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Processing speed as a mental capacity

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Abstract

Throughout the lifespan, there are pronounced age differences in speed of processing, differences that are consistently related to performance on measures of higher-order cognition. In this article, we examine domain-specific and global explanations of these age differences in processing speed; we conclude that although experience can play a role in age differences in speed, there is also evidence that a general mechanism limits speeded performance. We also review research that shows the influence of processing speed on the quality of performance on nonspeeded tasks such as reasoning and memory. We suggest that speed of processing should be viewed as a fundamental part of the architecture of the cognitive system as it develops across the entire lifespan.

1. Introduction

The speed of many types of processing follows a regular trajectory over the course of the lifespan. Speed increases throughout childhood and adolescence, reaches a peak in young adulthood, and declines slowly thereafter (Salthouse and Kail, 1983). This pattern of developmental change has been studied extensively in recent years. Interest in processing speed can be traced, in part, to the fact that the age differences are substantial. Consider, for example, Fig. 1, which illustrates age-related differences in performance on two perceptual speed tests from the Woodcock–Johnson Tests of Cognitive Ability (1990). The Visual Matching Test requires the individual "to locate and circle the two identical numbers in a row of six numbers" (p. 20), and The Cross Out Test requires the examinee to "mark the five drawings in a row of 20 drawings that are identical to the first drawing in the row" (p. 22). Similar age trends are evident in other measures, but this particular

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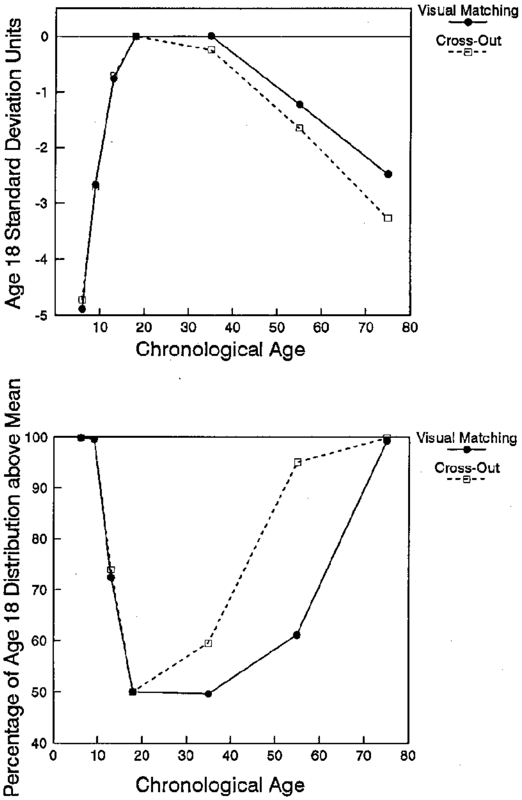

Fig. 1. Age differences in performance on two perceptual speed tests from the Woodcock–Johnson Tests of Cognitive Ability, expressed as z-scores (top panel) and as the percentage of the young adult distribution that exceeds the mean performance at each age (bottom panel).

test battery has the desirable characteristic of containing normative data on the same tests from over 6000 individuals between 6 and 80 years of age who were sampled to be representative of the United States population.

Mean performances of children and older adults in this figure are expressed in terms of units of the distribution of scores of a reference group of over 250 18-year-olds. The youngest children, at age 6, perform approximately 5 standard deviation units below the young adult mean, and performance falls to more than 2 standard deviations below the reference group mean by age 75. The bottom panel of the figure shows the results expressed in terms of the proportion of the young adult distribution that exceeds performance by children and by adults of various ages. children's mean performance is exceeded by almost the entire young adult distribution until approximately age 12, and divergence of the distributions is pronounced again by age 55. These illustrative data show that although the absolute times involved may be small – often fractions of a second – the differences are very large when expressed in units of the young adult reference distribution.

Another reason why speed differences are potentially important is that performance on perceptual speed tests such as these has consistently been found to be significantly related to measures of higher-order cognition. For example, correlations between the average of the two perceptual speed tests described above and composite scores representing Fluid Intelligence (Analysis-Synthesis Test and Concept Formation Test) and Short-Term Memory (Memory for Sentences Test and Memory for Words Test) from the Woodcock–Johnson battery are illustrated in Fig. 2 for each of the ages represented in Fig. 1. Notice that the correlations are generally in the moderate range, indicating that there is a substantial relation between measures of perceptual speed and measures of inductive reasoning and short-term memory.

The thesis to be developed in this article is that the two sets of results just described are consistent with the idea that among the most meaningful ways to conceptualize mental capacity is in terms of an individual's processing speed. That is, the maximum rate at which elementary cognitive operations are executed can be considered a processing resource, in the sense that time is finite and the faster processing can be performed, the better the resulting level of cognitive performance (Salthouse, 1985a, b, 1992a). Moreover, several different types of evidence suggest that age-related differences in speed contribute to age-related differences in at least some measures of cognitive functioning.

The concept of mental capacity or processing resources has been controversial because researchers using these terms have seldom been explicit about the properties of the presumed processing capacity, nor how it could be measured. As a consequence, the concept has been criticized for being circular in that age differences in resources are often inferred to exist on the basis of the same evidence these differences are used to explain (e.g., Light and Burke, 1988; Salthouse, 1988b, c).

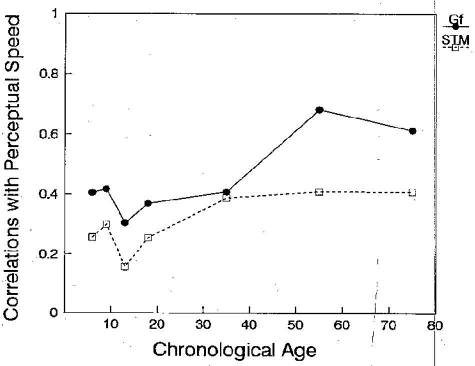

Fig. 2. Correlations from the Woodcock–Johnson Tests of Cognitive Ability between perceptual speed and (a) fluid intelligence (Gf), and (b) short-term memory (STM), as a function of chronological age.

There is much truth to these criticisms, but it would be premature to abandon the capacity concept, especially with respect to developmental phenomena. Vagueness concerning the properties of the construct and its measurement are not inherent shortcomings of mental capacity as a theoretical tool. A first step in clarifying the nature of the mental-capacity construct is to identify its critical characteristics, of which we believe three are key. These are the resource or capacity: (a) is limited in quantity, with a measurable aspect such as quantity or effectiveness of allocation increasing up until maturity and then decreasing across the adult years; (b) enables or enhances cognitive processing such that performance in many cognitive tasks is improved when greater amounts of the resource are available; and (c) is not local or specific in the sense that it is restricted to a small number of highly similar cognitive tasks, but instead is relevant to a broad range of cognitive processes.

Two properties sometimes attributed to the processing capacity view are not, in our opinion, intrinsic aspects of this interpretation. One is the idea that the mental capacity view holds that a *single* resource underlies cognitive processing. Few capacity theorists adhere to this view; instead, most assume multiple resources, although the number and their nature are much debated. A second misconception is that capacity theories intend that *all* aspects of cognitive performance are determined exclusively by capacity. Again, few capacity theories make this claim; instead, capacity is seen as but one of several forces in human performance and change. Thus a much more realistic position is that there may be several different types of processing resources, and that even in combination they are not the exclusive source of all of the performance variations evident in any particular cognitive task.

The three key features of processing capacity have generated a number of specific theories concerning the nature of mental capacity. Most of the proposals rely on metaphors of space, energy, or time (Roediger, 1980; Salthouse, 1985a,b). That is, space limitations correspond to restrictions on the size of the computational or working memory region available for processing, energy limitations correspond to attentional "fuel" restrictions, and time limitations refer to restrictions imposed by tradeoffs between the rate at which information can be processed and the rate at which it becomes unavailable through decay, interference or some other mechanism.

These metaphors are not necessarily independent because it is clearly quite possible that aspects of space, energy, and time are interrelated, and in certain circumstances may be interchangeable. For example, if working memory is dynamic and needs periodic refreshing, then the capacity of working memory will be determined by the time or energy available for refreshing. Conversely, if the amount of workspace available for computation is limited, more swapping of information to and from long-term memory will be necessary and the time for most activities will increase. In a similar manner, time and energy may be interchangeable because increased energy may contribute to faster time, and vice versa.

