leading to estimates of the proportion of age-related variance in the task-specific speed measures that was shared with a speed measure from a separate task (i.e., Digit Symbol Substitution Test score). Note that statistical control analyses of the type described earlier yield estimates that 49.1% of the age-related variance in the abstraction measure, and 62.5% of the age-related variance in the mean inspection time measure, was shared with the Digit Symbol speed measure.

The remaining entries in Table 5 are based on studies with a mixture of task-specific speed measures. Two distinct patterns are evident in these data. One is similar to that described earlier in that the age-related variance in the task-specific measure was greatly reduced after control of the variance in another speed

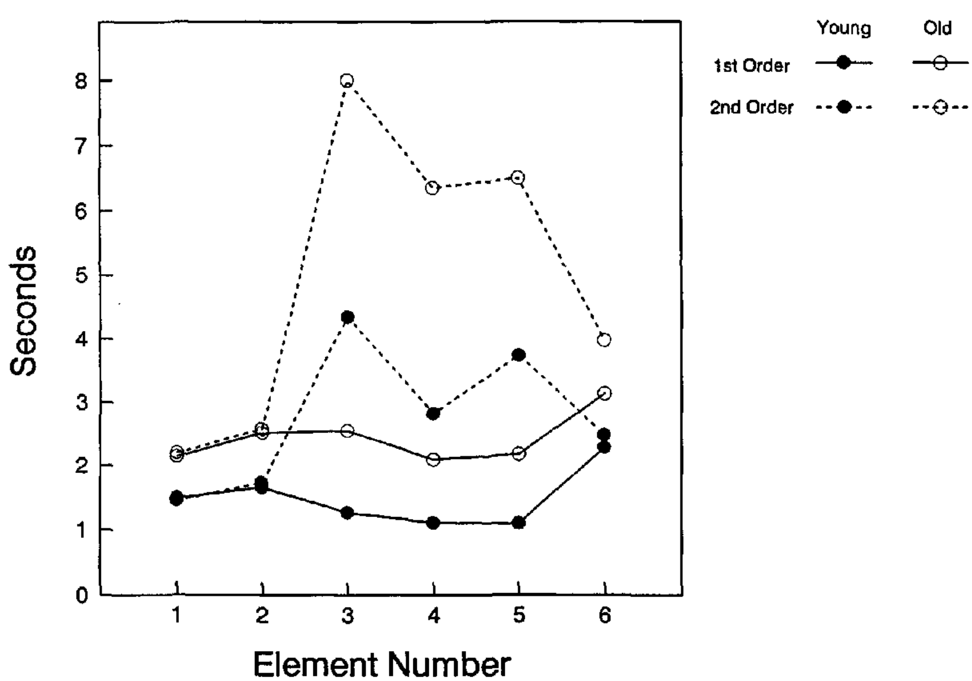

Figure 4. Time to inspect successive series completion elements for young and old adults in first-order and second-order abstraction problems (data from Salthouse & Prill, 1987, Study 2).

Table 5
Estimates of Shared Age-Related Variance in Different Speed Measures

Study and criterion variable	Age-related variance: Alone	After control of			Proportion of variance shared with		
Salthouse & Prill (1987), series completion (N = 48)			Digit Symbol			Digit Symbol	
Mean inspection time	.518		.194			.625	
Difference: 2nd order minus 1st order	.228		.116			.491	
Salthouse (1987), geometric analogies (N = 48)			Digit Symbol			Digit Symbol	
Mean inspection–decision time	.505		.054			.893	
Slope of time–element: complete problem	.280		.006			.979	
Slope of time–element: first 2 terms	.368		.053			.856	
Salthouse & Coon (1993), reordered letter memory span, Study 1 (N = 55)			RTS			RTS	
Mean recall time	.376		.034			.910	
Reorder time	.187		.001			.999	
Salthouse & Coon (1993), reordered letter memory span, Study 2 (N = 71)			RTS			RTS	
Mean recall time	.236		.013			.945	
Reorder time	.063		.001			.984	
Encoding time	.274		.101			.631	
Salthouse & Kersten (1993), symbolic arithmetic (N = 104)		PS	RTS	DART	PS	RTS	DART
Symbol arithmetic RT	.518	.068	.015	.047	.869	.971	.911
Digit arithmetic RT	.450	.050	.001	—[a]	.889	.998	—[a]
Salthouse & Coon (1994), Study 1, subtraction RT (N = 240)		PS	RTS	NBRT	PS	RTS	NBRT
Borrow RT	.051	.001	.004	.001	.980	.922	.980
No borrow RT	.087	.001	.002	—[a]	.989	.977	—[a]
Salthouse & Coon (1994), Study 2, arithmetic with 1 to 7 operations (N = 80)		PS	IRT	Intercept	PS	IRT	Intercept
Sequential arithmetic intercept	.193	.034	.001	—[a]	.824	.995	—[a]
Slope	.169	.036	.032	.334	.787	.811	—[b]
Hierarchical arithmetic intercept	.083	.099	.013	—[a]	—[b]	.843	—[a]
Slope	.401	.188	.026	.169	.531	.935	.579
Salthouse et al. (1995), arithmetic with 1 to 4 operations (N = 131)		PS	IRT	Intercept	PS	RT	Intercept
Single-task arithmetic intercept	.167	.074	.091	—[a]	.557	.455	—[a]
Slope	.018	.016	.003	.096	.111	.833	—[b]
Dual-task arithmetic intercept	.039	.024	.000	—[a]	.385	.999	—[a]
Slope	.069	.001	.001	.162	.986	.986	—[b]
Salthouse (1994d), digit symbol with 3, 6, and 9 digit–symbol pairs, Study 1 (N = 246)		PS	DDRT	Intercept	PS	DDRT	Intercept
Intercept	.284	.058	.024	—[a]	.796	.915	—[a]
Slope	.115	.008	.046	.124	.930	.600	—[b]
Salthouse (1994d), digit memory search with 1 to 4 items, Study 2 (N = 258)		PS	RTS	Intercept	PS	RTS	Intercept
Intercept	.164	.038	.004	—[a]	.768	.976	—[a]
Slope	.002	.000	.000	.022	1.000	1.000	—
Salthouse (1994d), letter memory search with 1 to 4 items, Study 2 (N = 258)		PS	RTS	Intercept	PS	RTS	Intercept
Intercept	.145	.026	.002	—[a]	.821	.986	—[a]
Slope	.001	.003	.000	.003	—[b]	1.000	—[b]

Table 5 (*continued*)

Study and criterion variable	Age-related variance: Alone	After control of		Proportion of variance shared with	
Salthouse & Meinz (1995), Stroop interference (incongruent − neutral; $N = 242$)		PS	RTS	PS	RTS
Color	.217	.033	.028	.848	.871
Number	.031	.002	.002	.935	.935
Position	.073	.001	.001	.986	.986
Salthouse (1996), Stroop interference (incongruent − neutral; $N = 172$)		PS	RTS	PS	RTS
Color	.361	.067	—[a]	.814	—[a]

