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From Presentation Time to Processing Time: A Psychophysics Approach to Episodic Memory

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Manipulations of presentation time have a long history in research on the development of memory, with a number of paradoxical results deriving from methodological shortcomings as well as from insufficient theoretical specifications. After a look at some of the problems in earlier research, a psychophysics approach to investigate episodic memory functions is presented in which criterion-referenced manipulation of presentation time is used to estimate the effects of experimental manipulations and the effects of individual differences. *Criterion-referenced presentation time* (CRPT), defined as the time required to score at an a priori specified level of accuracy, is interpreted as a preliminary indicator of internal processing time. CRPTs are shown to be valid predictors of traditional measures of memory accuracy. Moreover, an extension of this psychophysics approach yields estimates of complete condition-specific time-accuracy functions and of function-specific processing times (plus other parameters) for individual subjects. It is argued that both from a cognitive and a developmental perspective it is often advantageous to trade experimental equivalence in presentation times for functional equivalence in accuracy of performance; this applies not only to episodic memory processes.

THE MIXED MESSAGES OF PRESENTATION TIMES

Presentation time is an important variable in memory research because it limits the processing of information in working memory. The general expectation is that memory accuracy is monotonically related to presentation time, with longer presentation times leading to better performance. Consequently, manipulations of presentation time can be considered manipulations of general task difficulty: the shorter the presentation time, the more severe the limit on working memory, the worse the performance. Empirical results are generally consistent with this line of reasoning.

The notion that short presentation times imply high task difficulty led to specific expectations in developmental research: The more difficult a task, the larger age differences are expected to be; therefore, shorter presentation times should yield larger age differences than longer ones. For example, we initially thought of manipulations of presentation times as an instantiation of testing-the-limits, with especially large age differences predicted for short presentation times (Kliegl, Smith, & Baltes, 1989). This position was also consistent with the view by Craik and Rabinowitz (1984, 1985; Rabinowitz, 1989) and Bäckman (1986), that longer presentation times represent a higher degree of environmental support by reducing the demands on limited cognitive resources. Higher support is expected to decrease the negative effect of age on memory. A decrease in age differences with longer presentation times was also postulated by Burke and Light (1981) and Simon (1979).

In the field of cognitive aging, empirical support for this position was scant for episodic memory (for a recent review, see Craik & Jennings, 1992). The dominant result (aside from the usual main effect) was no Age × Time interaction (e.g., Kliegl et al., 1989), or interactions opposite to the expected pattern (i.e., age differences were larger for long presentation times; e.g., Craik & Rabinowitz, 1985; Thompson & Kliegl, 1991). Given these inconsistencies, the developmental implications of the relationship between presentation time and recall is in need of re-evaluation.

A THEORETICAL FRAMEWORK

The confusing state of affairs regarding the direction of effects of presentation time in age-comparative studies can be resolved in a model that assumes (a) a minimum amount of presentation time is required to initiate task-relevant memory processes, (b) beyond this threshold, presentation time is translated into constructing stable memory traces, and (c) after a certain maximum amount of presentation time there is little to be gained by having more presentation time available (Kliegl, Mayr, & Krampe, 1994). Figure 5.1 illustrates this conception assuming a negative exponential function for converting presentation time into memory strengths (recall probability) up to an asymptotic maximum strength.

The assumption that presentation time is converted into memory strength highlights the role of a time constant in these models that I call *processing time*. It is the reciprocal value of the slope (steepness) of the curves in Fig. 5.1. Traditionally, the slopes are interpreted as rates; rates are scaled in *unit per time*.

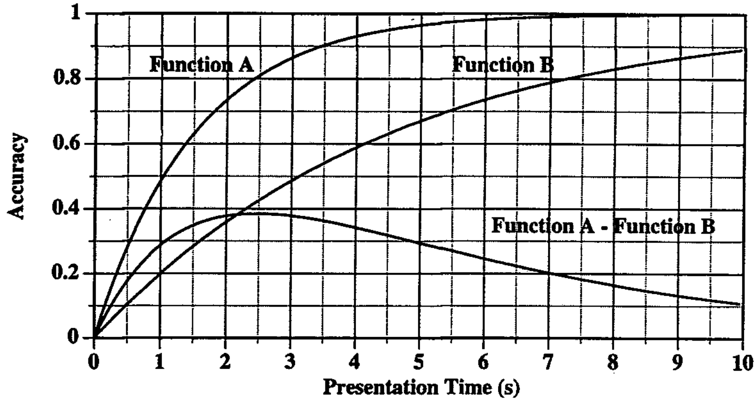

FIG. 5.1. Time-accuracy functions based on negatively accelerated exponential functions (Function A and Function B) and the corresponding vertical difference function.

