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Aging and measures of processing speed

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Abstract

Many variables have been assumed to reflect speed of processing, and most are strongly related to age in the period of adulthood. One of the primary theoretical questions with respect to aging and speed concerns the relative roles of specific and general age-related effects on particular speed variables. Distinguishing between specific (or unique) and general (or shared) age-related influences on measures of speed has been complicated, in part because the issues are sometimes framed in terms of extreme all-or-none positions, and because few researchers have employed analytical procedures suitable for estimating the relative contributions of each type of influence. However, recent methods focusing on partitioning age-related variance have indicated that large proportions of the age-related effects on individual speed variables are shared with age-related effects on other variables. Although these theoretical ideas and analytical procedures are fairly new, they may be relevant to a variety of psychophysiological or neurobiological variables. © 2000 Elsevier Science B.V. All rights reserved.

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At least six different types of variables have been used to assess the processing speed of an individual, with the particular variables varying according to the research tradition. For example, psychometric researchers have tended to emphasize decision speed and perceptual speed. *Decision speed* is assessed in terms of the time to respond in cognitive tests with moderately complex content. Because not everyone would be able to respond without errors if there were no time limits, these measures are almost certainly affected by the individual's level of relevant cognitive abilities in addition to aspects related to speed. In contrast, *perceptual speed* is

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assessed by the speed of responding (usually on paper-and-pencil tests) with simple content in which everyone would be perfect if there were no time limits. Perceptual speed tasks often involve elementary comparison, search, and substitution operations, with the test score consisting of the number of items correctly completed in the specified time.

Both psychometric and experimental researchers have used variables assessing *psychomotor speed*, typically with relatively simple tasks requiring repetitive finger tapping, or marking or drawing lines in specified locations on a piece of paper. Perhaps the most frequently used speed variable is some form of *reaction time*, such as choice reaction time with visual stimuli and manual keypress responses. *Psychophysical speed* variables have also been investigated, often in the form of decision accuracy with briefly presented visual or auditory stimuli (e.g. inspection time). Finally, psychophysiological researchers have relied on variables postulated to reflect the *time course of internal responses*, such as the latency of particular components of the event-related potential (ERP). A later section of this article focuses on the relations among some of these different types of speed variables, but first the relations of age on the variables, and possible moderators of those relations, will be discussed.

1. Relations to age

Speed variables have been of great interest to researchers concerned with aging because they are frequently found to have moderate to large relations with age across the period of adulthood. To illustrate, a recent meta-analysis of age–speed correlations for perceptual speed and reaction time variables reported in Verhaeghen and Salthouse (1997) revealed that the weighted-average correlation was 0.52. This value corresponds to what Cohen (1988) refers to as a large effect, and thus it is not surprising that significant age differences in speed variables are easily detectable even with small samples.

One means of illustrating the basic phenomenon is with data from two perceptual speed tests in a psychometric test battery (i.e. the Woodcock–Johnson Psycho-Educational Battery) administered to a nationally representative sample of adults between 18 and over 90 years of age (see Salthouse, 1998a). The visual matching test consists of sets of five, one- or two-digit numbers, and the task for the participant is to circle the two numbers within each set that are the same. The cross out test consists of sets of a target pattern and 19 alternative patterns, and the task for the participant is to cross out the alternatives that are identical to the target pattern. Both of these tests are typical of perceptual speed tasks in that the requirements are very simple, and the primary manifestation of individual differences is in terms of speed, as measured by the number of items correctly completed in the allotted time.

Fig. 1 portrays the mean and S.E. by 5-year intervals of the scores on these two tests in standard score units, created by subtracting the sample mean from each individual's score and dividing by S.D. Because the distribution of ages was unequal, with nearly 50% of the participants under the age of 40, the age relations in this sample are somewhat distorted when the scores are expressed in standardized units. Nevertheless, it can be seen that the total difference from age 25 to 75 is almost two S.D. If this cross-sectional difference is reflected in the same magnitude of age-related change within individuals, a person performing at the 64th percentile of the population at age 25 may perform at only the 36th percentile by age 75.

The phenomenon of age-related slowing can also be illustrated with reaction time data. Fig. 2 contains a scatter plot of median reaction times from a digit symbol substitution reaction time task performed by a sample of 383 adults described in Salthouse (1998b). This task involves the presentation of a code table containing pairs of digits and symbols at the top of the computer screen, and a series of probe pairs in the middle of the screen. The respondent is to press one key (/) if the digit–symbol pair in the probe matches the code table, and to press another key (Z) if they do not.

It is apparent in this figure that both the median, and the variability across individuals, increases with advancing age. However, it should be noted that age-related increases in variability are not always found in speed measures because much smaller trends are frequently apparent with scores on paper-and-pencil tests, which are usually expressed in terms of items completed per unit time (e.g. Verhaeghen and Salthouse, 1997; also observe the nearly constant S.E. bars across age groups in the data in Fig. 1).