Note. RTS = reaction time speed; PS = perceptual speed; DART = digit arithmetic reaction time; RT = reaction time; NBRT = no borrow reaction time; IRT = identification reaction time; DDRT = Digit Digit reaction time.
[a] Variable not available or not relevant in the analysis. [b] Estimates of shared variance not meaningful as a result of an apparent suppression relationship because the age-related variance increased rather than decreased after control of the other variable.

measure (i.e., symbol arithmetic reaction time, digit arithmetic reaction time, borrow reaction time, no borrow reaction time, sequential arithmetic intercept, Digit Symbol intercept, memory search intercept, and Stroop color interference). The second pattern is that the age-related variance in the criterion variable increased rather than decreased after control of the variance in the other speed variable (i.e., sequential arithmetic slope, hierarchical arithmetic intercept, single-task and dual-task arithmetic slope, Digit Symbol slope, and memory search slope). Instances with the second pattern indicate that statistical control need not always reduce the amount of age-related variance because it can also "release" the age-related variance that had been suppressed because of a negative relation between the two speed measures. For example, the intercept could operate as a third variable that obscures the relations between age and the slope unless its effects are taken into consideration. Even though the age-related variance in these cases increased rather than decreased after statistical control of the other measure, it is important to note that the results are still consistent with the interpretation that the age-related influences on the speed measures were not independent. Statistical control can alter the age relations, in either a negative or a positive direction, only if at least some of the age-related variance in the measures is shared, and not all is unique or specific.

A very similar pattern in which a large proportion of age-related variance in presumably specific speed measures was shared with more general processing-speed measures was also reported by Salthouse (1996). In that study, factor analysis procedures were used to derive an estimate of the general speed factor, and the specific measures represented the time to search a code table and substitute items, to search and retrieve an item from memory, to reorder items in memory, to articulate or rehearse items, and so forth. Statistical control of the general speed factor substantially reduced the age-related variance for all of the measures with significant age relations, implying that many of the age-related influences in the specific measures were shared with the general speed factor.

The results just discussed, and summarized in Tables 3–5, lead to the conclusion that a moderate to large proportion of the age-related variance in many speed variables is shared, or in common, rather than being completely independent and distinct. Moreover, the age-related influences are apparently not restricted to those reflecting overall performance in simple tasks because similar patterns are evident with measures presumed to reflect the duration of specific cognitive operations in moderately complex tasks. These results are thus consistent with the hypothesis of the processing-speed theory that a small number of common factors contribute to the age-related differences in many speed measures.

In summary, two important implications of the hypothesis that age-related slowing is a general phenomenon appear to have convincing support. The implication that the direction and magnitude of the age differences in certain speed measures are predictable from knowledge of the age differences in other speed measures is supported by the results described earlier involving systematic relations. And the implication that the age-related influences on different speed measures are not independent is supported by the finding that many speed measures share a considerable proportion of their age-related variance. This evidence is clearly consistent with the proposal that a small number of common factors contribute to the age-related influences in many measures of speed.

Because there has been frequent confusion on the issue of general slowing, it is important to be explicit about what is not implied from the current perspective. Although age-related slowing is assumed to be ubiquitous, it is not necessarily assumed to be universal, uniform, or unitary. Each of these latter characteristics is considered in turn.

First, the hypothesized common or general speed factors are not necessarily universal. That is, some measures may not exhibit age-related slowing because it is not assumed that every measure scaled in units of time is affected by common or general influence(s) (Kail & Salthouse, 1994; Salthouse, 1985b, 1992b, 1996; Salthouse & Somberg, 1982). Because not all speed measures are postulated to be influenced by the hypothesized common speed factor(s), a discovery that some speed measures have little or no age differences would not be inconsistent with the hypothesis that common factors affect many other speed measures. Ultimately, of course, explanations are needed to account for why some speed measures are related

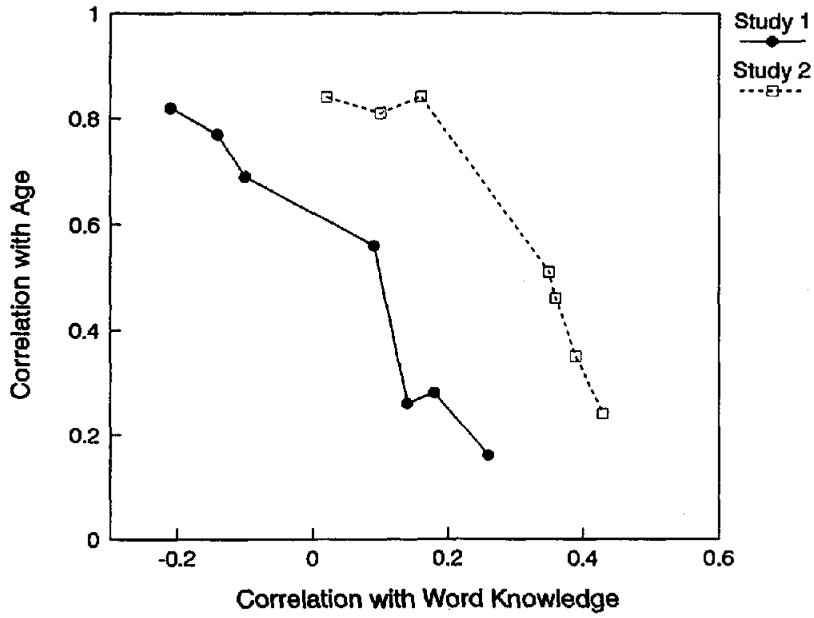

Figure 5. Functions illustrating the relation between the magnitude of the correlation with age and the correlation with a measure of word knowledge for seven speed measures in studies conducted by Salthouse (1993c).

to age, whereas others are not. For the purpose of the current argument, however, the important point is that universality is not a necessary concomitant of the existence of factors with relatively broad influences.

A second assumption of the processing-speed theory is that age differences on different speed measures should not necessarily be expected to be uniform. Instead, the age-related effects can be expected to vary in magnitude because of the operation of other influences, even if a common underlying mechanism is involved (cf. Salthouse, 1992b, 1992d; Salthouse & Coon, 1994). Considerable evidence indicates that a variety of factors contribute both to the absolute level of speeded performance and to the relations between age and measures of speeded performance. As an example, research on typing has revealed that the relations between age and measures of speed (i.e., interkey interval) systematically vary as a function of the amount of preview of to-be-typed text available during typing (cf. Salthouse, 1984, Figure 4). In the Salthouse (1984) project, the correlation between age and median interkey interval was about .5 with a visible window of one character, and it decreased to near 0 with unlimited preview.

Another illustration of the influence of other factors on age–speed relations is available in the results of a recent project (Salthouse, 1993c), portrayed in Figure 5. The variables in the two studies in this project were several measures of perceptual speed (e.g., Letter Comparison, Pattern Comparison, and Digit Symbol Substitution Test) and measures from other timed tests presumed to require word knowledge (e.g., various word fluency tasks and tasks such as anagrams). It is obvious in both studies that the magnitude of the relations between age and the speed measure decreased as the involvement of word knowledge (assessed by scores on two vocabulary tests) in the task increased. One interpretation of this pattern is that speed-dependent processing requirements were reduced as the amount of relevant knowledge increased, thereby resulting in a decrease in the relation of age to the measure. For example, when more knowledge is available, fewer transformations or novel processing operations might be required because much of the relevant information (or "solutions") may already exist in the individual's knowledge system.