In order to begin to investigate the feasibility of the mental-capacity perspective, it is necessary to operationalize the capacity construct using one of these three metaphors. Our research has focused on the processing speed metaphor because of the existence of: (a) strong relations to age in both the child and adult portion of the lifespan (cf. Fig. 1); (b) moderate to strong relations with cognitive performance (cf. Fig. 2); and (c) procedures to measure the processing speed construct.

The organization of the remainder of the article is as follows. First, the nature of the age-related speed variation is examined to determine whether it is more consistent with a relatively general processing-resource interpretation or with a local, specific-influence, interpretation. Next, research relevant to the influence of processing speed on relations between age and cognition will be reviewed. Finally, we conclude with a brief discussion of the implications of this perspective for research on the development and decline of cognitive functioning across the lifespan.

2. The nature of speed variation

Developmental changes of the sort implied in Fig. 1 have been analyzed in terms of two broad categories of explanation. One view emphasizes experiences that lead to changes in the speed of processes in specific domains. That is, age is postulated to be associated with experiences that produce changes that are specific to particular processes, tasks, of domains. For example, during childhood, adolescence, and young adulthood, age differences in processing speed may reflect acquisition with age of more efficient strategies for task solution (e.g., Chi, 1977). Similarly, age differences in processing speed might reflect the fact that knowledge in specified domains becomes more elaborate, consisting of more entries in memory and more links between these entries. These more extensive connections can be expected to lead to more rapid access of information (Anderson, 1983; Chi and Ceci, 1987). During the adult years these processes might work in reverse as changing patterns of experience or disuse gradually lead to the loss or unavailability of skills and knowledge that had once been possessed (e.g., Sorenson, 1933).

Logan's (1988) "instance" theory illustrates this approach to the impact of experience on speeded performance. In this theory, increased speed of performance with experience is represented as a shift from performance based on algorithms, which is relatively slow, to performance based on rapid, direct retrieval of the appropriate task response. That is, individuals initially respond using an algorithm (e.g., in addition, a counting procedure). However, each time a task is performed, the stimulus and the subject's response are stored in memory. Repeated performance of the task increases the number and strength of these representations, so that ultimately the presentation of a problem leads to automatic retrieval of the response.

The impact of experience within this perspective is quite specific, resulting in an increase in the number of certain types of representations in memory. An implication of this type of interpretation is that the pattern of age-related change in processing speed should not be systematic or consistent across domains. Instead, domain-specific change in processing speed would be expected, reflecting age-related differences in relevant experience in each domain.

An alternative view emphasizes more global changes – those that are not linked to specific domains. For development during childhood and adolescence, the prototypic theory of this sort would be Piaget's, but this theory does not lead to obvious hypotheses concerning age-related change in performance on speeded tasks. However, general neo-Piagetian theorists have recast Piaget's qualitatively different stages in quantitative terms that yield predictions about developmental change concerning processing speed. Pascual-Leone (1970), for example, proposed that Piaget's stages reflect change in "the size of central computing space *M* [that] ... increases in a lawful manner during development" (p. 304). Greater computing space could lead to more rapid processing of information. For example, increased processing space could mean that more processing occurs in parallel or that fewer objects or results of processing must be exchanged between the computing space and long-term memory. Furthermore, systemic change of this sort would not be specific to particular domains but could instead lead to age-related change in performance on most speeded tasks.

Similar global hypotheses have been proposed in the field of cognitive aging. For example, Birren (e.g, 1974) has suggested that an age-related reduction in processing speed may be a primary factor contributing to age-related differences in many aspects of cognition, and Welford (e.g., 1958) has emphasized the importance of short-term or working memory in cognitive aging phenomena.

In recent years, we and other investigators have attempted to determine whether developmental change in processing speed is better explained with domain-specific or global theories. This research is summarized in the next section of this article.

3. Research on the nature of age-related differences in speed of processing

3.1. Studies of experience

Experience is often thought to play a key role in age-related change in processing speed, but the nature of the role differs in children and older adults. Consider, first, the impact of experience during childhood and adolescence. Compared to young adults, children have less experience in virtually all domains, and indeed they have been characterized as universal or generalized novices. Some theorists (e.g., Chi, 1977) would argue that it is this lack of domain-specific experience that is responsible for age-related differences in performance on cognitive tasks during childhood and adolescence. Phrased somewhat differently, in this view age–cognition correlations are spurious because they reflect correlations (a) between age and specific experience and (b) between specific experience and speeded performance.

If age–cognition correlations are byproducts of the correlations (a) and (b), then links between age and speeded performance should vanish if children and adults are equated with respect to the amount of specific experience. That is, the age–speed correlation should be 0 if the age–experience correlation is also set to 0. Data relevant to this prediction with children have been reported by Roth (1983). Although this study is sometimes cited as demonstrating the impact of experience on age-related cognitive change during childhood and adolescence, we suggest that the results actually provide little support for this view.

Roth (1983) studied four groups of subjects: child and adult chess players as well as child and adult chess novices. Child experts had won local chess tournaments; the adults had experience playing chess but were not accomplished players. The two experienced groups did not differ significantly on two measures of chess knowledge: (a) selection of the best move in a particular game situation, and (b) the Knight's Tour task, in which subjects are timed as they use legal moves to reposition a Knight in an adjacent square on the chessboard. Both child and adult experienced players had significantly higher scores on those measures than did child and adult novices.

Each subject was also tested on a task in which pairs of chessboards were presented that included either 10, 18, or 26 chess pieces per board. On "same" pairs, matching pieces appeared in the corresponding location on the boards; on "different" pairs, matching pieces appeared in corresponding boards, except for one piece, which was placed in different locations on the two boards. On some boards, chess pieces were placed as they might appear in a game; on others, they were placed randomly; on still other boards, the pieces were replaced by digits. In all cases, the subject's task was to determine if the two chessboards were identical, in terms of the identities of individual pieces and their positions on the board.

Response times (RTs) typically increased linearly as a function of the number of pairs of pieces to be compared. Consequently, Roth (1983) inferred that most subjects compared boards piece by piece until either they found mismatching pieces (and then responded "different") or they had compared all pieces (and then responded "same"). Consequently, he used the slope of the function relating RT to number of pairs to estimate the speed of search and comparison. The often-cited result is that, on meaningful boards, this value did not differ for child and adult experts, a finding that has been interpreted as consistent with the prediction that age differences in processing speed should be eliminated when children and adults have comparable specific experience or expertise.

However, other aspects of Roth's (1983) results cast doubt on this conclusion. First, although search rates for experienced adult and child players did not differ significantly, experienced child players required 38 percent additional time to search boards (449 msec/piece for children vs 326 msec/piece for adults). The nonsignificant difference may reflect inadequate power in the design, which included only 40 subjects total. Second, although the difference between search rates for experienced children and adults should approach zero only on the meaningful boards (because only these boards allow experts to invoke their knowledge), the difference was nearly identical on boards that were organized, random, or contained digits rather than chess pieces. Thus, Roth's results do not provide compelling support that increases in speed during childhood and adolescence can largely be attributed to the acquisition of domain-specific expertise.

When we turn to studies of age-related differences in adulthood, experience plays a different role. Here, one view is that age-related declines in cognition may reflect deterioration of skill through lack of use. Stated in terms of correlations between age, experience, and speed, the interpretation is that the negative correlation between age and cognition reflects the facts that (a) age and specific experience are negatively correlated, that is, that some skills are used less often with age, and (b) experience and speeded performance are positively related.

Studies of adults with experience in specific domains are relevant to this interpretation because they represent an instance in which specific skills may not have declined with increased age. That is, among experienced adults, who may have maintained their skills through continuous exercise of the relevant abilities, age-related differences in speeded performance in relevant domains should be reduced or perhaps eliminated altogether. Unfortunately, only limited evidence is available concerning the influence of extensive experience on the relations between adult age and speeded performance. Two studies (LaRivier and Simonson, 1965; Smith and Greene, 1962) examined age-related effects on the speed of handwriting among members of different occupational groups. The results of the two studies were inconsistent, however, perhaps in part because no information was available concerning the extent to which handwriting was actually used by members of different occupational categories.

