Time as a Factor in the Development and Decline of Mental Processes

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The theme of this chapter is that it is meaningful to think of time as increasing and then decreasing as a function of age. Of course I am not referring to time in an objective physical sense, but rather functional time in the sense of the amount needed required to carry out many cognitive operations. Several years ago Robert Kail and I (Kail & Salthouse, 1994) suggested that time can be viewed as a processing resource that alters with age if changes occur in the time needed to execute operations since fewer operations will be able to be completed in a given period of time. In this chapter I will elaborate on this perspective, and will summarize some relevant empirical research concentrated on the adult portion of the lifespan.

I will begin by documenting the lifespan growth and decline of this resource-based conceptualization of time. For this purpose I will use several measures from tasks that are so simple that accuracy is nearly perfect, and consequently virtually all of the variation across people can be assumed to be in terms of how quickly the items can be performed. The first figure portrays results of measures from two perceptual speed tasks from the Woodcock-Johnson Test of Cognitive Abilities (Woodcock & Johnson, 1989, 1990) expressed in standardized units. Notice that there is a rapid increase in the period of childhood, followed by a gradual decrease across the adult years. This phenomenon is evident with a variety of different tasks, and strongly suggests that there are substantial age-related differences in measures that might be hypothesized to reflect the time required to execute elementary cognitive operations.

An immediate obvious question is why are measures of time important? Many other lifespan changes presumably have no consequences for cognition, such as running speed, bicep diameter, lung capacity, and the color of one's hair, and thus it is reasonable to ask what is special about measures reflecting speed of processing.

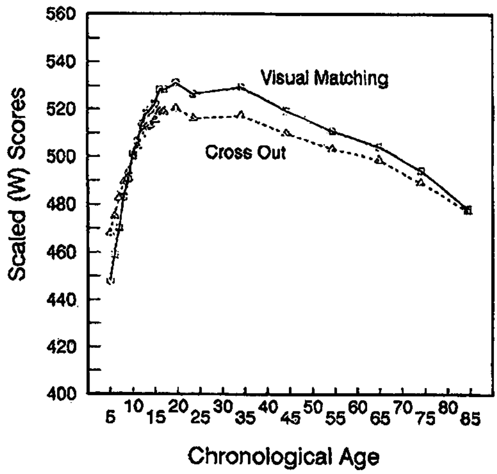

Figure 1: Mean performance between 5 and 95 years of age on two perceptual speed tests from the standardization sample in the Woodcock-Johnson Psycho-Educational Battery.

I have two responses to this question. First, I will argue that time is unique because plausible theoretical mechanisms have been proposed by which slower processing can affect cognitive functioning. And second, I will describe empirical evidence indicating that measures of processing time are actually involved in the age-related differences in many measures of cognitive functioning. The empirical evidence will be described first because discussions of hypothesized mechanisms are more meaningful when the to-be-explained relations have been established to exist.

The primary empirical question of interest is whether there is evidence for an influence of time or speed on the relations between age and various measures of cognitive functioning. The simple answer to this question is yes, but in order to understand the reasons for this answer it is important to briefly describe the types of analytical methods that have led to this conclusion.

Consider the general case of a potential mediator, X. In the present context X corresponds to an index of speed of processing, but it could be virtually any variable hypothesized to contribute to at least some of the age-related differences in cognition. How can one determine that age-related changes in X might be responsible for age-related changes in Y? Several sets of relations could be investigated, such as those between age and X, between age and Y, and between X and Y.

But how can one determine whether, and to what extent, the relations involving X actually contribute to the observed relations between age and Y? The mere existence of each relation is not sufficient because a great many variables are related to age, but it is unlikely that they are all involved in the relations between age and variables reflecting cognitive functioning. For example, both gray hair and poor memory are often related to increased age in adulthood, and in an age-heterogeneous sample they might be found to be related to each other merely because both are associated with increased age. However one could not conclude that gray hair mediates the decline in memory that often accompanies increased age because all of the relevant relations need to be considered simultaneously. That is, evidence is needed to establish that the combination of relations between age and X and between X and Y do in fact contribute to the observed relation between age and Y.

Three major techniques could be used to investigate the hypothesized linkages (see Figure 2). All involve examining the relation between age and Y after eliminating or controlling the relation between age and X. In each case the expectation is that the relation between age and Y will be greatly reduced or eliminated if much of it is mediated through X.