The typing results (Salthouse, 1984) and the data in Figure 5 are merely two illustrations that the relation between age and measures of speed varies as a function of other factors. Results of this type can be viewed as confirming the well-accepted principle that virtually every performance measure has multiple determinants. That is, one-to-one relations between a particular hypothetical process and a behavioral variable are extremely rare, and thus most variables can be assumed to be affected by several different influences. Identical age relations on different speed measures should therefore not be expected unless the measures have the same determinants, with exactly the same weightings or relative importance, and the measures are equivalent in reliability and sensitivity.[4]

[4] Age–speed relations will also vary according to the reliability of the speed measure because large age relations cannot occur if there is little systematic variance in the measure that is available for association with other variables. As an example, the finding of Madden et al. (1993) that priming difference scores (i.e., priming reaction time minus unrelated or neutral reaction time) had reliabilities of near zero suggests that lack of systematic variance may be one reason for the low correlations between age and measures of priming. Also consistent with this interpretation are the reports by Salthouse (1994a) of correlations in two studies of .51 and .85 between the reliability of the measure and the absolute magnitude of the correlation of the measure with age.

A third assumption of the processing-speed perspective is that there is not necessarily a single, or unitary, speed factor. Instead, several common factors could exist, as long as the number is substantially smaller than the number of relevant speed measures (Kail & Salthouse, 1994; Salthouse, 1992b, 1995c). Results of studies conducted by Earles and Salthouse (1995), Hertzog (1989), Salthouse (1993c, 1994d), Tomer and Cunningham (1993), and White and Cunningham (1987) suggesting that several speed factors can be distinguished in samples of young and old adults are therefore not incompatible with the present perspective.

An analogy may help to illustrate this point. Several different types of speed affect the performance of a computer, including the processor clock rate; the speed of specialized mathematical or graphics co-processors; hard disk access time; input rate from devices such as keyboards, scanners, or modems; and output rate to devices such as display monitors, printers, plotters, or modems. Nevertheless, knowledge of a small number of speed "factors" allows performance on an extremely large number of tasks to be predicted quite accurately. A central hypothesis of the processing-speed theory is that the human cognitive system can also be conceptualized as having a relatively small number of speed factors that are related to age and that contribute to the efficiency of many cognitive processes. This is in contrast to the view, which is often implicit, that every process or measure has an independent age-related influence.

A crucial point from the current perspective, therefore, is that the age relations in all speed measures should not be expected to be of the same magnitude, in either absolute or proportional terms. Instead, the proposal is that many, but not necessarily all, of those measures share substantial age-related variance because of the influence of common determinants or factors.

Hypothesis 2: Processing speed functions as an important mediator of the relations between age and measures of cognitive functioning.

Because it is assumed, and the available evidence seems consistent with the assumption, that there are general age-related effects on speed of processing, it is hypothesized that there are effects not only on the speed of many cognitive operations but also on the quality of the products of those operations. Two categories of evidence are relevant to the hypothesized mediational role of processing speed in age–cognition relations: results from path analyses and results from statistical control of an index of processing speed.

Path Analyses

Because path models can illustrate the complete pattern of interrelationships among variables, path analyses are valuable as a means of indicating the relations among several variables. Path models should not be considered definitive because they can vary in the degree to which they represent or fit the data, and alternative structural models often provide equally good fits to the data (MacCallum, Wegener, Uchino, & Fabrigar, 1993). Nevertheless, path analyses can be informative about the presence or absence of particular relations, and hence they are of obvious relevance to theories postulating that a construct like processing speed mediates some of the age-related effects on measures of cognitive performance.

As expected from the processing-speed theory, path analyses have revealed strong relations between age and speed, moderate relations between speed and various measures of cognitive functioning, and either a weak relation or no direct relation between age and measures of cognitive functioning. Examples with various cognitive measures as the criterion variable have been described in Lindenberger, Mayr, and Kliegl (1993) and Salthouse (1991b, 1992b, 1992f, 1993d, 1994a), and those with working memory as the criterion cognitive construct have been reported in Salthouse (1994c) and Salthouse and Babcock (1991).

A recent project by Salthouse (1994d) can be used to illustrate the features, and potential contributions of the path-analytic approach. Results from two independent studies with slightly different cognitive tests were reported in this article, with sample sizes of 246 (Study 1) and 258 (Study 2) adults ranging from 18 to 87 years of age. The participants in each study performed paper-and-pencil sensorimotor speed (Digit Copy and Boxes) and perceptual speed (Letter Comparison and Pattern Comparison) tasks, as well as tests of memory, reasoning, and spatial ability. Because the cognitive tests were administered on computers, it was also possible to obtain separate measures of study or solution time, decision time, and decision accuracy from each of the cognitive measures to represent distinct aspects of cognitive performance.

Figure 6 illustrates the best-fitting path model from the project, based on composite measures formed by averaging z scores across the three cognitive tests in each study. The degrees of freedom in the model were low because the number of estimated parameters was close to the number of available covariances, but the model nevertheless provided a good fit to the data (e.g., Adjusted Goodness of Fit Index model determination values of .987 in Study 1 and .955 in Study 2). All path coefficients in Figure 6 differed from zero by more than two standard errors, except for the path between age and decision accuracy in Study 2. No paths not represented in the figure had coefficients significantly different from zero in either study.

Several important results should be noted about this figure. First, there were moderate to strong relations between age and perceptual speed and between perceptual speed and decision accuracy, but there were weak relations between age and decision accuracy. These features are all consistent with the key assumption of the theory that a slower speed of processing partially mediates the adult age differences in a variety of cognitive tasks. In addition, however, Figure 6 illustrates that sensorimotor speed was related to perceptual speed and decision time but not to decision accuracy. Peripheral (i.e., input and output) aspects of speed therefore do not appear to be directly involved in the mediation of the relations between age and decision accuracy. Furthermore, study time was not related to perceptual speed, but it was related both to age and to decision accuracy. This pattern suggests that, with increased age, more time was spent working on the items and that longer time devoted to the items was associated with higher accuracy. However, because study or solution time was not related to perceptual speed, it may reflect strategic or stylistic factors rather than effects associated with a slower speed of executing relevant processing operations. Finally, it is noteworthy that perceptual speed was re-