Several studies in the domain of transcription typing have revealed that the age relations on domain-specific speeded performance may be small to non-existent among highly experienced typists (Bosman, 1993; Salthouse, 1984; Salthouse and Saults, 1987). In the Salthouse (1984) study, for example, moderate to strong age relations were reported in a measure of choice reaction time (i.e., $r = 0.60$), but no significant relation was found between age and median interkey interval in transcription typing (i.e., $r = 0.10$).

One of the interpretations proposed to account for the absence of age-related influences in the speed of typing in these studies was that extensive experience led to the development of compensatory mechanisms, particularly on the part of the skilled older typists. Evidence for one possible compensatory mechanism, in the form of an increase with age in the number of to-be-typed characters being processed at any given time, was reported by Salthouse (1984), and replicated by Bosman (1993). That is, manipulations of the number of characters visible during typing revealed that the eye–hand span, representing the minimum number of characters needed to avoid disruption of typing speed, was larger among older skilled typists than among younger, or less skilled, typists. It should be noted that this interpretation is not necessarily inconsistent with the hypothesis of age-related differences in a relatively general or global processing speed, because it could merely imply that the consequences of any general influence that may exist are minimized by the operation of compensatory mechanisms.

Another approach to investigating the influence of experience on adult age differences in speed involves examining performance on speeded tasks in which there is likely to be a substantial (experience-mediated) knowledge component. For example, Salthouse (1993a) recently compared young and old adults in the performance of verbal tasks such as word fluency, anagrams, and a version of the scrabble word game. As expected, significant positive correlations were found between performance in these tasks and scores on two vocabulary tests used as measures of word knowledge. Furthermore, older adults had somewhat higher scores than young adults on the vocabulary tests, and, as expected from the experience interpretation, the magnitude of the age differences in the verbal tasks was smaller than those in other speeded tests in which the relations with word knowledge were much smaller. However, another result of interest in this study was that the influence of word knowledge was very similar in young and old adults. That is, the regression coefficients for word knowledge in the prediction of speed in the verbal tasks did not differ between young and old adults. This suggests that although knowledge acquired through experience can moderate speed of performance in simple verbal tasks, the moderating influence appears to operate in an equivalent fashion in adults of different ages.

The two studies just described imply that increased experience could have at least two different types of influences on the adult age differences in speeded tasks. In both cases increased experience leads to reductions in the magnitude of the relations between age and speeded performance, but the processes may be quite different. On the one hand, experienced older adults could rely on different mechanisms than young adults to achieve a high level of overall performance. On the other hand, experienced older adults could use the same mechanisms but balance a disadvantage in speed with an advantage in relevant knowledge. It is important to point out that neither of these proposals is necessarily inconsistent with the assumption of a relatively general influence on processing speed; they may simply be alternative means by which experience minimizes the consequence of more general age differences in speed of processing.

To summarize, although highly specific, and perhaps experience-mediated, interpretations of age differences in speeded performance have been proposed, it is not yet clear that they are either necessary or sufficient to account for the variations in the relations between age and speed that have been observed. Some of the evidence assumed to be relevant is either rather weak, as in the Roth (1983) study, or is quite compatible with the existence of a general influence, as in the typing and verbal speed studies with adults.

3.2. *Studies comparing speeded performance across tasks*

Two analytical procedures have been used to examine the possibility that a relatively general mechanism contributes to the age differences in processing speed throughout the lifespan; these can be termed the method of systematic relations and the method of statistical control.

3.2.1. *Systematic relations*

The method that has been used most frequently in recent years consists of determining whether there is a systematic relation between the mean response times in groups of individuals of different ages. The rationale for this method is as follows. Assume that the response of young adults on a particular task consists of several processes, such that RT can be defined as

$$\mathrm{RT} = a + b + c + \ldots, \tag{1}$$

where a is the time to execute process A, b is the time for process B, etc. If individuals at some other age, i, execute each process more slowly, by a constant multiple, then the corresponding equation for individuals at age i would be

$$\mathrm{RT}_i = ma + mb + mc \ldots = m(a + b + c), \tag{2}$$

where m is simply the slowing coefficient, the factor by which individuals at age i are slower than young adults. Simplifying, and ignoring any additive constants, yields:

$$\mathrm{RT}_i = m\mathrm{RT}_a, \tag{3}$$

where RT_i and RT_a denote RTs for individuals at age i and young adults, respectively.

Eq. (3) leads to predictions for studies with experimental conditions that affect the number of processes included in RT, or that affect the duration of those processes. The result is a range of RTs, for both the reference group of young adults and for individuals at age i. According to the hypothesis that a relatively general mechanism contributes to the age-related slowing, the correlation across these conditions between RTs of young adults and those of individuals at age i should be very close to 1, because this is simply a correlation between a variable and that same variable multiplied by a constant, m. This is admittedly not a strong or unique prediction because a high correlation would be expected whenever the two groups exhibit a similar sensitivity to task variations, regardless whether one group is slower than the other (see Cerella et al., 1980; Salthouse, 1992a). However, an additional expectation is that the slope of the function relating RTs for individuals at age i to the RTs of the reference group of young adults from the corresponding conditions provides an estimate of m. Moreover, because the extent of slowing will depend upon the age of the individuals, m_i can be used to denote slowing coefficients at a particular age i.

In the remainder of this section, we first review studies that have examined the applicability of Eq. (3) in adulthood, then consider its applicability to cognitive change in childhood and adolescence. This order of coverage is followed because the method of systematic relations was first introduced in studies comparing young and old adults.

Studies of older adults..

A relatively large number of articles have reported the results of regression analyses relating the mean performance of groups of older adults to the mean performance of groups of young adults (e.g., Bashore et al., 1989; Cerella, 1985; Cerella et al., 1980; Myerson, et al., 1991; Salthouse, 1985b). Almost without exception, the regression equation has been found to account for a considerable

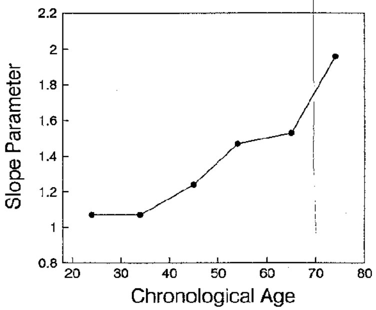

Fig. 3. Change in the m parameter of Eq. (3) as a function of chronological age. (From Salthouse, 1994.)

proportion of the variance in the group means, with the slope of the equation commonly falling in the range between about 1.3 to 1.8.

A specific example of this phenomenon, which has the advantage of reporting results based on analyses conducted at the level of individual subjects rather than at the level of group means, is available in a recent study by Salthouse (1993c). This study involved a reference group of 100 college students and a sample of 305 adults between 18 and 80 years of age who were each administered 11 speeded tasks. The mean times for the 11 speeded tasks in the reference group were used in regression equations to predict the times of each individual in those same 11 tasks. Means of the regression parameters across the 305 subjects were 0.93 for the correlation, 1.40 for the slope (m in Eq. (3)), and −0.13 for the intercept (ignored in Eq. (3)). The correlation coefficient was not significantly related to age, indicating that the fit of the regression equations did not vary as a function of age. However, the slope parameter did increase significantly with age, as can be seen in Fig. 3. When considered together, therefore, these results indicate that there is a highly systematic relation between the performance times of adults of different ages, and that the magnitude of the differences in speed increases with increased age.

Studies of children and adolescents..

The first study in which Eq. (3) was evaluated across a range of tasks in children was reported by Hale (1990). She tested 10-, 12- and 15-year-olds and a reference group of young adults on four speeded tasks: choice RT, letter matching, mental rotation, and matching abstract patterns. At each age, eight mean RTs were derived and correlated with adults' RTs for those conditions. The correlations between youth and adult RTs were greater than 0.99 at all ages. Values of m_i were 1.82, 1.56, and 1.00 for 10-, 12-, and 15-year-olds, indicating a gradual approximation to the processing time of young adults.