Some non-linear relations between age and measures of speed have been reported, but they are typically small relative to the linear relations (e.g. Earles and

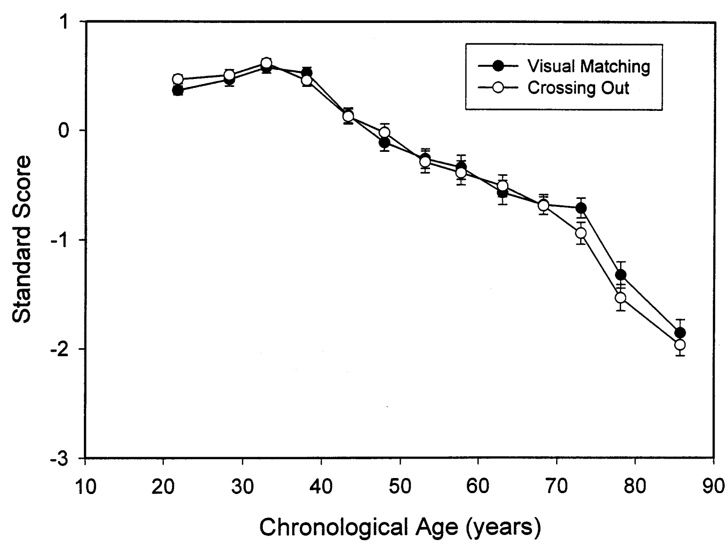

Fig. 1. Mean values in standard score units in two paper-and-pencil perceptual speed tests as a function of age. Bars around each point are S.E. Data from the normative sample ($N = 1580$) for the Woodcock–Johnson psycho-educational battery.

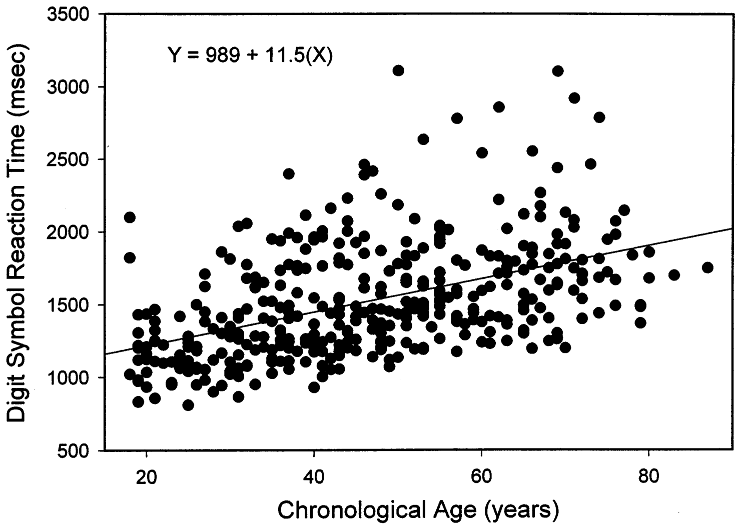

Fig. 2. Median reaction time in the digit–symbol substitution task as a function of age. Each point corresponds to the value of a different individual, and the line represents the best-fitting regression equation for the data. Data from Salthouse (1998a,b).

Salthouse, 1995; Earles et al., 1997; Salthouse, 1996a; Verhaeghen and Salthouse, 1997). To illustrate, in the data from the Woodcock–Johnson tests summarized in Fig. 1, the proportions of variance (R^2) associated with each trend for the visual matching variable were, linear, 0.316; quadratic, 0.040; and cubic, 0.002; and the proportions for the cross out variable were, linear, 0.396; quadratic, 0.038; and cubic, 0.001 (see Salthouse, 1998a). Finally, age-related slowing is also evident in longitudinal age comparisons (e.g. Schaie, 1989; Huppert and Whittington, 1993; Fozard et al., 1994), and Schaie (1989) has even suggested that the age-related effects in perceptual speed measures may be greater in longitudinal comparisons than in cross-sectional contrasts.

Results such as those just described have established that speed variables are among the biological and behavioral variables with the strongest relations to age. In part because of these strong age relations, they have been hypothesized to be especially informative about the nature of age-related effects in higher-level aspects of cognition, a topic that will be discussed in a later section.

2. Moderators of age relations on speed

What factors alter the relations of age on measures of speed, in the sense of leading to interactions with age? Because of space limitations only three potential moderators will be considered here, although many more could obviously be examined (for additional discussion of moderators of age-related slowing see reviews by Salthouse (1985), Cerella (1990), Bashore (1993), Birren and Fisher (1995)).

Health status has received the greatest interest as a potential moderator of age–speed relations because increased age is associated with a variety of health problems, and it has seemed plausible that level of health status might affect an individual's processing speed. A considerable number of studies have investigated the role of health status on age differences in speed, with much of the relevant literature cited in recent articles by Earles and Salthouse (1995), Earles et al. (1997) and Salthouse and Earles (1996). Health status has been assessed with a variety of different methods, but the most popular method because of its convenience has been to rely on self-reports. Reliance on an individual's own assessment of his or her health is obviously very crude, but even rigorous physical examinations may not be optimal because health status is clearly multidimensional, and there is still uncertainty with respect to which health-related aspects might be most important as determinants of speed.

Many studies have found small main effects of health on measures of speed, in the direction of healthier individuals performing at faster levels than less healthy individuals. However, there are seldom any interactions with age that would suggest that healthy adults are immune from or less susceptible to age-related declines in speed.

Several researchers have conducted analyses investigating possible mediational effects of health by comparing the magnitude of age-related effects on measures of speed before and after statistical control of measures of health status. For example, Earles and Salthouse (1995) found that statistical control of self-ratings of health reduced the age-related effects in various measures of speed by approximately 20%. In similar analyses on independent data, Earles et al. (1997) found that measures of self-rated health were associated with about 15% of the age-related variance in measures of perceptual speed. Finally, Salthouse and Earles (1996) focused on reaction time measures of speed, and found that age was associated with 29% of the variance in the speed measures without considering health, and this value was only reduced to 28% after control of health status. Results such as these suggest that health-related factors have relatively small influences on the relations between age and speed. Although it is true that the range of health was probably restricted in most of the convenience samples examined thus far; it is important to note that the finding of moderate to large age relations on measures of speed in samples of individuals who report themselves to be in good to excellent health implies that poor health is not the primary factor contributing to adult age differences in speed.