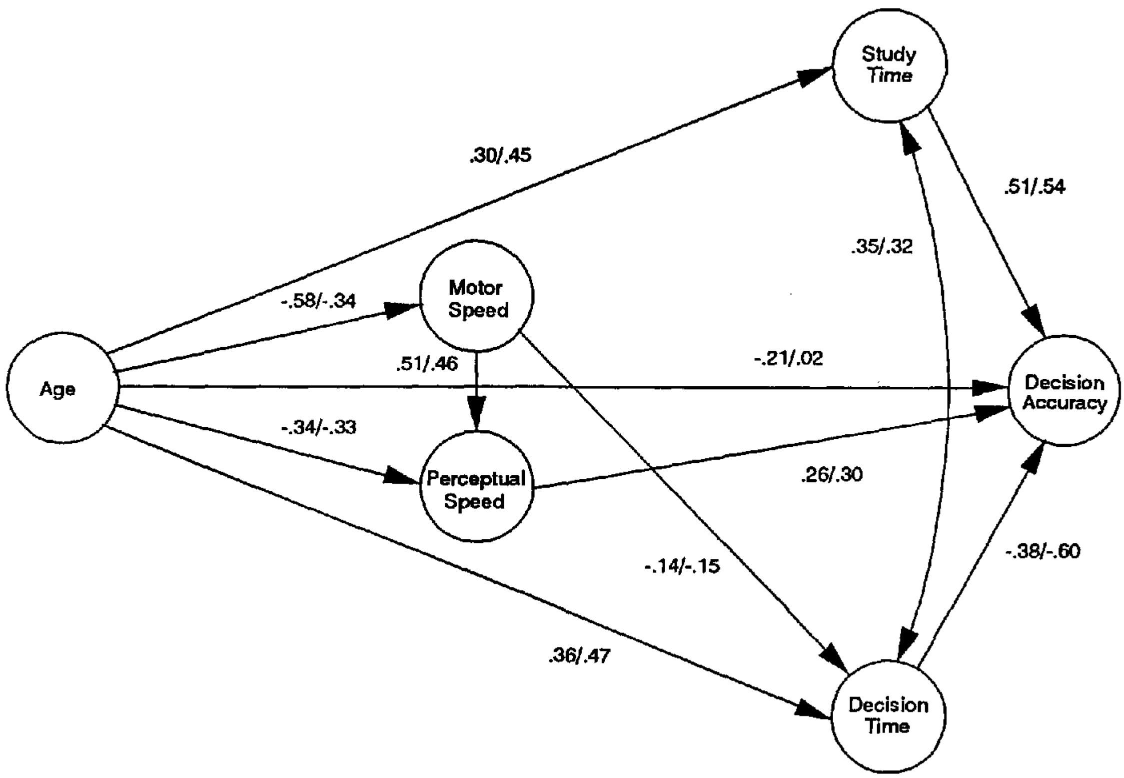

Figure 6. Path diagram illustrating relations among variables in two studies reported by Salthouse (1994d). Coefficients are reported in the format Study 1/Study 2.

lated to decision accuracy but not to decision time. This is additional evidence that processing speed, as indexed by the perceptual speed measures, affects the quality of cognitive processing and not simply the speed with which decisions about the products of the processing can be communicated.

Although only a small number of relevant path analyses have been reported, the available results have been quite consistent with the predictions of the processing-speed theory. In particular, moderate relations have been found between age and measures of speed and between speed measures and measures of cognition, but weak to nonexistent relations have been found between age and cognition. An additional contribution of path analyses apparent in the preceding example is that because the path analyses indicate how several different variables are interrelated, they are informative about how speed-mediated influences occur.

Statistical Control Procedures

One implication of the hypothesis that processing speed is a mediator of age–cognition relations is that age-related effects would be expected to be much smaller if the variation in the hypothesized mediator could be eliminated. An ideal investigative procedure would probably involve experimental manipulation of the level of the mediator, but this does not appear feasible with variables such as processing speed that are presumed to reflect relatively stable processing characteristics of an individual (Salthouse, 1992a, 1992b). Attempts can be made to match individuals of different ages on measures of speed; as illustrated later, however, this is not always successful, and it typically reduces the statistical power of the comparisons because of the decreased sample size. The most practical method of investigating hypothesized mediational relations therefore appears to be some type of statistical control procedure in which the variance in an index of the hypothesized mediator is held constant by statistical methods.

It is important to note that statistical control procedures will reduce the age-related effects on a criterion variable only if the measure of the hypothesized mediator is related both to age and to the criterion variable. If the mediator is related only to age, then there will be no effect of its control on the criterion variable; if the mediator is related only to the criterion variable, then its control will have no effect on the relation between age and the criterion variable. This is evident in Figure 3, which shows that the controlled variable can contribute to the mediation of age effects in the criterion variable only if the region of double overlap (i.e., Region b in Figure 3) is greater than zero.

One method of statistical control involves the use of hierarchical regression procedures similar to those described earlier. That is, the total amount of age-related variance in the criterion variable is determined, and then the amount of unique or independent age-related variance is assessed by controlling the variance in a measure of the hypothesized mediator. If the amount of unique or independent age-related variance is large relative to the total age-related variance, then considerable independence of the age-related influences in the controlled (hypothesized mediator) and criterion variables can be inferred. However, if the unique age-related variance is small relative to the total age-related variance, then one can infer that there is substantial commonality of influences in the two sets of measures. This second type of outcome is consistent with the mediation of at least some of the age effects in the criterion variable through the controlled variable (e.g., Salthouse, 1992a, 1992b; Salthouse & Babcock, 1991).

Application of statistical control methods does require several assumptions ranging from statistical (Cohen & Cohen, 1983) to substantive in nature. One of the latter is that the current level of the controlled variable, but not its etiology or developmental history, is relevant (Salthouse, 1991c, 1992a). It is also important to establish realistic expectations regarding the outcome of statistical control analyses because statistical significance tests in these types of analyses typically refer to the amount of variance that is not explained by the controlled variable rather than the amount that is explained. The age-related variance would be completely eliminated, with no residual variance, only if the controlled and criterion variables shared all of their age-related variance. This is an extremely demanding criterion because it would require not only that all variance attributable to the theoretical construct, but also all specific variance associated with methods, materials, and measures, was shared across the controlled and criterion variables (Salthouse, 1992a).

A potentially more meaningful basis for evaluating statistical control outcomes is in terms of the percentage reduction of age-related variance. For example, I (Salthouse, 1992a, p. 26) have suggested that percentage reductions of less than 20% are small, values between 20% and 40% are interesting, values between 40% and 60% are important, and values greater than 60% should be considered major because in that case all other determinants together would be responsible for less than half of the total age-related variance. These values are admittedly arbitrary, but even tentative guidelines may be useful in interpreting the results of statistical control analyses.

Percentage reduction in age-related variance is not the only possible metric of the importance of a hypothesized mediator, but if the variable is found to be associated with a very small reduction in age-related variance, then additional justification is probably needed to establish its importance. If the variable is associated with a large reduction in age-related variance, however, it can be considered important as a potential mediator for this reason alone.

Some of the earliest results from statistical control analyses with speed measures were described in Salthouse (1985b). Although the results of those initial analyses were generally consistent with the predictions from the processing-speed theory, the analyses were not optimal because the samples were often small, the speed and cognition constructs were assessed with single measures, and partial correlation rather than semipartial (i.e., hierarchical regression) correlation analyses were used. Numerous other studies sharing many of these characteristics have also been reported with mixed results (e.g., Bieman-Copland & Charness, 1994; Bors & Forrin, 1995; Bryan & Luszcz, 1996; Charness, 1987; Graf & Uttl, 1995; Hartley, 1986, 1993; Kwong See & Ryan, 1995; Nettelbeck & Rabbitt, 1992). As reported later, stronger evidence for a mediational role of processing speed has been obtained with larger samples and multiple indicators of both the speed and cognition constructs.