Additional evidence that the speed of many different tasks gradually approaches the speed of adults as the children mature is based upon a meta-analysis of studies of speeded performance that included 72 studies representing 1826 pairs of youth–adult mean RTs (Kail, 1991b). That is, each of 1826 data points consisted of a mean RT for youth and a mean RT for young adults for the same experimental condition. Data were divided into 11 sets based on the age of the youth – 3 through 14 years of age – and were fitted to Eq. (3). The fits were uniformly excellent, with r^2s > 0.90. As reported by Hale (1990), values for m_i became smaller with age, but nonlinearly: m_i changed substantially in early and middle childhood, and more slowly thereafter. Nonlinear change of this type is often well described by exponential functions of the form

$$m_i = a + b\,\mathrm{e}^{-ci}, \tag{4}$$

where a is the asymptote, e is the base of natural logarithms, $a + b$ is the intercept (for $i = 0$, $\mathrm{e}^{-ci} = 1$), and c is a "decay" parameter that indicates how rapidly the function approaches the asymptote. For the data from the meta-analysis, with $a = 1$ (because this is the expected value of m_i at maturity), $b = 5.16$ and $c = 0.21$, Eq. (4) accounted for 77% of the variance in m_i. Thus, the meta-analysis (Kail, 1991b) reveals that across a wide range of conditions, RTs of the young can be expressed as a multiple of the RTs of young adults and that the factor by which youth are slower than adults declines exponentially.

Eq. (4) leads to point predictions concerning the value of m_i. By inserting a specific age i into the equation, predicted values for m_i can be obtained. For example, with $a = 1$, $b = 5.16$ and $c = 0.21$, $m_{9.5} = 1.71$, which means that, regardless of the task, mean RTs for 9.5-year-olds are expected to be 1.71 times greater than those for adults. The accuracy of these predictions has been evaluated in several studies. One approach is to obtain RTs in different conditions from samples of young adults and multiple samples of youth, compute m_is at the different ages, and compare them with those predicted from Eq. (4).

A study by Kail and Park (1992, Expt. 1) illustrates this approach. Subjects between 8 and 20 years of age performed a variant of the Coding task of the WISC-R, and also solved reasoning problems like those on Raven's Progressive Matrices, analogical reasoning problems in which they determined if two pairs of geometric objects were related in the same way, a mental addition task in which they judged the truth of simple addition statements, and a mental rotation task in which they decided if stimuli presented in different orientations were letters or mirror-images of letters. These tasks yielded 48 conditions. Group means were calculated separately for the adults and for 14 age groups, and fitted to Eq. (3), with the values of m_i illustrated in Fig. 4. The percentage of variance in RT accounted for by Eq. (3) ranged from 74 to 98. Furthermore, Eq. (4) accounted for 93 percent of the age-related variation in values of m_i.

Another relevant study is that of Kail (1993). An adult comparison sample as well as 6- through 16-year-olds were testing on the modified Coding task, a choice RT task in which subjects pushed the button indicated by an arrow appearing on the screen, a number comparison task in which subjects pressed a button under the larger of two digits that were shown on a computer monitor, and a visual search task in which subjects determined if a string of letters contained a target letter presented previously. RTs from 6- to 16-year-olds were fitted to Eq. (3), along with the mean RTs from the adult comparison sample. Eq. (3) accounted for 52 to 80 percent of the variation in RTs at different ages. Furthermore, age-related differences in m_i, which are illustrated in Fig. 4, were well described by Eq. (4). Specifically, with $b = 5.16$ and $c = 0.21$, predicted values of m_i did not differ significantly from the observed values for 7- through 16-year-olds. Only at age 6 was prediction faulty, with the predicted value of m_i being significantly less than the values observed.

To summarize, these results indicate that there is frequently a highly systematic relation between the response times of individuals of different ages. Moreover, the slope of the function relating the times at any given age to the slope of young adults decreases from early childhood to maturity, and then increases from maturity to late adulthood. This pattern is similar to that evident with individual speed measures, such as those illustrated in Fig. 1, but it is important to note that the slope represents the relation between two sets of times rather than a single response time. The slope is therefore a more abstract index of processing speed because it indicates the magnitude by which the processing times increase with greater demands relative to the increases in a reference group. In this respect, the slope might be interpreted as an index of a relatively general or global processing speed characteristic of an individual or group of individuals of similar age.

At the same time, we need to note some reservations about the method of systematic relations, which may qualify some of the conclusions derived from this method. First, although the regression analyses that were used to assess the relation between RTs for young adults and RTs for either younger and older subjects assume that observations are independent, this is usually not the case. Instead, a typical RT experiment based on additive factors logic may involve a series of experimental conditions in which each additional condition is presumed to include all of the processes required for the previous conditions, plus an additional process. Condition 1 might, for example, be thought to require processes a, b, and c; Condition 2, processes a, b, c, and d; Condition 3, processes a, b,

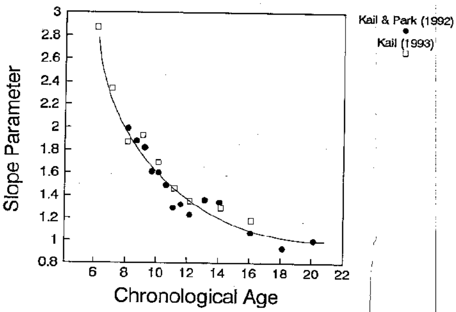

Fig. 4. Change in the m parameter of Eq. (3) as a function of chronological age, and values predicted by Eq. (4). The squares depict values of m obtained by Kail and Park (1992); the triangles, values obtained by Kail (1993). The curve depicts Eq. (4) with $a = 1$, $b = 5.16$, and $c = 0.21$.

c, d, and e; and the like. Such interdependencies can give rise to spuriously high values for r^2.

Second, sole reliance on r^2 can be misleading because it provides only a global estimate of the fit of the data. Some data points may deviate systematically from the general trend. This outcome can be evaluated by statistical tests (e.g., identifying data points whose residuals are more than double the size of their standard errors), but this practice has not been followed frequently. Consequently, systematic deviations from Eq. (3) may have gone unnoticed.

3.2.2. Statistical control

A second method of determining whether age-related speed differences are specific or relatively general involves the use of statistical control procedures. The primary purpose of statistical control procedures is determination of the relation between two variables when the variation in one or more other variables is held constant. This technique is extremely valuable when experimental manipulations are not feasible, such as is likely the case with the processing resources construct because resource quantity is often assumed to be a relatively stable and unmodifiable characteristic of an individual. A variety of different statistical control procedures can be used (e.g., partial correlation, analysis of covariance, hierarchical regression), but in all cases the goal is to minimize the influence of the controlled variable by eliminating the variance in that variable before examining the relation between the other variables.

In the present context, the control variable consists of measures postulated to reflect processing speed. The other variables of interest are age and either another measure of speed or a measure of cognitive functioning. For example, consider a hierarchical regression analysis in which a measure of speed in task Y is used as the criterion variable and a measure of speed in task X is used as the control variable. If scores from task X are entered in the regression equation prior to age, then the increment R^2 associated with age refers to the amount of age-related variance in performance on speeded task Y that is independent of the variance associated with speeded performance on task X. An indirect estimate of the relative contribution of the construct indexed by speeded performance on task X can therefore be obtained by contrasting the age-related variance in performance on task Y when age is the only variable in the regression equation with the age-related variance in performance on task Y after the variance in performance on task X is controlled. If the age-related variance in performance on task Y is reduced substantially by controlling for performance on task X, this suggests that performance on the two tasks is tapping a common, age-related construct.

Studies with older adults..

One application of the method of statistical control with older adults (Salthouse, 1992b) focused on the Digit Symbol Substitution Test from the Wechsler Adult Intelligence Scale (Wechsler, 1981) as one speed measure, and the average of the scores in two perceptual comparison tests (Letter Comparison and Pattern Comparison) as the other speed measure. Relevant data were available from a total of

910 adults between 18 and 84 years of age. Hierarchical multiple regression analyses were used to determine the amount of age-related variance in the Digit Symbol measure before and after removing the variance associated with the composite perceptual comparison speed measure. The increment in R^2 associated with age in the prediction of Digit Symbol performance was 0.273 before controlling the variance in perceptual comparison speed, but was only 0.009 after partialling out the variance in the measure of perceptual comparison speed. Although this residual age-related variance was still significantly greater than zero with a sample size of 910, the magnitude of the attenuation indicates that approximately 97% (i.e., $[0.273 - 0.009]/0.273 = 0.967$) of the age-related variance in the Digit Symbol measure was shared with the age-related variance in the perceptual comparison speed measures. (Very similar results were reported in a later study by Salthouse (1993c).)