One possible strategy consists of some type of experimental intervention to alter the level of X. Ideally the intervention would operate by improving X in older adults to the level of young adults, and thereby eliminate the relations between age and X. Experimental manipulation is clearly the most convincing way to establish the existence of a causal relation because if X is the only variable that has been altered then it must be responsible for the observed differences. Unfortunately, intervention approaches may not be feasible in the present context if the X variable changed slowly over a period of many decades. Not only might

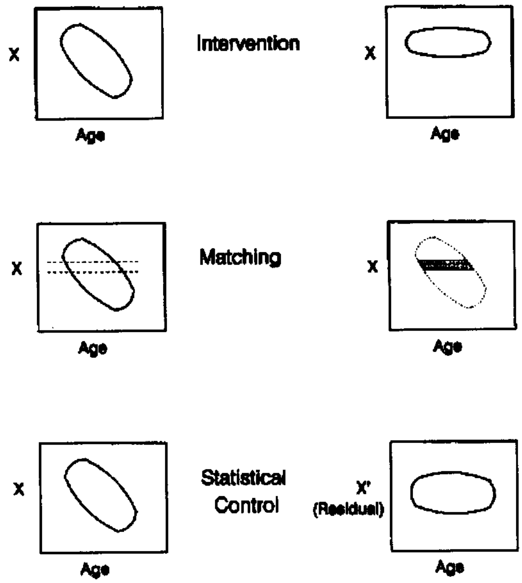

Figure 2: Schematic illustration of three techniques that could be used to eliminate the variation between age and some variable X.

interventions be ineffective in reversing changes that were slow and gradual, but if the change in X occurred gradually, it may have been accompanied by numerous adaptations that might not be easy to eliminate even if it were possible to restore the level of X to the earlier state.

A second possible strategy involves the use of matching by attempting to find people of different ages who have similar values of X. Although seemingly straightforward, this procedure also has at least two major limitations. First, when trying to match on a variable that has moderate to large relations with age, as is expected to be the case with X, the matched samples will likely be small and the range of ages probably restricted relative to the entire sample. Both of these factors will lead to low statistical power to detect relations between age and Y, and consequently the hypothesis of attenuated relations between age and Y might be supported for artifactual reasons. The second limitation of the matching procedure is that there is no assurance that the matching is only on the intended variable X because several variables may vary concomitantly with X, and one or more of them may influence Y in addition to, or instead of, X. To the extent that this is the case, one could not be certain that X was the critical variable responsible for the changes in Y.

The third strategy that could be used to investigate the role of a variable X in the relations between age and another variable Y relies on some type of statistical control. That is, statistical control procedures could be used to equate people of different ages on X by partialing out the linear relation between age and X. An advantage of equating with statistical procedures rather than through direct matching is that all of the available data can be used in the analyses, and thus there is minimal reduction in statistical power relative to the entire sample. Statistical control procedures also allow the influence of other measured variables to be examined and eliminated by similar partialing techniques. The primary assumption of statistical control procedures is that the relations between age and X, and between X and Y, are mostly linear, or that the variables can be transformed to yield linear relations. Once the linear relation is determined, it can then be used to adjust the values of Y to remove the influence of X, and allow examination of the relation between age and the portion of Y that is independent of X.

Because interventions do not yet appear feasible, and since matching leads to substantial reductions in power, statistical control procedures may be the most practical method for eliminating the influence of a hypothesized mediating variable at the current time. Two different statistical control methods can be used, both of which are based on related types of correlational procedures.

One method is known as commonality analysis, and it is useful for determining how much of the variance in Y is unique to X, how much is unique to age, and how much is shared between X and age. This technique is particularly helpful when partitioning the age-related variance because it can indicate how much of the age-related variance in the criterion variable (Y) is shared with the hypothesized mediator variable (X).

Various types of path analysis can function as the second statistical control procedure because they provide estimates of the relative strengths of paths from age to X, from X to Y, and from age to Y. The latter path is especially informative because it represents the influence of age on Y that is not mediated through X, and thus it can be used to estimate how much of the age-related variance in Y is not explained by the mediator (X). Ideally the path analyses should be conducted with latent constructs and structural equation modeling to reduce measurement error and minimize biases in the estimates of the magnitude of the relations. However, the analyses are still meaningful with observed or manifest variables, particularly if reliabilities are available to allow the estimates of the relations to be adjusted for measurement error.

In both commonality analyses and path analyses the methods are relevant to time-based interpretations if measures of processing speed are used as X, and measures of cognitive functioning are used as Y. Results from these procedures will be illustrated with perceptual comparison speed measures serving as the X variable, and measures of performance from three different cognitive tasks serving as the Y variable.