A graphical illustration of the effects of statistical control of measures of speed, and of matching individuals on speed, is presented in Figure 7. The data in this figure were obtained from a sample of 221 adults who were administered the Raven's Progressive Matrices Test with a 20-min time limit, along with the Letter Comparison and Pattern Comparison tests of perceptual speed (the sample, the same as that used in Figure 1, was reported as Study 1 in Salthouse, 1993b). The vertical axis represents performance on the Raven's test expressed in z-score units. Panels in the figure illustrate the initial age relations in the total sample (A); the age relations in the total sample after use of statistical adjustment to eliminate the variance in the composite speed measure, derived by averaging z scores for the Letter Comparison and Pattern Comparison measures (B); and the age relations in a subsample ($n = 90$) whose composite speed scores were within 0.5 standard deviations of zero (C). It is apparent that there was large attenuation of the age relations with the statistical control procedure (82%) and somewhat less (61%) attenuation when the sample was restricted to participants with a narrow range of speed. However, it is noteworthy that despite the substantial decrease in sample size from 221 to 90, there was still a significant correlation between age and speed (−.35) in the subsample. This is one of the reasons why matching is not the optimum method for these types of analyses.

Statistical control results resembling those portrayed in Panels A and B of Figure 7 have been obtained in an independent sample of adults by Babcock (1994), who found a 61% reduction (i.e., from an R^2 value of .212 to a value of .083) in the age-related variance in the Raven's score after control of perceptual speed measures. Similar results have also been reported with a computer-administered, self-paced, matrix reasoning task (Salthouse, 1993b, 1994d). In the latter study, the R^2 in decision accuracy associated with age in a sample of 246 adults from a wide range of ages was .149, and this was reduced to .014 (91% attenuation) after control of a composite measure of reaction time speed and to .015 (90% attenuation) after control of a composite measure of paper-and-pencil perceptual speed.

Many published studies now exist in which some index of processing speed has been controlled in examinations of age-related influences on a variety of cognitive measures ranging from reasoning and spatial abilities to working memory, associative memory, and free recall. To illustrate, a total of 44 comparisons with measures from individual cognitive tests were summarized by Salthouse (1993d). These comparisons were extracted from studies by Hertzog (1989) and Schaie (1989, 1990), as well as several studies by Salthouse and colleagues. Age was initially associated with a mean of 16.2% of the variance in these analyses, but the age-related variance was reduced to only 3.6% after measures of perceptual speed had been controlled. The average attenuation in the comparisons summarized in Salthouse (1993d) was therefore nearly 78%.

Comparisons with composite (i.e., average of z scores) cognition measures were summarized in Salthouse (1992b; e.g., see Fig. 3.6). Age was initially associated with a mean of 25.2% of the variance in these analyses, but the age-related variance was reduced to a mean of only 4.3% after control of speed. The

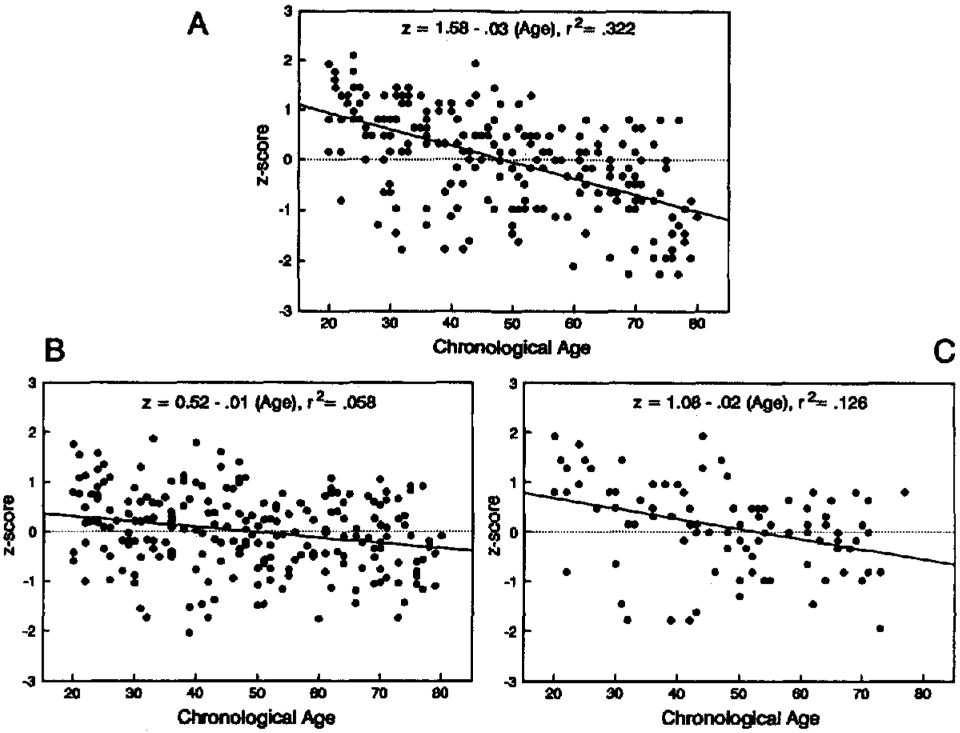

Figure 7. Relations between age and Raven's Progressive Matrices Test performance in the total sample (A), in the total sample after control of a measure of speed (B), and in a sample of participants within a narrow speed range (C; data from Salthouse, 1993b, Study 1).

average reduction of the age-related variance in these comparisons was therefore approximately 83%.

Similar magnitudes of attenuation have been found when the criterion cognitive tasks were self-paced and when separate measures of decision accuracy and decision time were obtained (i.e., Salthouse, 1993b, 1994d). In fact, the percentage attenuation of the age-related variance in the Salthouse (1994d) studies was actually greater for a criterion measure of decision accuracy (81.3% in Study 1 and 70.0% in Study 2) than for a criterion measure of decision time (74.5% in Study 1 and 54.8% in Study 2).

Substantial reduction of the age-related variance after control of relatively simple measures of processing speed has also been found when a variety of memory measures served as the criterion cognitive variable. To illustrate, results from several recent projects conducted in my laboratory are summarized in Table 6. The speed measures in these studies were composites formed by averaging z scores for the Digit Symbol and Digit Digit reaction time measures to create a reaction time speed composite measure or by averaging z scores for the Letter Comparison and Pattern Comparison measures to create a perceptual speed composite measure. Several of the memory measures were based on a single score (e.g., percentage correct recall in 12-word lists for free recall and percentage correct in study–test paired-associates trials). However, in the continuous associative memory tasks, the associative memory measures were aggregated across all presentation times to form a composite measure of associative memory performance. The working memory measures were also composites formed by averaging z scores from the spans obtained in the Reading Span and Computation Span working memory tasks.

Across all memory measures in Table 6, the age-related variance was reduced an average of 77.6% after control of the reaction time speed measure and was reduced an average of 85.1% after control of the paper-and-pencil perceptual speed measure. All of the values in Table 6 are thus in the important-to-major range according to the guidelines mentioned earlier, because more than 50% of the age-related variance in the measures of memory is shared with the variance in relatively simple measures of processing speed.