Studies of children and adolescents..

As is the case with older adults, analyses using the method of statistical control reveal a substantial general influence on the development of processing speed. In Kail (1992, Study 1), for example, 9-year-olds and adults were administered the Coding Task of the Wechsler Intelligence Scale for Children. In this task, as in the WAIS Digit Symbol Substitution Task, a code appears at the top of the page; the rest of the page depicts symbols, to which the subject is to respond with the correct code from the top of the page. Subjects were also administered two perceptual speed tasks (Number Comparison and Identical Pictures). Performance on these tasks was averaged. Age accounted for 66.1 percent of the variance before controlling the variance in perceptual speed, but only 5.8 percent after partialling out the variance associated with perceptual speed. The residual age-related variance was significant, but the 91 percent attenuation of age-related variance (i.e., $[0.661 - 0.058]/0.661 = 0.912$) indicates considerable common variance in the Coding and perceptual speed measures.

These findings are quite common. Table 1 summarizes the results of several analyses using the statistical control procedure with different criterion measures of

Table 1
R^2 associated with age in the prediction of task performance before and after statistical control of a measure of processing speed

Criterion	Sample size	R^2 for age alone	R^2 for age after speed	Attenuation
Simple RT	192	0.407	0.089	78.1
Tapping	192	0.309	0.072	76.7
Pegboard	192	0.398	0.096	75.9
Name retrieval	192	0.035	0.015	57.1
Analogical reasoning	112	0.293	0.039	86.7

Note: For all measures but analogical reasoning, analyses were based on data reported in Kail (1991c), in which the subjects ranged in age from 7.5 to 21 years. The data for analogical reasoning were reported in Kail and Park (1992, Expt. 1) and were obtained from 112 8- to 20-year-olds.

cognitive and motor skill. In each case, the result is the same: Age-related differences are attenuated substantially after variance associated with processing speed is eliminated, indicating a substantial role for processing speed in the age-related differences in many domains.

The statistical control procedure is relevant to the issue of general versus specific age-related influences because it provides estimates of the proportions of the age-related variance in one measure that are either in common with, or independent of, the age-related variance in another measure. A claim that the age-related effects on two measures originate because of highly specific influences can therefore be evaluated by determining the proportion of unique, or independent, age-related variance in each measure. In the cases just described, the evidence suggests that the hypothesis of specific influences is not very credible because nearly all of the age-related variance in the Digit Symbol measure is shared with that in the composite perceptual comparison speed measure. However, it is clearly possible that a sizable proportion of the age-related variance in one speed measure could be independent of the age-related variance in another speed measure. If this were to occur, then it would be reasonable to infer that at least some of the age-related influences in these particular measures were specific or unique. (Of course, one could not conclude from a result of this type that there were no common or non-specific age-related influences, but merely that there was little or no evidence of shared influences in that particular combination of measures.)

4. Implications of general developmental change in processing speed

The possibility that a relatively general mechanism may limit speeded performance is significant for our understanding of typical patterns of cognitive development beyond the domain of speeded tasks. Such a mechanism may be implicated whenever rate of stimulation or pacing of responses is controlled externally, or, more generally, whenever processing extends over a period of time such that the products of early processing may have decayed or have been displaced before later processing has been completed.

This view leads to the prediction that the speed with which individuals process information should be related to their performance on tasks that lack obvious speeded components (e.g., self-paced memory or reasoning tasks). That is, slower processing speed means that children or older adults may not be able to complete, in the time available, all of the processing necessary for satisfactory performance. Moreover, if much of the age-related variation in the accuracy or quality of performance is attributable to changes with age in the speed with which many types of information can be processed, then statistical control of the variance in an index of processing speed should greatly reduce the amount of age-related variance in measures of performance accuracy or quality. For example, many kinds of higher-order processing such as integration or abstraction are dependent on the simultaneous availability of several sources of information, and if the rate of processing is slow, then not all of the relevant information may be available when needed. An implication of this interpretation is that statistical control of an index of the hypothesized global processing speed should reduce the magnitude of the age-related differences in many measures of higher-order cognitive functioning. This prediction has received impressive support in several recent studies involving comparisons of adults of different ages (e.g., Hertzog, 1989; Salthouse, 1991a, 1992a, 1993c, 1994; Salthouse and Babcock, 1991).

An illustration of the type of results that have been obtained from the statistical control procedure can be provided by summarizing studies in which performance on matrix reasoning tests such as the Raven's Progressive Matrices Test served as the criterion cognitive measure. This test consists of the presentation of a 3 × 3 matrix containing geometric patterns in all cells except the one in the bottom right. The task for the subject is to inspect the matrix, and then select the alternative that provides the best completion of the missing cell in the matrix. Performance on this test is sometimes considered to reflect the essence of intelligence (e.g., Carpenter et al., 1990; Jensen, 1982).

Variants of this test, along with tasks designed to assess perceptual speed, have been administered in recent studies to children and adolescents as well as to samples of adults of different ages. Relevant results from multiple regression analyses conducted on the data from these studies are presented in Table 2. Values in the column labeled "R^2 for Age Alone" indicate the proportion of variance in the measure of matrix reasoning performance associated with age. In all cases the values are substantial, corresponding to correlations of between about 0.4 and 0.6. These results confirm the findings of many earlier studies indicating that performance on tests like Raven's matrix reasoning measure increases with age during childhood and adolescence and then decreases during adulthood (e.g., Salthouse, 1991b). Of greater interest in this context are the values in the next column, representing the proportion of age-associated variance remaining after

Table 2

R^2 associated with age in the prediction of Matrix Reasoning performance before and after statistical control of a measure of processing speed

Study	Ages	R^2 for age alone	R^2 for age after speed	Attenuation
Paper and Pencil Tests				
Salthouse (1993b, Exp. 1)	20–80	0.322	0.056	82.6
Babcock (1992)	21–83	0.212	0.035	83.5
Computer-administered tests				
Kail and Park (1992, Exp. 1)	8–20	0.274	0.018	93.4
Salthouse (1993b, Exp. 2)	20, 62			
Successive presentation		0.347	0.062	82.1
Simultaneous presentation		0.228	0.021	90.8
Salthouse (1993b, Exp. 3)	20, 61	0.375	0.111	70.4
Salthouse (1994, Exp. 1)	18–84	0.149	0.015	89.9

eliminating the variance in the measures of perceptual speed. Notice that these values are all much smaller than those in the third column. The numbers in the last column indicate the percentage by which the variance associated with age alone was attenuated after control of perceptual speed, and hence can be interpreted as estimates of the importance of speed in the age-related differences in this task. The percentage attenuation values range from about 70% to 90%, indicating that processing speed, as reflected in the perceptual speed measures, plays an important role in the age-related differences in this particular test.

One relatively uninteresting explanation for the relation between the speed measures and performance on the matrix reasoning test is that the matrix reasoning test is often administered with relatively short time limits (e.g., 20 minutes), and consequently the relation might simply reflect the fact that many subjects do not even attempt the later items in the test. Although this interpretation could apply in some of the statistical control studies (see Table 2, paper and pencil tests), it is not plausible for the studies in which the tests were administered on computers and the measure of performance was decision accuracy because subjects were allowed as much time as needed to respond (Table 2, computer-administered tests). Inspection of the entries in the bottom of Table 2 reveals that the percentage attenuation of the age-related variance was also very large when there were no external time constraints during the task, and performance was represented solely in terms of the accuracy of the decisions.