As mentioned earlier, perceptual speed measures are assumed to reflect how quickly elementary cognitive operations can be performed. That is, the tasks are so simple that few people make mistakes, and consequently virtually all of the variation across normal adults is reflected in the time needed to perform the tasks. Administration time for the measures can be as brief as 60 seconds, but estimates of reliability are often .8 or higher. Although I will be describing results based on paper-and-pencil procedures, it should be noted that similar patterns of results in commonality analyses and path analyses have been obtained with reaction time speed measures, and thus the conclusions do not seem to be specific to a particular method of assessing processing speed.

Results with three different criterion measures will be illustrated, and in each case the data were based on samples of 200 or more adults ranging from 18 to over 80 years of age. One of the criterion variables is the score on the Raven's Progressive Matrices, which is a popular test of inductive reasoning in which 8 of 9 cells in a matrix contain geometric patterns and the respondent is required to select the best completion of the missing cell in the matrix. A second criterion variable is the sum of the number of items recalled across the first five trials in the Rey Auditory Verbal Learning Test. In this test the same list of 15 unrelated words is read aloud five times, with the respondent attempting to recall as many words as possible after each presentation. A measure reflecting time and accuracy on the Block Design test from the Wechsler Adult Intelligence Scale – Revised is the third criterion variable I will describe. This test involves the respondent attempting to assemble blocks to match a target pattern.

These three tests are obviously quite different, and they are generally assumed to reflect distinct psychometric factors (i.e., inductive reasoning, episodic or short-term memory, and spatial visualization). Each of the tests has been established to have good reliability, and scores on the tests typically exhibit moderately large age differences. The next figure illustrates results from studies conducted in my laboratory, with the scores in each test converted to standard deviation units from the entire sample to facilitate comparisons across variables. Notice that the range of performance from the youngest to the oldest age groups is almost two standard deviations with each variable.

The next figure illustrates results with commonality analyses (in the form of a pie chart depicting variance accounted for in the criterion variable) and path analyses (in the form of a path diagram with estimates of the relevant coefficients). Results from both sets of analyses are consistent with the interpretation that time to execute simple operations is an important factor in the age-related differences in cognitive functioning. This is apparent in the commonality analyses because estimates of the percentages of the total age-related variance shared with speed (i.e., the ratio of shared to the sum of shared plus unique-to-age multiplied by 100) were 98.1 for the Raven's variable, 73.2 for the Rey Verbal Learning variable, and 86.3 for the Block Design variable. The path analysis results are also