Thus, the reciprocal value is a measure of *time per unit*; processing times were 1.5 sec and 4.5 sec for Functions A and B of Fig. 5.1, respectively. Thinking in terms of processing time instead of rates has two advantages. First, mental schemata imprinted on us by decades of response-latency research can be transferred: Large processing times are characteristic of more difficult tasks, less able groups, and early stages of practice. In Function B of Fig. 5.1, more processing time is needed to reduce the error probability by a constant proportion of the level of accuracy already attained than is the case for Function A. Second, a latent time measure of memory efficiency allows us to think about developmental differences in terms of cognitive slowing in adult development, or speed-up of information processing in child development. It represents an attempt to operationalize time as an external resource of cognitive processing that can be tracked with respect to general, domain-specific and process-specific effects of development (e.g., Kail, 1991; Salthouse, 1985). In other words, we define a metric for describing the efficiency of cognitive performance at different levels of generality.

The proposal to trace age-related memory differences to specific or general slowing of cognitive processing, to my knowledge, was first advanced in the context of models of short-term or working memory. Salthouse (1980) and Waugh and Barr (1980) postulated differences in rehearsal rate as the source of age differences (see also Baddeley, Thomson, & Buchanan, 1975; Balota & Duchek, 1988; Hasselhorn, 1988). Speech rate served as an indicator of rehearsal rate in these studies. Only recently was this idea generalized to episodic memory in terms of age differences in elaboration rate (cf. Kausler, 1991; Kliegl et al., 1989; Salthouse, 1985; Salthouse & Kail, 1983). This conceptual extension was made without much empirical support.

How might one explain the systematic relation between recall accuracy and presentation time? What are the theoretical mechanisms? In memory tasks conducted in our laboratory, subjects have to forge a mental image between two words, typically between a location cue such as church, museum, and so forth, and a concrete randomly selected noun such as tiger or car. If it takes young adults 1.5 sec and old adults 4.5 sec to establish such a relation, then, if both are given 9 sec, the young will have forged three times as many elaborations (six) than the old adults, who would only have had time for two; with identical presentation times, young adults' recall should be much better than that of old adults. Note that with this kind of reasoning we explain age differences in memory accuracy in terms of processing time: The less time one needs to generate an elaboration, the more of them can be generated in a fixed amount of time. The search for new elaborations probably becomes more difficult; it is hard not to think of the same elaborations again and again. Previously used thoughts or images may contribute negligibly, if at all, to the strength of the trace to be constructed. In this case, the relation between presentation time and accuracy will take the form of a negatively accelerated exponential function as shown in Fig. 5.1. The negative exponential function is compatible with the stochastic replacement model of learning; the assumption is that sampled images (elaborations) are put back into the memory store (e.g., Restle & Greeno, 1970). Therefore, the likelihood of resampling the same images or thoughts increases across time. Consequently, there will be diminishing returns of elaborative processing cycles as presentation time is extended.

In the context of developmental research, the model can account for an increase, a decrease, and the absence of age differences in correct recall across presentation time—independent of possible problems of statistical power or floor and ceiling effects. Figure 5.1 contains a function depicting the difference between Function A and Function B. Assume Function A and Function B represent performance of high ability (e.g., young) and low ability (e.g., old) adults. Whether we obtain an increase or a decrease of the age difference in accuracy by extending presentation time, or whether or not there is an interaction between age and presentation time depends on the times used. If we sample times from the segment left of the peak of the difference function we observe an increase, if we sample from the segment to the right the age difference decreases, and it will appear to be independent of presentation time if we use times with identical difference scores from the left and the right of the peak. If accuracy is determined by the stochastic sampling of images, these interactions (or their absence) would be spurious; they are the consequence of a difference in the processing time required for one elaborative cycle. Thus, what might look like a presentation-time specific age difference in terms of absolute accuracy differences between age groups could be the consequence of age-related slowing in sampling of images.