A number of studies have also been conducted in which attempts have been made to identify the specific processes by which speed mediates the relations between age and cognition. An assumption underlying our interpretation of this research is that even when it is possible to identify measures of processing time that are specific to particular tasks, those measures are likely to share considerable age-related variance with more general or global measures of processing speed. This perspective is illustrated in Fig. 5. Age-related changes in global processing speed (path 1) have been documented throughout this article. We assume that these changes sometimes affect cognitive performance directly (path 5) and some-

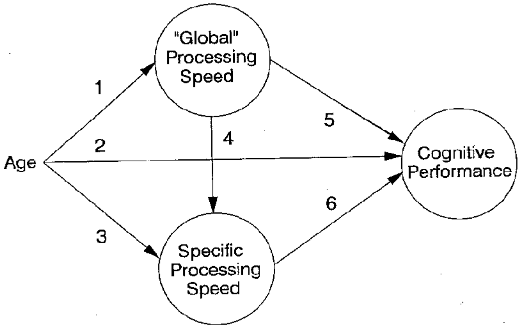

Fig. 5. A model showing possible relations among age, global processing speed, specific processing speeds, and cognitive performance.

times do so indirectly, by influencing speeds of particular processes (paths 4 and 6). These latter speeds also typically change with age (path 3), and may reflect age-related experience in particular domains. Finally, this conceptual framework will certainly be insufficient to explain age-related change in all domains; the strength of the link between age and performance (path 2) provides an indicator of the extent to which other age-related explanatory variables need to be added to the framework.

One area in which the general conceptual framework represented by Fig. 5 has been investigated is memory, because of the presumed importance of articulation rate or rehearsal speed to memory performance. According to the articulatory loop hypothesis (e.g., Baddeley, 1986; Hitch and Halliday, 1983), working memory includes a central executive and an articulatory loop used to store phonological information. Information is lost rapidly from the articulatory loop but can be refreshed through rehearsal. Here, rate of rehearsal determines the amount of information that can be refreshed per unit of time. If information is lost from the articulatory loop at a rate that is constant with age but rehearsal becomes more rapid with increased age during childhood, then rehearsal rate should predict recall, a result obtained frequently (e.g., Hulme et. al., 1984). For example, Hitch et al. (1989) examined 8- and 11-year-olds' articulation rates and recall for 1-, 2-, and 3-syllable words. At both ages, articulation was slower and recall was less accurate for longer words. More important, however, was the finding that for both ages and all word lengths, recall increased linearly as a function of articulation rate. Thus, short words were remembered more accurately than long words, presumably because they could be refreshed more often during a fixed interval; older children could remember more accurately than younger children because they refreshed words more often during rehearsal.

What was ignored in much of this research, however, is the possibility that age differences in articulation rate may be related to a more global developmental change in processing speed. That is, increased processing speed with advancing age in childhood appears to be associated with more rapid articulation, which, in turn, is associated with more accurate retention. In terms of Fig. 5 the specific measure of speed is articulation rate. Conceivably, the effects of age on memory might be mediated entirely by a path that runs from age to processing speed to articulation rate to memory (paths 1, 4 and 6). However, multiple paths are also possible: Age might have direct effects on the rate of articulation (path 3), in addition to those mediated by processing speed. For example, an age-related increase in word familiarity might lead to more rapid articulation. Moreover, processing speed might have direct effects on memory (path 5) in addition to those mediated by articulation rate: Initial encoding of words might become more rapid, independently contributing to greater recall.

Research by Kail (1992) provides relevant evidence for the childhood segment of the lifespan. Global processing speed, rate of articulation, and memory performance were measured in 9-year-olds and young adults. General processing speed was assessed with paper-and-pencil tests known to load heavily on speed factors in psychometric research; Coding, Number Comparisons, and Identical Pictures. The memory measures – digit span, letter span, and free recall – were chosen because each is known to change with age, and to be sensitive to articulatory loop rehearsal. Articulation rate was measured by timing subjects as they repeated sets of words aloud, as rapidly as possible.

Composite measures were created for the speed and memory tasks. The memory composite included both span tasks and free recall; the speed composite included the three paper-and-pencil tasks. Age was correlated positively with the memory composite (0.61), negatively with the speed composite (−0.78) and negatively with articulation rate (−0.57). Path analyses revealed that coefficients for paths 1, 3, 4, and 6 in Fig. 4 were significantly different from zero. That is, age was linked to the index of relatively general processing speed and to articulation rate, but not to memory. The general speed measure was related to articulation rate, which was related to memory. The path linking general speed to memory approached significance (i.e., $p < 0.10$). In summary, as individuals develop during childhood and adolescence, they gradually are able to execute most cognitive processes more rapidly (path 1). There is an association between general processing speed and the rate at which words are refreshed in the articulatory loop (path 4). In addition, age contributes independently to more rapid rehearsal (path 3). Finally, more rapid rehearsal of words is associated with more accurate recall (path 6).

There have been no analogous studies contrasting adults of different ages in measures of global processing speed, articulation rate, and memory performance, although older adults have been reported to be slower than young adults at rehearsing or articulating verbal items (e.g., Kynette et al., 1990; Salthouse, 1980). A recent study by Salthouse and Coon (1993) employed the same type of reasoning as the Kail (1992) study, but used a measure of stimulus re-ordering time as the estimate of task-specific processing time. The task in this study was to recall, using a computer keyboard, a list of digits or letters either in the original order of presentation, or in a different order corresponding to the numerical sequence (for digits) or to the alphabetic sequence (for letters). The interval between each successive keystroke during recall was monitored to allow an estimate of the additional time required to recall re-ordered lists relative to lists in the original order. Because the instruction about the order of recall was not presented until the beginning of recall, the difference in the two recall times was interpreted as a measure of the duration needed to re-order the items. An estimate of global or general processing speed was obtained from the median response times in two computer-administered versions of the Digit Symbol Substitution test. The results, which were consistent across two independent studies, revealed strong relations for paths 1, 4, and 5 represented in Fig. 5, but weaker relations for the paths labeled 2, 3, and 6.

The framework illustrated in Fig. 5 is also expected to apply if the specific processing speed is derived from manipulations of presentation duration in a memory task. That is, some rates of presentation are so rapid that chance performance is the result, and as the stimuli are presented for longer durations performance will improve until it reaches some asymptotic level. To the extent that

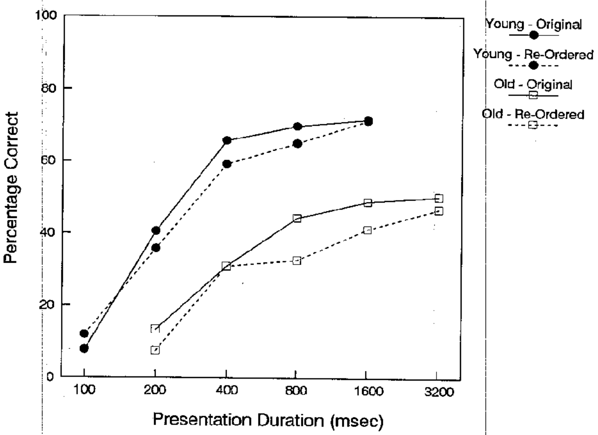

Fig. 6. Change in percentage of correct recall as a function of presentation duration, separately for young and old adults (from Salthouse and Coon, 1993). (Figure used by permission).

processes independent of presentation time contribute to performance, the asymptotic level of performance may vary across individuals and age groups, but the presentation duration needed to achieve some specified level of accuracy can still be considered another measure of task-specific processing speed.

Evidence concerning age-related shifts in the presentation time needed to achieve a specified level of accuracy were found in a recent comparison of young and old adults (Salthouse and Coon, 1993). The results are illustrated in Fig. 6, where it can be seen that increased age is associated with a longer time to achieve the same level of accuracy. Because the participants in the Salthouse and Coon study also performed two tests designed to assess global or general processing speed, it was possible to estimate the strengths of the linkages represented in Fig. 5 with the presentation duration needed to achieve a fixed level of accuracy serving as the specific processing speed measure. As in the analyses with re-ordering time as the specific speed measure, strong relations were found between the general and specific speed measures (path 4), although in these analyses there was also a strong relation between the specific speed measure and memory performance (path 6).

5. Conclusion

We have argued that mental capacity can be conceptualized in terms of the speed with which an individual processes many types of information. Among the evidence and arguments in support of this interpretation are the following. First, the systematic relations between the times of individuals of different ages and the results of statistical control analyses with different measures of speed suggest that there are common influences in the age-related differences in various measures of speed. Second, although the magnitude of the relations between age and speed may vary according to the amount of specific experience, results such as these are not necessarily inconsistent with the existence of a relatively general or common influence on speed. Third, there are strong relations between measures of speed and cognitive performance throughout the lifespan. And fourth, variations in speed appear to contribute to age-related variations in cognition because statistical control of measures of speed has been found to greatly attenuate the age-related variance in measures of cognition.