Another potential moderator of the relations between age and speed is amount of experience or practice with the tasks. An early study by Murrell (1970) suggested that age differences in reaction time might be eliminated with extensive practice, but this report should probably be considered a case study rather than a true age-comparative study because there was only one 'older' (i.e. age 58) adult and two 'young controls' (i.e. adults in their 20s). Later research with larger samples of participants has revealed that although there are certain main effects of practice, in the direction of everyone becoming faster with additional practice, little or no interactions of age and practice have been apparent, with the possible exception of the initial trials in which older adults sometimes improve to a somewhat greater extent than young adults. This same general pattern has been reported across tasks ranging from the time in various types of memory and visual search tasks (Salthouse and Somberg, 1982; Fisk and Rogers, 1991; Rogers et al., 1994; Hertzog et al., 1996) to the time to perform mental arithmetic (Charness and Campbell, 1988).

A third category of potential moderators of the relations between age and speed consists of various task characteristics. As an example, there have been several suggestions that the degree of slowing is greater for tasks involving spatial information than for those involving verbal information (Tomer and Cunningham, 1993; Babcock et al., 1997). Hale et al. have also reported results leading them to propose that the amount of age-related slowing is less for tasks involving lexical information than for tasks involving non-lexical information (Lima et al., 1991; Hale and Myerson, 1996; Hale et al., 1995). Although their results do suggest that the magnitude of slowing varies across tasks, some ambiguity remains with respect to the classification of particular tasks (e.g. should a single letter, or a random string of letters, be considered lexical?), and whether the tasks being compared are equivalent in processing requirements and differ only with respect to the type of information being processed.

Another type of speeded task in which smaller than expected age relations have been reported are those involving various forms of arithmetic. These findings are interesting because arithmetic operations can usually be readily distinguished from other types of operations, and there are reports not just of smaller age differences, but either no age differences or even differences in the direction of better performance of older adults than young adults. The empirical pattern with respect to age differences in arithmetic tasks varies according to the type of task and comparison. For example, although there are some reports of small to non-existent age differences in paper-and-pencil tests (Geary and Wiley, 1991; Geary et al., 1996; Schaie, 1996), nearly all studies with reaction time tasks have found that young adults respond faster than older adults (Charness and Campbell, 1988; Geary and Wiley, 1991; Geary et al., 1993; Rogers and Fisk, 1991; Allen et al., 1997; Salthouse and Kersten, 1993; Salthouse and Coon, 1994; Siegler and Lemaire, 1997). However, a number of studies have reported no interactions of age with manipulations, such as answer magnitude (Geary and Wiley, 1991; Geary et al., 1993; Allen et al., 1992, 1997) or close versus far alternative to the correct answer (Allen et al., 1997), and the authors have concluded that young and old adults do not differ in the speed of certain operations. Furthermore, Geary et al. (1993) actually found an interaction in the direction of a smaller increase in subtraction for older adults when a borrow operation was required, which led to an inference that older adults were faster in executing the borrowing operation than were young adults (although this latter finding is very intriguing, unfortunately it was not replicated in a subsequent study by Salthouse and Coon, 1994).

3. Interpretation of interactions

As just noted, the lack of significant interactions in studies examining the effects of various manipulations in age-comparative studies has frequently been interpreted as evidence for the absence of specific or unique age-related influences on the critical process. However, this interpretation has been questioned by Salthouse and Coon (1994), who suggested that from an individual differences perspective a conclusion that a separate process is involved requires evidence that the measure presumed to reflect the added process had at least a moderate amount of variance that was independent of the variance in the original measure assumed to reflect the operation of all other processes involved in the task. In other words, if the correlation between the two scores was very high, then there may be little basis for concluding that the measures actually reflect processes that are distinct with respect to the influences related to individual differences. These authors proposed that the most convincing evidence for an inference of a specific or unique age-related effect requires a demonstration that each of the variables being compared had enough independent individual differences variance to merit a claim that they could reflect somewhat distinct processes. Because this condition has seldom been established in past research, Salthouse and Coon (1994) suggested that researchers need to be cautious in interpreting null results involving tests of interactions between age and various manipulations.

There is also evidence that the age-related effects on purportedly specific measures may not be as distinct from the effects on general measures as is sometimes assumed. For example, Salthouse and Earles (1996) found that an average of over 40% of the age-related variance in presumably specific measures, such as a difference score or the slope of a regression equation relating reaction time to a manipulated variable, was shared with non-specific measures such as time in the simplest condition or the intercept of the regression equation. Similar findings with independent data were also reported by Salthouse (1996b).

This shared variance occurs because the various speed measures are not independent, but instead have moderate to large correlations with one another. Therefore, when one of the variables is statistically controlled, much of the individual difference variance in the other variable will be reduced. The correlations can also be negative, as has sometimes been found with the slope and intercept parameters from the Sternberg memory paradigm, where a high intercept may be associated with a low slope, and vice versa (Salthouse and Earles, 1996). (One way in which this negative relation could occur is if some research participants adopt an 'undifferentiated set' in which responses in all conditions are relatively slow, such that the intercept of the regression equation is large and the slope is small.) In cases such as this, statistical control of one variable (e.g. the intercept) will often result in an increase in the magnitude of the age differences in the other variable (e.g. the slope).