It should also be noted that, in several studies, the proportional attenuation of the age-related variance was greater with speed measures from tasks involving perceptual or cognitive operations, such as substitution, transformation, or comparison, than with tasks merely requiring copying or line drawing responses (Salthouse, 1992b, 1993d, 1994a, 1994d; Salthouse & Kersten, 1993; Salthouse et al., 1995). As suggested by the path analysis results illustrated in Figure 5, the speed most relevant to the mediation of adult age differences in cognition therefore appears to reflect the duration of cognitive operations rather than simply the speed of sensory and motor processes.

The results just described reveal that an average of 75% or more of the age-related variance in a wide range of memory and cognitive variables is shared with measures of processing speed. Moreover, this is true for different combinations of speed and cognitive measures, with both paper-and-pencil and computer-

Table 6
Age-Related Variance in Measures of Memory Performance

Measure and study	N	Age-related variance: Age alone	After reaction time speed	After perceptual speed	Proportion of shared variance
Free recall					
Salthouse (1993d)	305	.162	—	.021	—/.87
Salthouse (1993e)	146[a]	.546	—	.049	—/.91
Salthouse (1995b)	172	.289	—	.013	—/.96
Paired associates					
Salthouse (1993d)	305	.162	—	.024	—/.85
Salthouse (1993e)	146[a]	.596	—	.069	—/.88
Long-term memory for activities					
Earles & Coon (1994)	177	.195	—	.057	—/.71
Associative learning					
Salthouse & Kersten (1993)	104[a]	.152	.016	.025	.89/.84
Salthouse (1994a)					
Study 1	240	.165	.032	.059	.81/.64
Study 2	125	.117	.044	.049	.62/.58
Continuous associative memory					
Letters and Digits					
Salthouse (1994a)					
Study 1	240	.105	.002	.000	.98/1.00
Study 2	125	.038	.004	.000	.89/1.00
Kersten & Salthouse (1993)	78[a]	.265	.046	—	.83/—
Words and Digits					
Salthouse (1994d)					
Study 1	246	.071	.010	.006	.86/.92
Study 2	258	.071	.002	.010	.97/.86
Salthouse (1995d)	100[a]	.369	.087	.061	.76/.83
Working memory					
Paper-and-pencil procedures					
Salthouse & Babcock (1991), Study 2	233	.211	—	.007	—/.97
Salthouse (1991b)					
Study 1	221	.292	—	.050	—/.83
Study 2	228	.254	—	.014	—/.94
Study 3	223	.208	—	.012	—/.94
Computer-administered procedures					
Salthouse (1992a)					
Study 1	180[a]	.279	.081	—	.71/—
Study 2	100	.146	.014	—	.90/—
Salthouse (1995b)	117	.141	.029	.031	.79/.78
Salthouse & Meinz (1995)	242	.033	.001	.001	.97/.97
Combined samples from several studies	184[a]	.155	.031	—	.80/—
Miscellaneous (Salthouse, 1995a)					
Matrix memory					
Verbal	173	.277	.113	.086	.59/.69
Spatial	173	.402	.202	.148	.50/.63
Element memory					
Verbal	173	.087	.040	.005	.54/.94
Spatial	173	.070	.020	.000	.71/1.00
Keeping track					
Verbal	173	.170	.050	.029	.71/.83
Spatial	173	.142	.046	.036	.68/.75

Note. Dashes indicate that measures were not available.
[a] Only young and old adults.

administered tests, and across different types of tests (e.g., those requiring reasoning, spatial, and memory abilities). The statistical control results therefore provide strong evidence for a major role of processing speed in the relations between age and measures of cognitive performance.

In summary, research examining the relational prediction of the processing-speed theory has provided impressive support for that prediction. Not only have the path analyses revealed patterns consistent with the expectations, but the statistical control analyses indicated that nearly 75% of the age-related variance in many cognitive measures is shared with measures of processing speed. Because similar estimates of shared age-related variance have been obtained across timed and self-paced measures of reasoning and spatial abilities, across a wide range

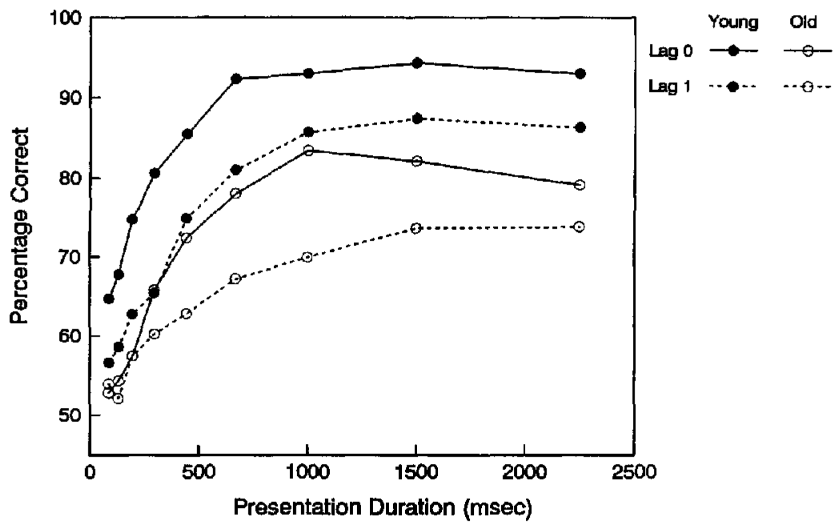

Figure 8. Accuracy as a function of stimulus presentation time with zero items and one item intervening between presentation and test of digit–letter pairs (unpublished data from Kersten & Salthouse, 1993).

of memory measures, and with different types of speed measures, it seems indisputable that processing speed is involved in the relations between age and cognitive performance.

Hypothesis 3: The limited time mechanism and the simultaneity mechanism are primarily responsible for the relations between processing speed and measures of cognitive functioning.

Limited Time Mechanism

The basic idea underlying the limited time mechanism is that slower speed of executing many processing operations means that less processing can be completed in a given amount of time. One method of illustrating the hypothesized relations involves manipulating the amount of time available to process the stimulus. Although it is unlikely that variations in stimulus presentation time will affect the speed of internal processing operations (Salthouse, 1991c, 1992b), this manipulation can still be informative about how level of cognitive performance is related to time available for processing.

Results from manipulations of stimulus presentation time can be portrayed in time–accuracy functions in which accuracy is represented along the vertical axis and time is represented along the horizontal axis. Vertical contrasts in this type of representation reflect the level of accuracy at a given time, and horizontal contrasts reflect the amount of time needed to achieve a given level of accuracy. If the complete function is available, then parameters of the mathematical function can be examined and compared across experimental conditions or age groups (e.g., Kliegl et al., 1994; Mayr & Kliegl, 1993; Salthouse & Coon, 1993).

Figure 8, based on results of an unpublished study by Kersten and Salthouse (1993), illustrates a typical pattern from manipulations of stimulus presentation time in adults of different ages.[5] The task in this study, which was performed by 39 young adults (*M* age = 20.5 years) and 39 older adults (*M* age = 67.9 years), was a continuous associative memory task involving letter–digit pairs. Probes, requiring a decision of whether the items in the test pair had been paired with one another when either item last occurred, were presented either immediately after the letter–digit pair (Lag 0) or after one intervening pair (Lag 1). This task is interesting because it allows the influence of stimulus presentation time to be examined not only on a relatively simple measure (i.e., accuracy at Lag 0) but also with another measure that presumably requires processing beyond that needed for the first measure (i.e., accuracy at Lag 1). That is, in addition to the registration and encoding required for the Lag 0 measure, relevant information needs to be preserved during the presentation and processing of additional items in the Lag 1 measure.