Although we are suggesting that processing speed plays an important role in the age differences revealed in many types of cognition, we want to emphasize that we are *not* claiming that this is the only factor contributing to age-related change in cognitive functioning across the lifespan; other factors are almost certainly involved. Nevertheless, the available evidence suggests that speed is a major influence on age–cognition relations both in childhood and in adulthood. We therefore suggest that the influence of processing speed be considered in the design and interpretation of research in cognitive development. For example, statistical control procedures could be used to ensure that the age-related variance to be explained by alternative hypotheses is independent of that associated with speed.

If age-related cognitive change is mediated in a fundamental way by change in processing speed, an important developmental issue is the basis of age-related change in processing speed. One approach to this problem has been to attempt to determine if processing speed is simply a byproduct of change in other components of mental capacity. That is, as we noted previously, mental capacity has been construed in terms of limits of space, energy, and speed. Perhaps age-related change in processing speed simply reflects age-related change in the space or energy that is available for information processing. While this is a plausible hypothesis, the experimental evidence is not supportive. Illustrative evidence comes from studies of dual-task performance in which subjects perform a task alone as well as concurrently with another task. If both tasks require limited processing space (or energy), then concurrent performances of the two tasks should be inferior to performance without the secondary task.

Studies of mental rotation illustrate the conventional logic of the dual-task paradigm. In this research, subjects are shown stimuli at different orientations; their task is to decide if the stimulus is a letter or a mirror-image of a letter. RTs increase as a function of the orientation of the stimulus, typically at more rapid rates for children and older adults than for young adults (e.g., Kail, 1991a). This difference is usually interpreted to mean that children and older adults mentally rotate stimuli less rapidly than do younger adults.

In dual-task studies of mental rotation, subjects perform the mental rotation with a concurrent task (e.g., remembering digits) and without the concurrent task. For young adults, the slope of the mental rotation function is the same when the task is performed alone and when performed concurrently with memory tasks (Corballis, 1986). Apparently, adults' rate of mental rotation does not depend upon limited processing space. Furthermore, the same result is obtained with children (Kail, 1991a). By the traditional logic of dual-task experimentation, neither children nor adults tap limited processing space while mentally rotating stimuli. By this interpretation, age differences in the speed of mental rotation cannot reflect a developmental change in limited processing space (or energy) because a manipulation that increases demand on that space has no influence on processing speed.

It should be emphasized that this interpretation depends on the acceptance of several assumptions that are not easily verified. For example, this method assumes that (a) performance is invariant in the mental rotation task under single- and dual-task conditions; (b) performance on the mental rotation and concurrent tasks are based on the same limited resource; (c) performance in the dual-task condition is not limited by structural (i.e., input or output) restrictions; and (d) the critical aspect of processing resources is a relatively stable characteristic or an individual at a given age, and does not vary widely across tasks or situations (Salthouse, 1991b).

These assumptions indicate that results from dual-task studies need not undermine the argument that increased processing speed reflects increased processing space. One could argue that the concurrent tasks do not tap the same resource pool as the mental rotation task. However, this account is problematic when applied to the findings of a common rate of developmental change across tasks. To explain these results, it would be necessary to assume further that the distinct resource pools all develop at a common rate.

An alternative approach is to take processing speed as a cognitive primitive. That is, speed of information processing may be a fundamental part of the architecture of the developing cognitive system, one that is unlikely to be explained in terms of other cognitive processes. In this regard, processing speed may be analogous to the operating speed of the central processing unit (CPU) of a microcomputer. This speed is, for all practical purposes, fixed for a given CPU, and, consequently, is simply considered to be a part of the architecture of the computer in which it is installed. Differences between CPUs in rate of processing are explained at a lower level of analysis, in terms of the complexities of the electronic circuitry (e.g., more transistors in a faster CPU).

The suggestion that processing speed be considered a fundamental parameter of the cognitive system is made more plausible by two facts. The first is that extant cognitive theories typically include a temporal parameter that could be fixed by the assumption that processing speed is a primitive. The second is that we can readily identify factors at a lower level of analysis that might be responsible for age-related change in processing speed.

Consider, first, the nature of the temporal parameter that would be fixed. In cognitive theories that are based on a network metaphor, processing is described in terms of activation that spreads through an associative network. The network's organization include many nodes with interconnecting links. Networks are thought to be analogous to brain processes and neural networks, but at a somewhat a higher level of abstraction that fails to approach the complexity of the human nervous system.

Typically, a limited number of nodes in the network can be active at any time and such activation is said to spread via links to adjacent nodes. In this framework, processing speed would correspond to the rate of propagation from one node to another. Indeed, changing this parameter yields systemwide differences that resemble those associated with development and aging (Salthouse, 1988a).

An alternative to network models are cognitive theories based on production systems. The essential unit in this approach is a *production*, which is simply a condition–action rule of the form

> IF the goal is to add $m+n$ THEN extend m fingers on one hand, extend n fingers on the other, count the fingers, and say the result.

Theories based on production systems include a limited capacity working memory used to store data elements (e.g., goal = add $3+5$). Cognition entails cycles of activity in which the data elements in working memory are compared with the conditions of productions stored in long-term memory. When a production whose conditions match data element is recognized, that production is executed, typically modifying the data elements in working memory. This recognition–act cycle occurs repeatedly and is postulated to be fundamental to all cognition (Klahr, 1989). Obviously, the speed with which cycles are completed would be a basic system parameter that might correspond to processing speed.

These examples illustrate that, within extant cognitive theories, it is quite plausible to posit a systemwide speed parameter. Neither example, however, provides clues as to how such a parameter might change over time. Here a lower level of analysis is needed. That is, to explain changes in the speed of elementary cognitive processes, in which the time scale is on the order of 10–100 milliseconds, we need to move to the neural level, where the speed of operations may range from 100 microseconds to 1 milliseconds (Newell, 1989). A number of neural mechanisms might account for the age-related changes observed at the cognitive level; we will simply cite a few illustrative possibilities. During childhood and adolescence, there are age-related changes in the number of transient connections in the central nervous system (e.g., Huttenlocher, 1979) as well as age-related increases in myelinization (e.g., Yakovlev and Lecours, 1967). Among older adults, pertinent changes would be more "neural noise" due to weakened inhibitory circuitry (Welford, 1965) as well as decreased levels of dopamine, acetylcholine and other neurotransmitters (Rogers and Bloom, 1985). These neural mechanisms act at different levels – some within individual neurons and others with entire neural circuits – but the result in both cases would be slowing of all cognitive processes.

These arguments only help to establish the plausibility of processing speed as a fundamental component of the architecture of human cognition. Assessing the reality of these conjectures will require further investigation. And, while such admonitions for "more research" are commonplace, exploration of processing speed would seem to be particularly fruitful because processing speed is an unusual construct in that it may be linked to explicit changes in neural structure and functioning on the one hand and to higher-order mental processes like reasoning and abstraction on the other. As such, processing speed may well provide the cornerstone for integrative theories in the cognitive and developmental sciences.

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References

Anderson, J.R., 1983. The architecture of cognition. Cambridge, MA: Harvard University Press.

Babcock, R.L., 1992. Analysis of adult age differences on the Raven's Advanced Progressive Matrices Test. Ph.D. Dissertation, Georgia Institute of Technology.

Baddeley, A., 1986. Working memory. Oxford: Clarendon Press.

Bashore, T.R. A. Osman and E.F. Heffley, 1989. Mental slowing in elderly persons: A cognitive psychophysiological analysis. Psychology and Aging 4, 235–244.

Birren, J.E., 1974. Translations in gerontology – From lab to life: Psychophysiology and speed of response. American Psychologist 29, 808–815.

Bosman, E.A., 1993. Age-related differences in the motoric aspects of transcription typing skill. Psychology and Aging 8, 87–102.

Carpenter, P.A., M.A. Just and P. Shell, 1990. What one intelligence test measures: A theoretical account of the processing in the Raven Progressive Matrices Test. Psychological Review 97, 404–431.

Cerella, J., 1985. Information processing rate in the elderly. Psychological Bulletin 98, 67–83.

Cerella J., L.W. Poon and D.M. Williams, 1980. 'Age and the complexity hypothesis'. In: L.W. Poon (Ed.), Aging in the 1980s (pp. 332–340). Washington, DC: American Psychological Association.