The issues and associated empirical findings just discussed raise questions about the meaningfulness of quantitative estimates of the age relations on what are postulated to be the measures of specific cognitive processes when those measures are analyzed as interactions in analyses of variance or are examined in separate sets of analyses. A preferable procedure is to conduct analyses which include both the nonspecific or general measures in addition to the specific measures of primary interest, to allow unique age-related effects on each measure to be determined. Some analytical methods that might be used for this purpose are described in the following section.

4. Analytical methods

Many speculations have been advanced about the factors contributing to adult age differences in particular speed variables. For example, one of the issues that has been debated with respect to certain reaction time tasks is whether the age differences are primarily attributable to processes associated with stimulus encoding, or to processes associated with response, selection and execution. Although this micro level of analysis is useful, it is also important to examine the phenomenon from a broader, macro, perspective to more precisely specify exactly what needs to be explained. One way of conceptualizing the micro/macro distinction is as a contrast between whether we should be attempting to account for age-related effects presumed to be specific to a particular variable or process (micro), or for age-related effects that are shared across a wide range of variables or processes (macro)?

Because such a large number of speed, and other cognitive, variables have been found to be related to age, a key question is whether each variable has separate and independent age-related effects, or whether at least some of the effects are shared, or in common, with other variables. In order to provide meaningful answers to this question, analytical methods are needed to evaluate the degree to which age-related influences are shared across several variables, or are unique to a particular variable. Multiple variables are needed for this purpose because when the focus is restricted to a single variable, as has often been the case in past research on aging, there is no possibility of examining the relative contributions of different types of influences. It is important to note that the multivariate analytical methods being advocated do not assume that broad or general influences are dominant, or even that they necessarily exist. Instead, they merely provide a means of allowing those types of influences to be investigated, instead of simply being ignored.

A variety of different multivariate analytical methods can be used, and each involves somewhat different sets of assumptions. However, outcomes from most of the analytical procedures seem to converge on the conclusion that large proportions of the age-related effects on individual speed variables are not independent of the effects on other variables. That is, the results of these analyses indicate that the relations of age on a particular speed variable do not occur in isolation, but instead in the context of relations of age on many variables.

Several analytical methods are relevant when all of the variables in the analyses are similar, and are assessed in the same measurement scale. One example of this type is the method of systematic relations, or what are sometimes referred to as

Brinley plots. This analytical method is applicable when the same sets of variables are available from two groups of research participants such that the mean speeds of one group can be plotted against the mean speeds of another group. When the groups consist of samples of young and old adults, a highly linear relation between the two sets of reaction times is often found, with an intercept close to 0 and a slope that frequently falls in the range 1.4–2.0. These orderly relations have led some researchers to suggest that nearly all of the age differences in speed variables are attributable to the operation of a single slowing factor (Cerella, 1990; Myerson et al., 1994).

This particular analytical technique has been quite controversial because although some researchers have used it to infer that all age-related speed effects are general, other researchers have argued that it is actually a rather crude method for distinguishing between general and specific age-related effects (Cerella, 1994; Perfect, 1994; Fisk and Fisher, 1994; Myerson et al., 1994). For example, general age-related effects are often postulated to be reflected in the systematic relation between the speeds of the two groups, but the precision of that relation is determined by the number of individuals contributing to each data point and the number of separate data points included in the analysis, and in many cases the analyses have been based on small samples with a limited number of data points. The method is also controversial because proponents and critics often interpret the results in terms of extreme all-or-none alternatives (e.g. completely general, or completely specific), when it is probably more likely that both types of influences are operating in various degrees.

A variant of this analytical strategy suggested by Madden et al. (1992) involves using the quantitative parameters of the systematic relation as an estimate of the general age-related influences in those variables and with those particular groups of participants, and then testing whether individual variables deviate significantly from the values predicted by the regression equation. The assumption in this technique is that a significant deviation indicates that the variable cannot be accurately predicted by the general relation between the speeds of the two groups, and thus a specific age-related influence can be inferred to be operating for that variable. The power of this type of analysis may be limited because it is dependent on the fit of the systematic relation to the data and on the number of variables included in the analysis, but there are several reports of variables with age differences that were not predictable from the general relation, and for which unique or specific age-related influences were inferred to be operating (Madden et al., 1992; Salthouse and Kersten, 1993).

Exactly how the existence of systematic relations should be interpreted is still unclear. For example, Brinley (1965) and others have found that similar orderly relations are also evident with accuracy variables, and thus the phenomenon of a systematic relation between the mean levels of performance in different groups is not restricted to speed variables. This implies that if the existence of a general speed factor is inferred on the basis of systematic relations among speed variables, then a general accuracy factor would presumably have to be inferred on the basis of systematic relations with accuracy variables. Because it is not obvious how such a general accuracy factor would be interpreted, there is still some ambiguity with respect to what systematic relations truly represent.

Although there is still uncertainty about their interpretation, the existence of systematic relations has led to questions about the meaning of the age differences observed with many speed variables. That is, given an intercept close to 0 and a slope greater than 1.0, interactions of age and various manipulations (usually in the direction of larger effects of the manipulation among older adults) would be expected whenever there are main effects of the manipulations, even when there were actually no specific age-related effects on any variables (Salthouse, 1985; Cerella, 1990). Various attempts have been made to deal with this issue, such as transforming reaction times into logarithms or proportions, but they are not necessarily effective in eliminating the problem if the relation between the times of the two groups is not linear with an intercept of 0. In fact, some researchers have suggested that the relation between the mean times of young and old adults is best characterized by a power or exponential function rather than a linear one (Cerella, 1990; Myerson et al., 1991), and the intercept of the functions has frequently been found to be somewhat less than 0 instead of exactly 0 as assumed when a logarithmic or proportional transformation is imposed.