Although the model was described in terms of encoding operations, it does not fix the age difference in the encoding stage. For example, in Fig. 5.1, Function A could represent performance for a cued and Function B performance for a free recall format. The effect of this experimental manipulation would also be reflected in a difference of the fundamental processing-time parameter: More presentation time is required for the same level of accuracy to overcome the greater difficulty of free-recall compared to cued-recall retrieval. Moreover, sampling of ideas for the construction of images during encoding requires retrieval from memory. Thus, longer processing times associated with elaborative cycles may reflect a retrieval problem embedded in the encoding phase. Any experimental or organismic manipulation impeding performance in traditional experimental designs will increase the time demand for equal accuracy. In summary, the processing-time constant governing the translation of presentation time into accuracy (precisely, the proportional reduction of error probability) is not necessarily tied to a particular processing stage. As is shown in the course of this chapter, however, its determination promises to alleviate methodological problems that constrained the interpretation of developmental differences in the past.

METHODOLOGICAL PROBLEMS OF INFERRING PROCESSING TIMES FROM PRESENTATION TIMES

There have been few attempts to map developmental differences in episodic memory onto differences in such processing times. One reason may be that the traditional approach is to use presentation time as a proxy for processing time. In other words, manipulations of presentation time were interpreted as direct manipulations of processing time. This would be true only if the function mapping presentation time into processing time were strictly linear but, unfortunately, this is unlikely to be the case. There is still a lack of good empirical indicators of processing time for memory-related processes (Salthouse, 1985). The main point of the following argument is that there are problems inherent to the experimental designs involving manipulations of presentation time for the investigation of memory processes. After illustrating a few such problems with data from our own studies, we describe an alternative approach, consistent with the psychophysics tradition of experimental psychology.

Functional Limits of Processing: Floor and Ceiling Effects

Figure 5.2 (top panel) shows performance at the end of a 38-session mnemonic training study in which participants received extensive practice in the method-of-loci mnemonic (Baltes & Kliegl, 1992; Kliegl, Smith, & Baltes, 1989). As a final assessment, we presented 12 lists of 30 words with 12 different presentation times ranging from 20 sec down to 0.8 sec per word. The vertical line shows that the four slow lists and the eight fast lists were administered in two consecutive sessions. Obviously, there are three segments with respect to age differences: they are small for short, very large for medium, and large for long presentation times. There is restriction of variance for short presentation times for young and old adults, and possibly also for long presentation times for young adults only.

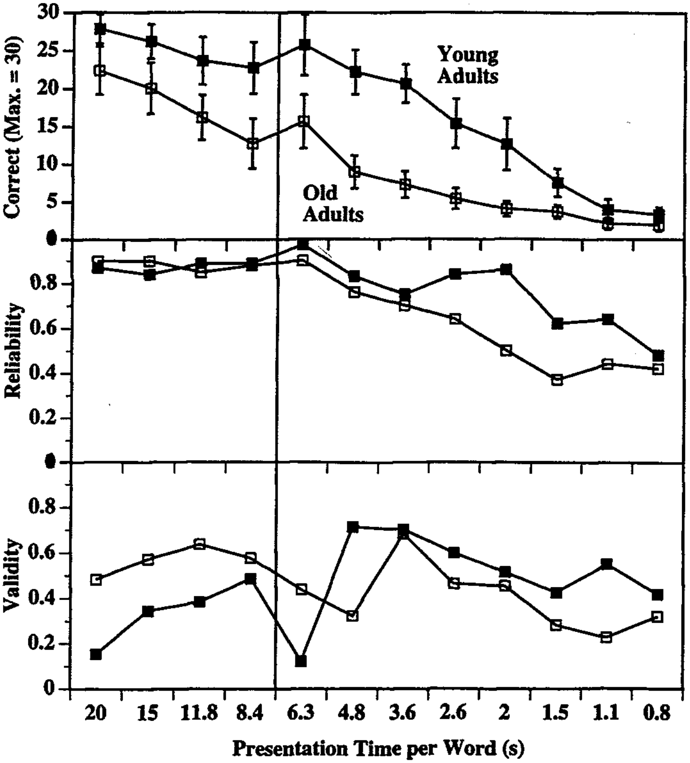

FIG. 5.2. Top panel: Correct serial recall of young and old adults for 12 lists of 30 words presented for the times listed on the x-axis. Error bars are 95%-confidence intervals. Middle panel: Reliability (Cronbach's alpha) for the twelve lists. Bottom panel: Correlation of correct serial recall with the logarithm of presentation times required for 50% correct recall.