Three points should be noted about the results portrayed in Figure 8. First, all of the functions appear to have a similar negatively accelerated relation between accuracy and presentation time, but with asymptotes of less than 100%. The finding of asymptotes below 100% suggests that factors other than the duration of the stimulus contribute to performance on this task. Second, the functions for the Lag 0 measure (solid lines) are consistently above and to the left of those for the Lag 1 measure (dashed lines), indicating that, as expected, more time was needed for the processing associated with Lag 1 decisions than for that associated with Lag 0 decisions. This indicates that the effects of restricted processing time propagate to more complex forms of processing and are not simply confined to the simplest type of processing. The third point to be noted about Figure 8 is that the functions for older adults (open circles) are consis-

[5] The functions in this figure have asymptotes below 100%, indicating that perfect performance was not achieved even at the longest available duration. A similar finding has been reported by Salthouse and Coon (1993), and this may be characteristic of relatively difficult tasks in which only limited amounts of practice are provided (cf. Kliegl et al., 1994).

tently to the right and below those for younger adults (filled circles). It can thus be inferred that older adults complete less processing in a given amount of time than young adults in this task. This, of course, is exactly what is predicted from the limited time mechanism.

Simultaneity Mechanism

The key assumption in the simultaneity mechanism is that a slower speed of processing results in a smaller amount of information that is in a high enough level of activation to be available for other forms of processing. The concept of working memory is another way of referring to the amount of simultaneously active information, and there are many reports of age-related declines in measures of working memory (e.g., see Salthouse, 1994b, for a review). Furthermore, in all of the studies in which measures of processing speed were available, statistical control of the speed index greatly reduced the age-related variance in the working memory measures (cf. Table 6).

Although the evidence regarding age and speed influences on working memory is consistent with the predictions from the processing-speed theory, a number of questions remain regarding the simultaneity mechanism. For example, are working memory tasks the best means of assessing the amount of simultaneously available information, or is performance on those tasks heavily influenced by strategies, knowledge, and other factors? And do the reductions in the amount of simultaneously available information originate simply from slower rates of activating information, or are there also alterations in the rate of loss of information over time? Despite these uncertainties, the simultaneity mechanism remains a plausible candidate for relating processing speed to quality of cognitive functioning.

Additional Issues

A central issue concerning age-related slowing is whether it is best conceptualized as a cause or as a consequence of age differences in more basic behavioral constructs (e.g., Mayr & Kliegl, 1993; Salthouse, 1985b). This is not an easy question to resolve, but relevant information can be derived from comparisons of the relative proportions of age-related variance shared between measures of speed and measures reflecting what might be considered more basic constructs. The reasoning is that the most fundamental and basic construct, at least in terms of age-related influences, should be one that has a large amount of overlap with the age-related variance in other variables but has a smaller proportion of its own age-related variance overlapping with that of other variables. Evidence relevant to this issue can be obtained by contrasting the proportions of age-related variance shared between a variable reflecting another construct and a speed variable. Values of these comparisons from studies involving a variety of "other" variables are summarized in Table 7. Not all of the variables in Table 7 might be considered equally plausible as candidates for a basic construct important for cognition, but each reflects a factor that could potentially contribute to age-related differences in perceptual speed.

It is clear from the entries in Table 7 that the speed variables shared more of the age-related variance in the measures reflecting working memory, inhibition, pattern memory, serial learning, pattern comparison, vigilance, and hand–eye coordination than those variables shared with the age-related variance in the speed variables. These results are therefore more consistent with the interpretation that age-related variations in speed contribute to the age-related variations in these other constructs than with the view that the age effects in these other constructs contribute to the age effects in the measures of speed. It should also be noted that in studies in which the appropriate comparisons could be performed, the amount of reduction of age-related variance in measures of cognitive functioning was greater after control of measures of speed than after control of measures of working memory (e.g., Salthouse, 1991b).

One factor that complicates the distinction between cause and consequence with the construct of speed is that because the tasks used to assess processing speed are so simple, the principal way that variations in performance can be manifested is in terms of alterations in how rapidly the tasks can be performed. That is, because very few normal adults would make mistakes in these simple comparison and substitution tasks if allowed unlimited time, any factor that influenced basic processing efficiency would probably have its effects on measures of speed of performance. It is therefore possible that a slower processing speed is not the critical mediating factor in many of the age-related declines in cognition; rather, rate of performance is merely the manner in which differences in processing efficiency are exhibited in very simple tasks. The challenge in this alternative interpretation is to identify independent measures of other possible determinants of basic processing efficiency that would allow direct comparisons with the processing speed interpretation.

Another issue concerned with the age-related slowing phenomenon is whether the slower speeds are an artifact of a relatively small number of very slow responses. If this were the case, then the slowing phenomenon might be attributable to failures to sustain concentration or to inhibit distraction. However, analyses reveal little support for this attentional block interpretation. That is, statistical control analyses similar to those described earlier, but with reaction times from different percentiles of each individual's reaction time distribution as the controlled and criterion variables, have been reported by Salthouse (1993a). Because almost all of the age-related variance in the slow (90th percentile) responses was shared with the age-related variance in the fast (10th percentile) responses, there was no evidence for a failure to sustain high levels of attention or concentration as a factor contributing to age-related slowing. Moreover, because this same pattern was found in two reaction time tasks across four separate data sets, it can be regarded as fairly robust. These results therefore indicate that age-related slowing is evident throughout the individual's entire distribution of responses and is not simply manifested in his or her slowest responses.

One final issue concerned with the age-related slowing phenomenon is whether it merely reflects sensory and motor aspects. This does not appear to be the case because independent and distinct age-related influences have been found on measures from tasks involving comparison or substitution processes. Relevant results are available in a contrast of sensorimotor speed measures and perceptual speed measures. As noted earlier, the sensorimotor speed measures in these projects in-

Table 7
Proportions of Shared Age-Related Variance in Measures of Speed and Other Potentially Fundamental Constructs

Other variable and study	Speed variable	Proportion of shared age-related variance: Speed with other variable	Proportion of shared age-related variance: Other variable with speed
Backwards digit span	Digit symbol		
Salthouse (1988b), $N = 200$		.95	.23
Working memory (paper and pencil procedures)	Perceptual speed		
Salthouse & Babcock (1991), $n = 233$		.97	.60
Salthouse (1991a), $n = 221$		.83	.69
Salthouse (1991a), $n = 228$		.94	.55
Salthouse (1991a), $n = 223$		.94	.64
Working memory (computer-administered procedures)	Reaction time speed		
Salthouse (1992a), $n = 180$		.71	.35
Salthouse (1992a), $n = 100$		.90	.33
Salthouse (1995b), $n = 117$		.79	.32
Salthouse & Meinz (1995), $n = 242$		.97	.10
Combined samples from several studies ($N = 184$)		.80	.24
Inhibition (Stroop color–word interference measure)	Perceptual speed		
Salthouse & Meinz (1995), $n = 242$		.85	.48
Salthouse (1995b), $n = 172$		.81	.65
Salthouse et al. (1994)			
Backwards digit span	Symbol-Digit Substitution Test		
$n = 165$		.97	.20
$n = 239$		1.00	.18
Pattern memory	Symbol-Digit Substitution Test		
$n = 165$		.76	.11
$n = 223$		1.00	.24
$n = 239$		.63	.16
Serial learning	Symbol-Digit Substitution Test		
$n = 223$		.80	.26
$n = 239$		.45	.18
Pattern comparison	Symbol-Digit Substitution Test		
$n = 165$		.97	.51
$n = 223$		.90	.55
$n = 239$		.77	.43
Vigilance (continuous performance)	Symbol-Digit Substitution Test		
$n = 165$		.75	.01
$n = 223$		.77	.10
$n = 239$		.88	.19
Hand–eye coordination (tracking)	Symbol-Digit Substitution Test		
$n = 223$		.68	.24
$n = 239$		.49	.35
Tapping speed	Symbol-Digit Substitution Test		
$n = 223$		.11	.25
$n = 239$		.64	.30