Another type of analysis is possible when there are many trials within a single task such that the pattern of age-related effects can be examined at different levels of the same variable. To illustrate, analyses could be conducted at various regions within each individual's distribution of reaction times to determine whether the age-related effects are equivalent across different percentiles of the distribution. Analyses of this type are interesting because it is possible that age-related effects are most pronounced at, or perhaps even restricted to, the slowest percentiles of an individual's distribution of reaction times. However, Salthouse (1993) found little support for this hypothesis, and instead observed roughly equivalent age-related effects throughout the entire distribution of reaction times. Those results have recently been replicated and extended by Salthouse (1998b) in analyses of data based on the digit–digit and digit–symbol reaction time tasks from 383 adults. The top panel of Fig. 3 portrays the means across five reaction time percentiles from each individual's distribution of digit–symbol reaction times as a function of age. The greater gap between the 70th and 90th percentiles than between other percentiles indicates that the reaction time distributions were skewed, but it is noteworthy that positive age relations were evident on all percentiles, including those representing the individuals' fastest reaction times. The bottom panel of Fig. 3 contains the age correlations for the measures from this task and for a digit–digit choice reaction time task as a function of successive percentiles in each individual's reaction time distribution.

The two panels of Fig. 3 reveal that although the absolute magnitudes of the age-related differences are somewhat larger at the slower percentiles, the correlations with age are actually weaker for those percentiles than for the faster percentiles. (This is likely attributable to the increase in within-age-group variability from the fastest to the slowest percentiles.) Furthermore, in additional analyses, it was found that if the variability in the measures from the early percentiles was statistically controlled, then there were little or no independent age-related effects on the measures from the late percentiles. The apparent implication is that most of the age-related influences are evident throughout the entire reaction time distribution, and are not simply apparent in the right tail corresponding to the slowest responses (as might be the case if the age-related slowing were primarily attributable to an increase in the frequency or duration of lapses of attention (cf. Salthouse, 1993).

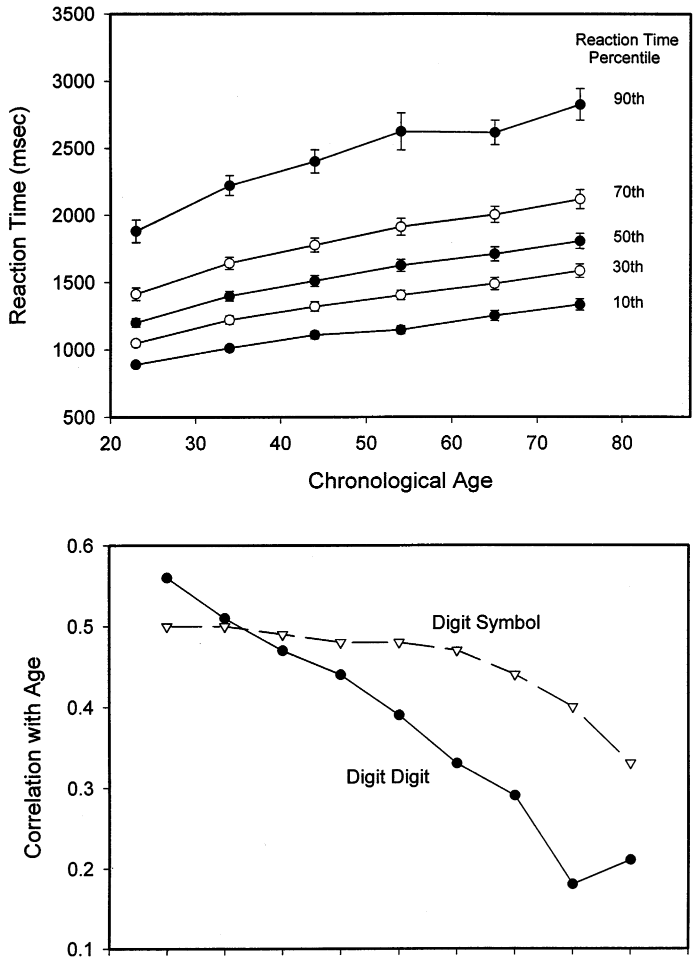

Fig. 3. Mean reaction time at five percentiles of each individual's reaction time distribution (top) and correlations of reaction time with age as a function of percentile of the distribution (bottom). Bars around each point in the top panel are S.E. Data from Salthouse (1998b).

Somewhat different analytical methods are appropriate when the variables being considered are derived from different kinds of tasks, and hence may not all be in the same units of measurement. One of the major questions that can be addressed with these methods is whether it is meaningful to think of speed as a unitary construct, at least when viewed from the perspective of age-related influences. A variety of correlational methods can be used to investigate this issue, but it should be recognized that results from correlational analyses are always somewhat dependent on the other variables included in the analysis. In other words, relatively fine distinctions are possible when many similar variables are included in the analysis (e.g. reaction times with index finger responses might be distinguished from reaction times with responses from other fingers), but the classifications are likely to be much coarser when speed variables are analyzed together with other types of variables, such as those reflecting higher-order cognitive functioning or sensory-motor capabilities. It is therefore important to think carefully about the level of analysis considered to be the most appropriate when interpreting the results from correlational analyses (and indeed, from all types of analyses).