The pattern of results is somewhat consistent with the theoretical curves of Fig. 5.1, but obvious floor and potential ceiling effects render it difficult to decide which presentation times could be included in the analysis of variance; in the Baltes and Kliegl (1992) article, data for the four shortest presentation times were excluded due to the analyses reported in the next section. In general, the pattern of results was counter to our original expectations of larger age differences for shorter presentation times. However, the data were consistent with the assumption that below a minimum amount of time, about less than three sec in this case, neither young nor old adults could execute the processes required for elaborative processing.

The results suggest an interpretation of presentation time as a *threshold time* for deploying the effective mnemonic strategy. If the available time is below a critical value, it cannot be used, and performance collapses. If the time is beyond the threshold, the mnemonic device can be used. It is difficult to determine from these data whether or not there are age differences in the efficiency with which presentation time is converted into accuracy. Depending on the difficulty of the memory task (e.g., manipulations of material, training, mnemonic instructions) or individual differences (e.g., age or expertise) one or more conditions are frequently too difficult for one, and other conditions too easy for other experimental or nonexperimental manipulations. Functional limits that give rise to such floor and ceiling effects are probably rarely identical across individuals—even within age-homogeneous groups. For example, in the 20 sec condition, 4 of 16 young but none of 19 old adults had perfect scores. Thus, interactions between presentation time and age group could be the consequence of, for example, the experimental curtailing of maximum performance for a larger proportion of young than old adults. Without the task ceiling, for example with longer word lists, we might have observed larger age differences for 20 sec than 15 sec per word.

Problems of Internal Consistency (Reliability)

Changes in the consistency of cognitive processing, perhaps even a shift from one mode of processing into a different one, might be indicated in systematic changes of internal consistency (reliability) of performance. If the 30 words of a memory list are considered as items of a scale, one can compute Cronbach's alpha as an indicator of internal consistency or reliability. This provides an index of whether or not performance over a group of items (words) reflects an ability to remember that is congruent with performance over other groups of items (words). The age differential effects of presentation time on internal consistency are illustrated in the middle panel of Fig. 5.2. Obviously, internal consistencies were high and similar for both groups up to presentation times of 3.6 sec. For the four short times, the drop was more rapid for old than young adults; values were similar again for the shortest time (0.8 sec) administered. We took some comfort from the age similarities in internal consistency for long presentation times; as values were smaller and less regular for pretraining scores, this was partially due to the extensive training participants received. Nevertheless, there were also age differences in internal consistencies for a segment of the presentation time spectrum (below 3.6 sec). Thus, it would be problematic to interpret the Age × Presentation Time interaction in terms of a global construct of internal processing time, assumed to determine all levels of functioning between chance and maximum performance. Rather, it may also be taken to indicate different types of processing. As a further complication, it is likely that such shifts in the cognitive algorithm occur at different presentation times for persons of different ages. Averaging data across subjects without concern for individual differences in such algorithmic breakpoints leads to group curves that represent a mixture of qualitative (cognitive algorithms) and quantitative (processing times) differences.

CRITERION-REFERENCED PRESENTATION TIMES

The following proposal, intended to overcome the difficulty in interpreting time-accuracy relations, originated in the design of the practice sessions of our memory experiments (e.g., Kliegl et al., 1989). We wanted to provide all participants with as beneficial a learning environment as possible. To this end, practice sessions were closely tailored to each individual's ability. In particular, we aimed at intermediate levels of difficulty for each individual (e.g., adjusted presentation times so that subjects maintained a 50% accuracy rate over lists), at which they would practice the skill. In this way, we hoped to avoid boredom due to lack of challenge and frustration due to performance demands beyond the reach of the current ability. The inequivalence in presentation times between participants is of minor concern because task demands focused on accuracy (they always tried to get 100% correct), rather than on the time required to achieve accuracy.