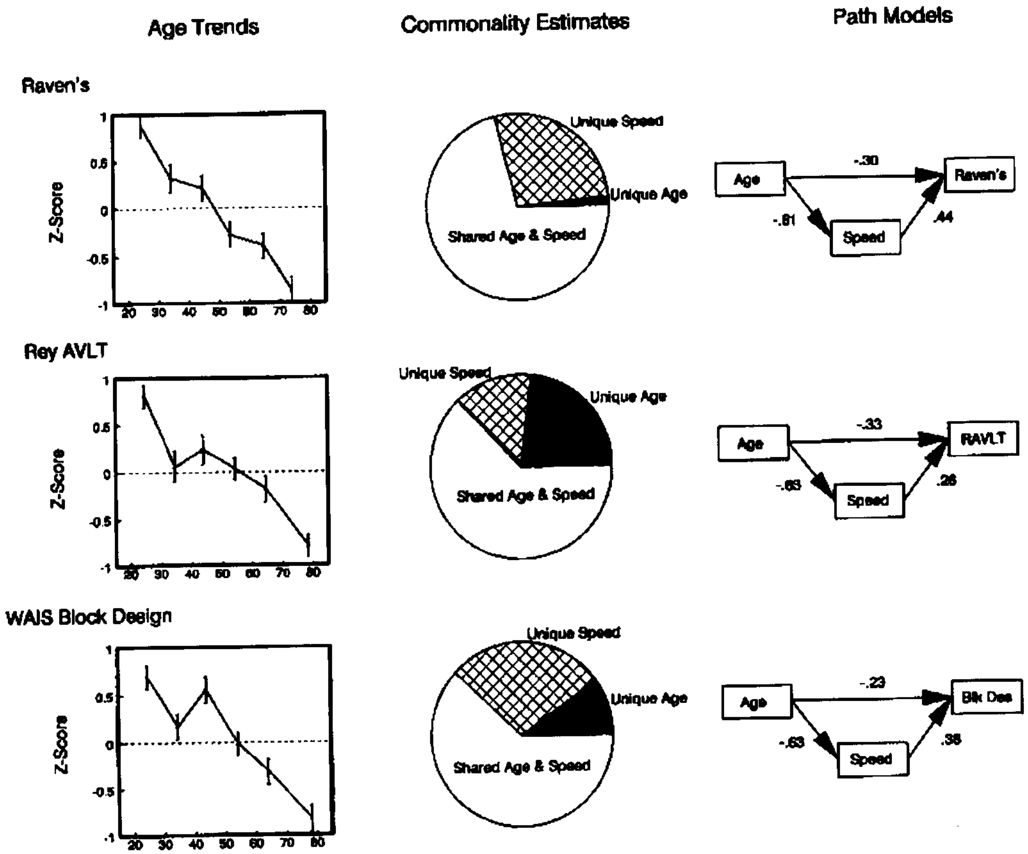

Figure 3: Mean standard scores (and standard errors) as a function of age for the Raven's Progressive Matrices (Salthouse, 1993), and the Rey Auditory Verbal Learning Test and Wechsler Block Design Test (Salthouse, Fristoe & Rhee, 1996). Also portrayed are results from commonality analyses and path analyses with these variables as criterion variables.

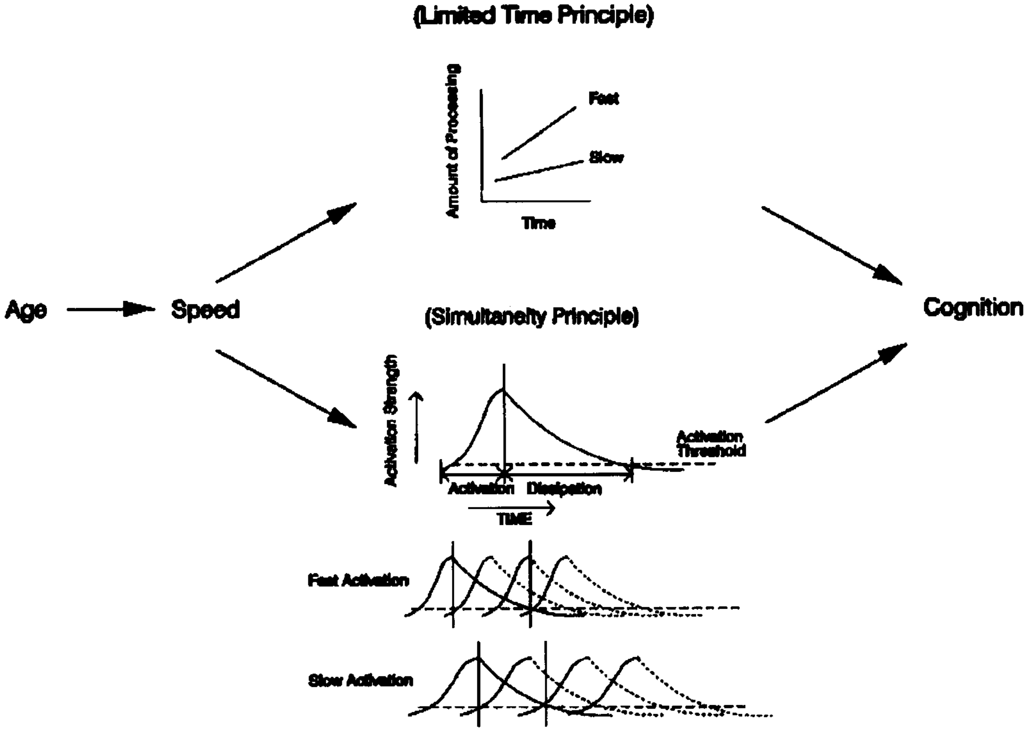

Figure 4: Schematic illustration of two hypothesized mechanisms that might account for the influence of speed on the relations between age and measures of cognitive performance.

consistent with the hypothesized speed mediation because moderately large coefficients were evident for the paths from age to the speed variable and from the speed variable to the cognitive variable. Moreover, in each case the direct or unmediated relation between age and the cognitive variable was substantially smaller than the corresponding correlation (e.g., for Ravens, -.30 vs. -.57; for RAVLT, -.33 vs. -.50; and for Block Design, r = -.23 vs. -.47).