Another important distinction is whether the analyses are conducted before or after considering the influence of age on the variables. With conventional types of analyses, in which age is either ignored, or is examined in terms of its relations with factors derived from the analyses, several distinct speed factors are often found. For example, separate factors corresponding to type of task (e.g. reaction time vs. paper-and-pencil) or type of stimulus material (e.g. verbal vs. spatial) have been reported in studies by White and Cunningham (1987), Tomer and Cunningham (1993), Earles and Salthouse (1995), Babcock et al. (1997). However, the factors in these analyses usually have moderate to large correlations with one another, and most have significant relations to age. It is therefore possible that many of the age-related influences on the factors operate through a higher-order factor that represents the variance common to all factors.

Indeed, somewhat different patterns of results are often found when the analyses are conducted after taking the age-related effects on the variables into account. One approach of this type consists of focusing only on the age-related variance in the variables instead of all of the variance. For example, a special type of correlation coefficient (termed the quasi-partial correlation) has been used to express the relative overlap of age-related variance in two variables (Salthouse, 1996a,b). Another approach involves examining the proportions of unique age-related variance derived from the hierarchical regression analyses. Results from both of these types of analyses suggest that much of the age-related variance in many speed variables is shared rather than being independent. To illustrate, Salthouse (1996b) reported that the median proportion of shared age-related variance ranged from 0.62 to 0.86 across four separate studies with different combinations of speed variables. One way of accounting for this covariation is by postulating the existence of a common or general factor that contributes to each variable, and is negatively associated with increasing age. In fact, in what can be termed shared influence analysis, a single common factor is explicitly specified, and then the age relations on individual variables are examined after taking into consideration the age-related influences operating through the common factor (see Kliegl and Mayr, 1992; McArdle and Prescott, 1992). A typical finding in this type of analysis is that the unique age-related influences on individual variables are few in number and small in magnitude (Salthouse, 1994a, 1996a, 1998a; Verhaeghen and Salthouse, 1997).

Because the preceding descriptions are rather abstract, the different types of analyses will be illustrated with two recent data sets, each involving six speed variables. One data set consists of the same data used in Earles and Salthouse (1995), and was based on a sample of 744 adults between 18 and 87 years of age. The six variables in this data set were, letter comparison, pattern comparison, boxes, digit copying, digit–digit reaction time, and digit–symbol reaction time. The first two variables are fairly typical measures of perceptual speed, the next two variables can be postulated to reflect psychomotor speed because they merely require drawing lines to complete boxes or copying digits, and the last two variables are measures of choice reaction time. The other data set, from an unpublished study, is based on a sample of 58 adults between 18 and 61 years of age. The variables in this set were the letter comparison, pattern comparison, digit–digit reaction time and digit–symbol reaction time variables, and two variables designed to measure the minimum duration needed to achieve a given level of accuracy with respect to the equivalence of a pair of digits or of a digit–symbol pair. That is, in these two psychophysical speed tasks, the stimulus duration was systematically varied to find the minimum time at which a specified level of accuracy was achieved, and then this time served as the measure of speed.

The initial analysis in each data set was an exploratory factor analysis. In the first data set only a single factor emerged with an eigenvalue greater than one. Three separate factors can be forced (as in Earles and Salthouse, 1995) with a confirmatory factor analysis, but the resulting factors all had moderate to strong correlations with one another (i.e. absolute correlations of 0.60, 0.81, and 0.81). Three factors were obtained in the other data set, with the first factor having primary loadings from the letter comparison and pattern comparison variables (both 0.84) as well as the digit–symbol reaction time variable (− 0.78), the second factor having loadings of 0.90 and 0.88 for the two duration threshold variables and all other loadings less than 0.40, and the third factor having loadings of 0.95 for the digit–digit reaction time variable and 0.57 for the digit–symbol reaction time variable with all other loadings below 0.25. The patterns from these two data sets are generally consistent with the results of other studies in that distinct factors, or separate groupings of variables, are sometimes found, and sometimes not found, when the data from speed variables are analyzed without consideration of age.

As noted earlier, an analytical procedure that can be used to investigate the degree to which the age-related influences on different variables are shared is a type of common factor analysis known as shared influence analysis. The basic idea in this procedure is to obtain an estimate of what all variables have in common and then control the age-related effects on that estimate before examining the age-related effects on individual variables. If the variables, and the age relations on them, are all independent, then they should have no common effects, and the direct age-related effects on the variables should be nearly the same magnitude as the total age-related effects (corresponding to the sum of the direct effects and the indirect effects mediated through the common factor). However, to the extent that the variables share variance then they will load on a common factor and at least some of the age-related influences on the variables may be shared with the influences on other variables. By controlling the age-related effects on the common factor when examining age-related effects on individual variables, this method allows the operation of unique age-related influences to be determined. That is, because the common factor in this type of analysis represents the variance shared by all variables, any direct age-related effects on the variable are necessarily independent of the effects mediated through the common factor, and hence can be inferred to correspond to specific or unique age-related effects.

Quantitative estimates of the magnitude of shared age-related influences on each variable can be obtained by deriving estimates of the relations from a structural equation program (such as AMOS, EQS, or LISREL), and then multiplying the coefficient from age to the common factor by the coefficient from the common factor to the individual variable. Fig. 4 contains all of the relevant coefficients for the two illustrative data sets, with the predicted values of the total age-related effects immediately below each variable and the actual correlations with age below the predicted values[1]. Inspection of the figure reveals that the two sets of values are all very close to one another, which implies that nearly all of the age relations on the individual speed variables in these data sets are shared with the other variables. To the extent that the assumptions of this analytical procedure are valid, these results suggest that relatively little of the age-related effects on individual speed variables are independent of the effects on other speed variables. Considerably more research is obviously needed, but the available findings are intriguing in suggesting that explanations for many of the age-related effects on individual speed variables may not lie in processes unique to that specific task, but in more general characteristics that affect a wide range of variables.