Criterion-referenced testing corresponds to the psychophysical method of limits in which the amount of stimulus energy (e.g., quanta of light) is varied contingent on stimulus identification to determine perceptual thresholds. In our application, presentation time assumes the role of stimulus energy. For example, when persons practiced the recall of word lists with a mnemonic technique, we decided on a performance criterion, for example, 15 out of 30 words. If, in a given list, a participant met this criterion, the presentation time was shortened in the following list. If he or she did not meet the criterion, more presentation time was available on the next list. As shown in Fig. 5.3 from Kliegl and

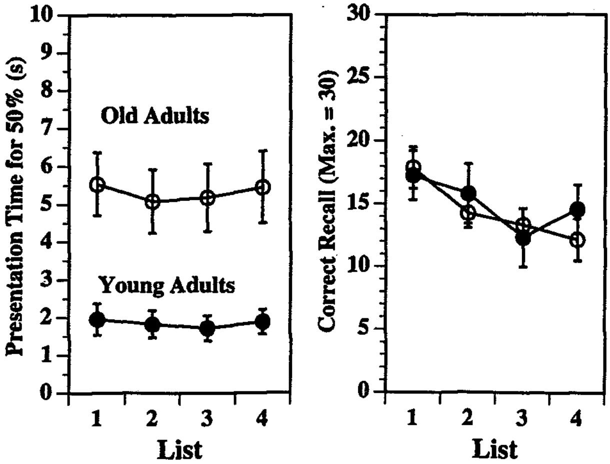

FIG. 5.3. Illustration of criterion-referenced testing across four lists of an experimental session. Age differences are reflected in the presentation times needed to maintain a 50% level of correct recall. Data are from Kliegl and Lindenberger (1993).

Lindenberger (1993), on average, old adults were allotted more presentation time per word than young adults, and there was no difference between age groups in recall accuracy, as expected.

Descriptive Statistics and Construct Validity

Can we consider the criterion-referenced presentation time (CRPT) as an alternative global measure of memory ability? We converted the CRPTs to proportional elaboration times by taking logarithms (and adding one to avoid negative values); the logarithmic transformation also brought the data in line with various distributional statistical assumptions (e.g., homogeneity of variance, homoscedasticity of regression residuals). Equal-accuracy elaboration times should be shorter for young than old adults. Table 5.1 summarizes age-comparative statistics from two experiments (i.e., Kliegl & Lindenberger, 1993; Thompson & Kliegl, 1991). The data of Experiment 1 were collected in Sessions 22 and 23 of the Baltes and Kliegl (1992) study previously mentioned. In both experiments, test–retest stabilities were high; there was no difference in recall accuracy. In previous research, we showed that mnemonic training leads to an almost complete separation of young and old adults' distributions of recall accuracy (Baltes & Kliegl, 1992; Kliegl et al., 1989). As shown in Fig. 5.4, elaboration times lead to a similar separation.

The next question was one of validity. As a construct validation, we asked whether or not equal-accuracy elaboration times predict traditional memory-accuracy scores that are based on the recall of lists administered under identical presentation-time conditions for all participants. The analyses of internal consistency (reliability) suggested that age groups were similar for times longer than 2.5 sec per word. The bottom panel of Fig. 5.2 displays the within-group correlations between correct recall (i.e., the scores summarized in the top panel) and elaboration times based on criterion-referenced testing (i.e., data shown in Fig. 5.4, Exp. 1). The higher the correlation, the more similar the rank orders. Such

TABLE 5.1
Statistical Characteristics of Elaboration Times

	CRPT (s)		*Elaboration Time*		*Stability*	*Correct Recall*	
	M	SD	M	SD	*r*	M	SD
Exp. 1							
Young	1.84	0.74	1.63	0.40	0.86	15.0	2.1
Old	5.31	1.64	2.62	0.30	0.83	14.4	1.2
Exp. 2							
Young	2.40	1.05	1.76	0.46	0.87	14.6	1.3
Old	7.73	3.30	3.93	0.50	0.89	14.5	0.7

Note. Exp. 1 = Kliegl and Lindenberger (1993, Exp. 1); Exp. 2 = Thompson and Kliegl (1991); CRPT = criterion-referenced presentation time (sec); elaboration time = ln (CRPT) + 1.