volve copying digits or drawing lines in specified locations, whereas the perceptual speed measures involve determining whether two sets of lines or two sets of letters are identical.

Because of the increased reliability, and the potential of minimizing specific variance while emphasizing construct variance, comparisons of different types of speed are most meaningful when expressed in terms of composite scores. Although the two types of speed measures have a large proportion of age-related variance in common, significant residual age-related variance in the composite perceptual speed measures has been found after the variance in the composite sensorimotor speed measure has been controlled. To illustrate, the percentages of age-related variance in the composite perceptual speed measure that were unique and distinct from the age-related variance in the composite sensorimotor measure were 29% for a sample of 744 adults (Earles & Salthouse, 1995), 32% for a sample of 200 adults (Salthouse, 1993c, Study 1), and 25% for a sample of 154 adults (Salthouse, 1993c, Study 2).

Similar analyses have been conducted with the Digit Digit and Digit Symbol reaction time measures. Although both tasks require choice decisions, the choice in the Digit Digit task is based on physical identity, whereas the choice in the Digit Symbol task is based on the substitution of digits and symbols. The percentages of age-related variance in the Digit Symbol measure that were distinct or independent of those in the Digit Digit measure were 24% for a sample of 744 adults (Earles & Salthouse, 1995), 34% for a sample of 694 adults collapsed across several studies, 23% for a sample of 104 (Salthouse & Kersten, 1993), and 39% for a sample of 131 (Salthouse et al., 1995, Study 1). Because these results indicate that there are unique and distinct age-related influences on speed measures involving more cognitive operations, it can be inferred that the age-related slowing phenomenon is not simply restricted to sensory and motor aspects.

Relations to Other Theories

The processing-speed theory has both similarities and differences with respect to other theoretical perspectives within the field of aging and cognition. The focus on processing speed as a central construct is very similar to Birren's (e.g., 1965, 1974) speculation that the speed with which many cognitive operations can be carried out may function as an independent variable for many behavioral outcomes. The current theory differs from Birren's perspective, however, in that specific mechanisms are proposed to account for the speed–cognition relations, and empirical evidence derived from several different analytical methods has been generated to support the predictions. The processing-speed theory also shares the assumption that a general speed factor plays a major role in age-related slowing with theories proposed by Cerella (1985, 1990) and Myerson et al. (1990). It differs from those theories in that the primary focus here is on explaining relations between age and cognition rather than between age and speed and in treating analyses of systematic relations (i.e., Brinley plots) as only one source of evidence relevant to the hypothesis of a general slowing factor.

The processing-speed theory also has a resemblance to theories attempting to account for age–cognition relations in terms of broad explanatory mechanisms such as processing resources (e.g., Craik & Byrd, 1982) and aspects of attention such as inhibition (e.g., Hasher & Zacks, 1988). Unlike those theories, however, the central construct in the processing-speed theory has been reliably operationalized, and a large body of evidence based on statistical control and path analysis procedures has accumulated indicating that the construct has a major role in mediating relations between age and cognition.

Finally, regardless of whether one accepts the interpretation that at least some of the age-related declines in various measures of cognitive functioning are attributable to a slower speed of carrying out relevant processing operations, the discovery that measures of how quickly very simple tasks can be performed share large proportions of age-related variance with complex measures of cognitive performance has implications for the nature of virtually all theories concerned with aging and cognition. That is, nearly every theory, including those attributing age-related differences to impairments in specific cognitive processes or to deficits in certain types of strategies, will presumably need to take factors related to basic processing efficiency into consideration or else they may run the risk of focusing on merely another symptom of what could be a broader and more fundamental phenomenon.

Summary

Additional research is needed before the mechanisms responsible for the relations between age and speed, or between speed and cognition, can be fully understood. Not only is there still relatively little knowledge of why increased age is associated with a slower speed of performing many activities, but little is known about precisely how the limited time and simultaneity mechanisms, and possibly other mechanisms, relate slower processing to lower levels of cognitive performance. Among the important issues to be investigated are the neurophysiological basis for age-related slowing and what the processing-speed construct actually reflects. With respect to the first issue, a number of neurophysiological mechanisms could be proposed to account for age-related slowing, including

> a slower speed of transmission along single (e.g., loss of myelination) or multiple (e.g., loss of functional cells dictating circuitous linkages) pathways, or . . . delayed propagation at the connections between neural units (e.g., impairment in functioning of neurotransmitters, reduced synchronization of activation patterns). (Salthouse, 1992b, p. 116)

Multidisciplinary research will almost certainly be needed to distinguish among these alternatives because it is unlikely that they can be differentiated solely on the basis of behavioral observations.

The processing-speed construct is postulated to represent how quickly many different types of processing operations can be carried out. The moderate to high proportions of shared age-related variance across a wide range of speed measures, including those presumed to reflect the duration of task-specific cognitive processes, are clearly consistent with this hypothesis. However, there is still uncertainty as to the breadth of the processing-speed construct and whether more primitive behavioral constructs might contribute to the age differences in processing speed. Principled bases for specifying which variables are likely to be exempt from age-related slowing are also currently lacking. Further research is therefore needed before the processing-speed construct can be considered well understood.

Despite these limitations, there is currently strong evidence that measures hypothesized to reflect speed of processing are involved in the adult age differences found in many measures of cognitive functioning. The processing-speed theory thus appears to have sufficient plausibility to merit serious consideration as an explanation for at least some of the age-related effects on cognition.

Finally, two additional advantages of focusing on the processing-speed construct in research on cognitive aging warrant mention. One is that processing speed is a parsimonious target construct for research concerned with distal determinants of cognitive aging phenomena. That is, because speed appears to play a central role in many age-related cognitive differences, an explanation of the factors occurring earlier in one's life that are responsible for age-related decreases in speed would probably account for a large proportion of the age differences in a variety of measures of cognitive functioning.

The second advantage of focusing on the processing-speed construct is that speed may function as a bridging construct between behavioral and neurophysiological research. Because time is an objective and absolute dimension rather than a norm-reference scale, as is the case with most behavioral measures, it is inherently meaningful in all disciplines and thus has the potential to function as a Rosetta stone in linking concepts from different disciplines (Salthouse, 1985b).

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