5. What do scores on speed variables represent?

Although the question of what speed variables represent appears quite straightforward, it is unlikely to have a simple answer. One reason is that all variables have multiple determinants, and there are probably few theoretical constructs that can be

[1] In addition to comparing the predicted and observed values of the age correlations, the degree to which the models fit the data can be evaluated with a variety of fit statistics. Values of several of them for the model in the top of Fig. 4 are, X^2 ($N = 744$, df = 20) = 314.45; NNFI = 0.87; CFI = 0.88; and standardized RMR = 0.06; and those for the model in the bottom of Fig. 4 are, X^2 ($N = 58$, df = 20) = 39.76; NNFI = 0.78; CFI = 0.79; and standardized RMR = 0.11. However, because these statistics indicate how well the model fits all of the data, including relations among the existing variables that are not represented in the model, they are not particularly informative about how accurately the model accounts for only the age relations on the variables.

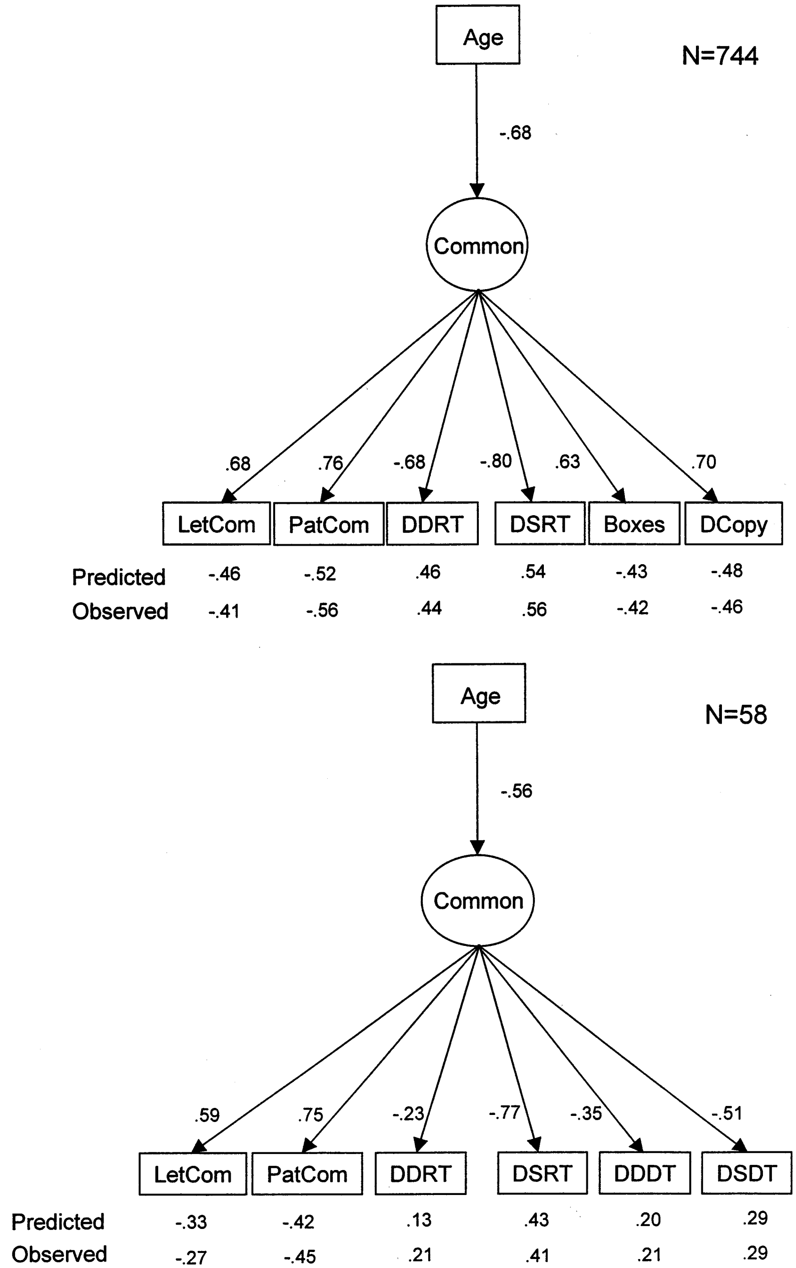

Fig. 4. Illustration of results of shared influence analyses on six speed variables from two different data sets. Numbers adjacent to the arrows are standardized regression coefficients, and numbers in the rows labeled predicted and observed are the estimated and actual correlations between the variable and age. Data in the top panel are from Earles and Salthouse (1995), and those in the bottom panel are from an unpublished study.

completely assessed by a single variable. That is, it is probably the case that most variables are influenced by more than one theoretical construct, and that most constructs are broader than what can be represented by a single variable. Therefore, because there is seldom a one-to-one correspondence between observable variables and theoretical constructs, there will usually be some uncertainty with respect to the interpretation of most variables.