The results just described clearly indicate that a substantial proportion of the age-related variance in several complex cognitive measures is shared with simple measures that are hypothesized to reflect how quickly simple processing operations can be executed. However, it is important to emphasize that not all age-related effects on complex cognitive measures are shared with simple speed measures. Results such as those I have just described are sometimes misinterpreted as implying that a single monolithic factor is responsible for all of the age differences observed in measures of cognition. In fact, an advantage of these types of correlational procedures is that they allow the relative contribution of different types of influences to be determined, instead of focusing exclusively on whether the influence of a particular variable is different from zero, as is often the case with other analytical procedures. The results of these analyses, and of similar analyses of other data, suggest that measures of simple processing efficiency share large proportions of age-related variance with several different types of complex cognitive variables. They are thus consistent with the interpretation that factors related to processing speed contribute to *some* of the observed age differences in variables representing higher-order cognitive functioning.

Now that the relations involving processing speed have been established to exist, it is appropriate to ask about the mechanisms that might be responsible for those relations. I believe that at least two speed-based mechanisms, which are schematically illustrated in the next figure, are involved in the age-related effects on cognition (Salthouse, 1996). I refer to one mechanism as the *limited time* mechanism because if elementary processing operations take longer to be performed, then fewer of them can be completed in a given period. This mechanism is likely to be very important in timed tests, and especially those with low levels of difficulty in which performance is primarily assessed in terms of the number of items completed in the specified time. However, the limited time mechanism could also affect performance in more complex situations where a sequence of operations must be performed and slow execution of the early operations means that later, and possibly higher-order, operations are not successfully completed. A relevant metaphor for the limited time mechanism might be an assembly line in which if early operations are not completed rapidly, the products at subsequent stages may be defective.

Considerable evidence indicates that with increasing age less processing can be accomplished in the same amount of time. For example, this phenomenon is evident with manipulations of stimulus presentation time, with post-hoc analyses of the level of accuracy obtained at specified reaction times, or with functions relating reaction time to the amount of completed processing or to the number of operations that must be performed.

The second mechanism by which slower processing could lead to impairments in the quality of cognitive functioning is known as the *simultaneity* mechanism, and it may operate even when there are no external time limits. The critical assumption in this mechanism is that in order to be successful many higher-level cognitive operations such as association, integration and abstraction require that all of the relevant information is simultaneously available. If it is not all accessible when needed, then the operations may not be completed successfully, and the quality of the relevant performance will be impaired. Several factors probably affect the amount of simultaneously available information, but the time to activate the information is postulated to be a particularly important determinant.

It could be argued that if information remains in the same state of availability indefinitely then the completion of processing will merely be delayed when the speed of activation is slower. However, if information is lost through decay or displacement then there will be a limited period when all relevant information is available, with the duration of that period dependent on the dynamics of the speed of activation and the rate of loss or forgetting. Moreover, because it is unrealistic to expect information to remain in a high state of availability indefinitely, speed of activation is likely to be a critical variable affecting the amount of information that is simultaneously available.

It might still be possible to achieve the same eventual level of higher-order products if the rate of loss of information was slowed to the same extent as the rate of activation. However, in order for this to occur the information must not be lost as rapidly in older adults compared to young adults, and there is no evidence to suggest that the rate of forgetting is slower with increased age. Instead most of the relevant research suggests that the rate of forgetting for older adults is either the same as that of young adults, or possibly even faster, but certainly not slower (see Salthouse, 1992).

Because it is difficult to obtain precise measures of the time course of information availability, very little evidence directly relevant to the simultaneity mechanism is currently available. Although this mechanism is largely speculative at the present time, it seems plausible as a mechanism by which slower speed of processing could lead to lower levels of cognitive performance.

Summary and Implications

I will now summarize the major points of this chapter. First, I suggested that effective or functional time decreases with increasing age, and that it seems likely that this decrease has consequences for many types of cognitive functioning. Second, results from two correlational procedures were described that indicate that measures of processing speed are closely involved in the relations between age and several types of cognitive functioning. And third, two mechanisms hypothesized to contribute to the role of speed on cognition, limited time and simultaneity, were discussed. I believe that the combination of plausible argument together with relevant empirical evidence lends credibility to the time-based interpretation of developmental differences in cognition. However, much more research is clearly needed before this interpretation would be completely convincing. For example, more analytical research is desirable on the mechanisms that are responsible for the speed mediation that has been established to exist. Finally, it is important to capitalize on the strengths of different methodological approaches, because both correlational and experimental procedures provide valuable information. For example, correlational procedures are useful to estimate the strength of relevant relations, and experimental procedures are useful to explore the nature of the mechanisms responsible for the relations.

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