Chi, M.T.H., 1977. Age differences in the speed of processing: A critique. Developmental Psychology 13, 543–544.

Chi, M.T.H. and S.J. Ceci, 1987. 'Content knowledge: Its role, representation and restructuring in memory development' In: H.W. Reese (Ed.), Advances in child development and behavior, Vol. 17 (pp. 91–142). New York: Academic Press.

Corballis, M.C., 1986. Is mental rotation controlled or automatic? Memory & Cognition 14, 124–128.

Hale, S. 1990. A global developmental trend in cognitive processing speed in children. Child Development 61, 653–663.

Hertzog, C., 1989. Influences of cognitive slowing on age differences in intelligence. Developmental Psychology 25, 636–651.

Hitch, G.J. and M.S. Halliday, 1983. Working memory in children. Philosophical Transactions of the Royal Society London B 302, 325–340.

Hitch, G.J., M.S. Halliday and J.E. Littler, 1989. Item identification time and rehearsal rate as predictors of memory span in children. The Quarterly Journal of Experimental Psychology 41A, 321–337.

Hulme, C., N. Thomson, C. Muir and A. Lawrence, 1984. Speech rate and the development of short-term memory span. Journal of Experimental Child Psychology 38, 241–253.

Huttenlocher, P.R., 1979. Synaptic density in human frontal cortex – Developmental changes and effects of aging. Brain Research 163, 195–205.

Jensen, A.R., 1982. 'The chronometry of intelligence'. In: R.J. Sternberg (Ed.), Advances in the psychology of human intelligence, Vol. I (pp. 255–310). Hillsdale, NJ: Erlbaum.

Kail, R., 1991a. Controlled and automatic processing during mental rotation. Journal of Experimental Child Psychology 51, 337–347.

Kail, R., 1991b. Developmental change in speed of processing during childhood and adolescence. Psychological Bulletin 109, 490–501.

Kail, R., 1991c. Processing time declines exponentially during childhood and adolescence. Developmental Psychology 27, 259–266.

Kail, R., 1992. Processing speed, speech rate, and memory. Developmental Psychology 28, 899–904.

Kail, R., 1993. Processing time changes globally at an exponential rate during childhood and adolescence. Journal of Experimental Child Psychology 56, 254–265.

Kail, R. and Y. Park, 1992. Global developmental change in processing time. Merrill-Palmer Quarterly 38, 525–541.

Klahr, D., 1989. Information-processing approaches. Annals of Child Development 6, 133–185.

Kynette, D., S. Kemper, S. Norman and H. Cheung, 1990. Adults' word recall and word repetition. Experimental Aging Research 16, 117–121.

LaRiviere, J.E. and E. Simonson, 1965. The effect of age and occupation on speed of writing. Journal of Gerontology 20, 415–416.

Light, L. and D. Burke, 1988. 'Patterns of language and memory in old age'. In: L.L. Light and D.M. Burke (Eds.), Language, memory, and aging (pp. 244–271). New York: Cambridge University Press.

Logan, G.D., 1988. Toward an instance theory of automatization. Psychological Review 95, 492–527.

Myerson, J., S. Hale, D. Wagstaff, L.W. Poon and G.W. Smith, 1991. The information loss model: A mathematical theory of age-related cognitive slowing. Psychological Review 97fs, 475–487.

Newell, A., 1989. 'Putting it all together'. In: D. Klahr and K. Kotovsky (Eds.), Complex information processing. Hillsdale, NJ: Erlbaum.

Pascual-Leone, J., 1970. A mathematical model for the transition rule in Piaget's developmental stages. Acta Psychologica 32, 301–345.

Roediger, H.L., 1980. Memory metaphors in cognitive psychology. Memory & Cognition 8, 231–246.

Rogers, J. and F.E. Bloom, 1985. 'Neurotransmitter metabolism and function in the aging central nervous system'. In: C.E. Finch and E.L. Schneider (Eds.), Handbook of the biology of aging (2nd ed., pp. 645–691. New York: Van Nostrand Reinhold.

Roth, C., 1983. Factors affecting developmental changes in the speed of processing. Journal of Experimental Child Psychology 35, 509–528.

Salthouse, T.A., 1980. 'Age and memory: Strategies for localizing the loss'. In: L.W. Poon, J.L. Fozard, L. Cermak, D. Arenberg and L.W. Thompson (Eds.), New directions in memory and aging. Hillsdale, NJ: Erlbaum.

Salthouse, T.A., 1984. Effects of age and skill in typing. Journal of Experimental Psychology: General 113, 345–371.

Salthouse, T.A., 1985a. A theory of cognitive aging. Amsterdam: North-Holland.

Salthouse, T.A., 1985b. 'Speed of behavior and its implications for cognition'. In: J.E. Birren and K.W. Schaie (Eds.), Handbook of the psychology of aging (2nd ed.). New York: Van Nostrand Reinhold.

Salthouse, T.A., 1988a. Initiating the formalization of theories of cognitive aging. Psychology and Aging 3, 1–16.

Salthouse, T.A., 1988b. 'The role of processing resources in cognitive aging'. In: M.L. Howe and C.J. Brainerd (Eds.), Cognitive development in adulthood. New York: Springer-Verlag.

Salthouse, T.A., 1988c. Resource-reduction interpretations of cognitive aging. Developmental Review 8, 238–272.

Salthouse, T.A., 1991a. Mediation of adult age differences in cognition by reductions in working memory and speed of processing. Psychological Science 2, 179–183.

Salthouse, T.A., 1991b. Theoretical perspectives on cognitive aging. Hillsdale, NJ: Erlbaum.

Salthouse, T.A., 1992a. Mechanisms of age–cognition relations in adulthood. Hillsdale, NJ: Erlbaum.

Salthouse, T.A., 1992b. What do adult age differences in the Digit Symbol Substitution Test reflect? Journal of Gerontology: Psychological Sciences 47, P121–P128.

Salthouse, T.A., 1993a. Speed and knowledge as determinants of adult age differences in verbal tasks. Journal of Gerontology: Psychological Sciences 48, P29–P36.

Salthouse, T.A., 1993b. Influence of working memory on adult age differences in matrix reasoning. British Journal of Psychology 84, 171–199.

Salthouse, T.A., 1993c. Speed mediation of adult age differences in cognition. Developmental Psychology.

Salthouse, T.A., 1994. The nature of the influence of speed on adult age differences in cognition. Developmental Psychology 30, 240–259.

Salthouse, T.A. and R.L. Babcock, 1991. Decomposing adult age differences in working memory. Developmental Psychology 27, 763–776.

Salthouse, T.A. and V.E. Coon, 1993. Influence of task-specific processing speed on age differences in memory. Journal of Gerontology: Psychological Sciences 48, 245–255.

Salthouse, T.A. and R. Kail, 1983. 'Memory development throughout the lifespan: The role of processing rate'. In: P.B. Baltes and O.G. Brin (Eds.), Life-span development and behavior, Vol. 5 (pp. 89–116). New York: Academic Press.

Salthouse, T.A. and J.S. Saults, 1987. Multiple spans in transcription typing. Journal of Applied Psychology 22, 187–196.

Smith, K.U. and D. Greene, 1962. Scientific motion study and aging processes in performance. Ergonomics 5, 155–164.

Sorenson, H., 1933. Adult abilities. Minneapolis, MN: University of Minnesota Press.

Wechsler, D.A., 1981. Wechsler adult intelligence scale – revised. New York: Psychological Corporation.

Welford, A.T., 1958. Ageing and human skill. London: Oxford University Press.

Welford, A.T., 1965. 'Performance, biological mechanisms, and age: A theoretical sketch'. In: A.T. Welford and J.E. Birren (Eds.), Behavior, aging, and the nervous system. Springfield, IL: Charles C. Thomas.

Woodcock, R.W. and M.B. Johnson, 1989, 1990. Woodcock–Johnson Psycho-Educational Battery – Revised. Allen, TX: DLM Teaching Resources.

Yakovlev, P.I. and A.R. Lecours, 1967. 'The myelogenetic cycles of regional maturation of the brain'. In: A. Minkowski (Ed.), Regional development of the brain in early life. Oxford: Blackwell.