What may be one of the most interesting questions with respect to the topic of aging and speed is whether age-related slowing is most meaningfully interpreted as a cause of age differences in cognitive performance, or as a consequence of age differences in more fundamental or primitive cognitive processes. That is, with very simple tasks, such as most perceptual speed and choice reaction time tasks, all of the individual difference variation will likely be reflected in measures of speed of performance, but this does not necessarily mean that variations in some type of internal speed factor are the primary causes of those individual differences. Before one can be confident about a conclusion of this type other possible determinants of the variations in performance should be examined, ideally with additional measures of performance (e.g. accuracy, amplitude, synchronization). If separate measures of each relevant construct are available, then the plausibility of different causal arrangements of the variables can be examined to determine which construct appears to be the most fundamental with respect to age-related influences.

Two recent examples of this approach will be briefly described because they serve to represent the range of outcomes that have been found (results of other analyses of this type are summarized in Salthouse (1996b)). First, Salthouse and Meinz (1995) investigated measures of interference or inhibition from the Stroop interference procedure under the assumption that the ability to sustain attention and to resist interference might be keys to rapid responding. Comparisons were then made of the relative attenuation of the age-related variance in one variable (e.g. measures of interference) after statistical control of the variance in the other variable (e.g. measures of perceptual speed), with the variable resulting in the greatest attenuation assumed to be more fundamental with respect to age-related influences. However, there was little evidence in the Salthouse and Meinz (1995) study that interference measures were more fundamental than the speed measures, and a similar conclusion was recently reached by Verhaeghen and De Meersman (1998) on the basis of meta-analyses of Stroop results from several different studies.

The second example investigated measures of attention switching (Salthouse et al., 1998). This study found some evidence for the existence of distinct speed and switching constructs, but the data were ambiguous with respect to which construct was more fundamental in terms of age-related influences.

Although the results of prior studies have not been definitive, the approach of examining several constructs simultaneously to determine which appear to be primarily responsible for the age-related variations in speeded performance remains promising and should continue to be pursued.

6. Relations of speed to other cognitive variables

Because of its strong relations to age and its apparently simple nature, there has been considerable interest in how speed might be involved in the age relations on other cognitive variables. One manner in which this question has been addressed is by conducting analyses in which speed variables are included along with variables reflecting higher-order cognition such as memory, reasoning, and spatial abilities. Various types of statistical control and path analysis procedures can then be applied, and a general finding has been that measures of speed tend to share about 75% of the age-related variance with various cognitive measures (Salthouse, 1996a,b).

A particularly interesting pattern was apparent in two studies reported by Salthouse (1994b). The participants in these studies performed memory, reasoning, and spatial tasks presented on computers in a manner that allowed them to work on the items at their own pace. Results from both studies revealed that measures of perceptual speed were more closely related to the accuracy of the decisions than to the time spent working on the items (i.e. study time), or to the time to communicate the decision after inspecting the alternatives (i.e. decision time). This pattern is intriguing because it implies that processing speed is related to decision accuracy even under self-paced conditions. Furthermore, the results suggest that study time and decision time may be reflections of strategy or style rather than simply additional manifestations of some type of broad speed factor. Horn et al. (1981) have also argued that perceptual speed is distinct from other aspects of speed that can be assessed in cognitive tests, such as correct decision speed.

There are now a relatively large number of studies in which various measures of speed have been examined as potential mediators of the relations between age and variables reflecting different types of memory and cognition (e.g. see Salthouse, 1996b, for a review). Many of the results from these types of analyses are consistent with the idea that a slower processing speed contributes to at least some of the age-related differences in a variety of cognitive variables. However, it is important to emphasize that the results do not imply that all age differences in cognitive variables, or in variables measured in units of time, are determined by a single factor, or that the magnitude of the age effects should necessarily be equivalent across all variables. Instead they are probably best interpreted as indicating that the age-related differences in a wide variety of memory and cognitive variables are not independent, and that speed variables appear to be involved to at least some degree in whatever contributes to the lack of independence.

7. Relevance to psychophysiological research

This article has briefly reviewed research on adult age-related effects on measures of processing speed. The evidence clearly indicates that increased age is associated with slower performance in a wide range of speeded tasks, although there are still vigorous debates with respect to the degree to which age-related slowing is specific to particular processes or also reflects broader and more general influences. Analyses attempting to distinguish shared and unique age-related effects with psychophysiological variables such as various ERP components may help to resolve some of these issues. Of particular interest would be shared influence analyses in which the latency or amplitude of various ERP components are considered together with a variety of variables reflecting perceptual or reaction time speed and other cognitive abilities because the results should be informative about the degree to which the age-related effects on these different types of variables are unique. It is also likely that some of the analytical procedures that have been used with behavioral variables may be informative with psychophysiological variables. For example, hierarchical regression analyses conducted on measures of different ERP components may reveal the extent to which age-related effects on later components are independent of effects on early components, and which measures are more fundamental than others in terms of mediating age-related effects on other types of variables.

Ultimately, of course, we would like to know why increased age during the adult years is associated with decreased levels of speed, and this is another area where psychophysiological and neurobiological research can be expected to make important contributions. Among the speculations proposed to account for age-related slowing are that because of diffuse cell loss the transmission of neural impulses must traverse lengthier and more circuitous pathways to reach the same end state (Salthouse, 1985; Cerella, 1990), that a slower propagation of neural impulses with increased age is attributable to a reduction of dendritic branching, a decrease in the number of active synapses, or a loss of myelin (Miller, 1994), and that age-related slowing may be a consequence of a loss of synchronization of neural impulses, possibly due to a reduction of particular neurotransmitters such as dopamine. It seems unlikely that these possibilities can be distinguished with only behavioral research, and thus research with various types of psychophysiological or neurobiological variables may be necessary to help resolve the fundamental issue of the causes of age-related slowing.

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