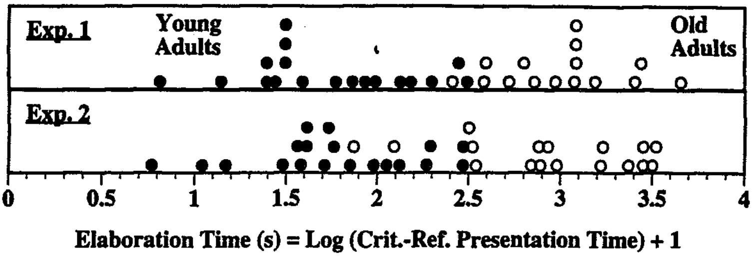

FIG. 5.4. Distributions of elaboration times (= logarithm of criterion-referenced presentation time + 1) for young and old adults; Exp 1: Kliegl and Lindenberger (1993; Exp. 1); Exp. 2: Thompson and Kliegl (1991; Exp. 1).

correlations are consistent with an underlying process similarity between serial recall with a fixed presentation time and processes required for maintaining 50% accuracy across lists of words.

The presentation-time profile is different between internal consistencies and validities. The major result was a reversal in the sign of age-related differences for the size of correlations associated with short and long presentation times. For short presentation times, elaboration time predicted young adults' correct recall better than that of old adults; this result was to be expected on the basis of the age differences in internal consistency (middle panel of Fig. 5.2). For long presentation times, elaboration time predicted old adults' correct recall better than that of young adults. In addition, old adults' correlations were largest for long presentation times.

As there was no age difference in internal consistency for presentation times of 3.6 sec and longer, a sufficiently general age-related shift in processing strategy must have been responsible for the divergence. One possibility is that, with long presentation times, young adults did not use all of the available presentation time to generate elaborations; perhaps they were content with two, three or four elaborations and stopped processing after that. In this case, presentation time is no longer a valid indicator of processing time as specified in the simple model depicted in Fig. 5.1. In contrast, longer times may have been a prerequisite for old adults to fully deploy the mnemonic strategy. Therefore, one conclusion from this analysis is that it is difficult to maintain the assumption of age-invariant cognitive processing across the presentation-time spectrum even after extensive training in the cognitive strategy to be used.

Criterion-referenced presentation times are valid indicators of the ability traditionally measured in terms of accuracy (coefficients were always significant) but, obviously, the degree of correspondence depended on the presentation time. For presentation times with similar values in internal consistency and validity for the two age groups, interindividual differences in accuracy should be predicted by elaboration time. Figure 5.5 illustrates this point for the regression of serial recall (averaged across presentation times ranging between 2.7 sec and 5 sec per

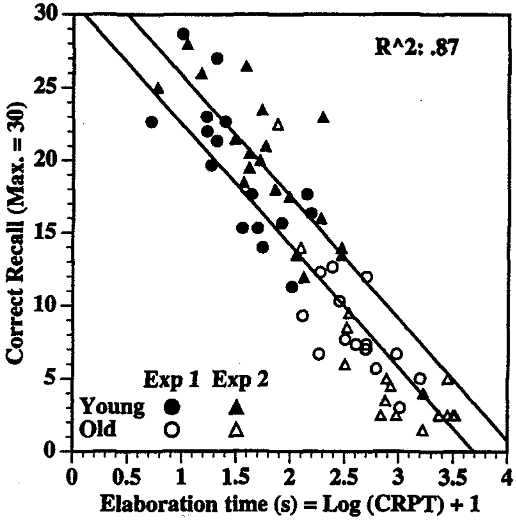

FIG. 5.5. Regression of serial recall (based on presentation times between 2.5 sec and 5 sec; see Fig. 5.1) on elaboration times. Exp. 1: Kliegl and Lindenberger (1993); Exp. 2: Thompson and Kliegl (1991).

word) on elaboration time for the participants of two experiments. CRPTs accounted for 87% of the variance in serial recall; within-group correlations were .72 for young and .81 for old adults. There was a remaining significant age difference in serial recall (reflected in the difference between the two regression lines), probably due to differences between the assessment format; this difference did not interact with CRPT. Finally, neither the main effect of experiment nor any interaction terms were significant. We interpret Fig. 5.5 as strong evidence for the proposition that CRPTs capture individual differences reflected in traditional memory accuracy scores.

Equal-Accuracy Young–Old Functions

There is an interesting twist to CRPTs. On the one hand, CRPTs indicate that older adults have a much worse memory than young adults. On the other hand, they indicate that old adults can have as accurate a memory as young adults if given enough time to generate the memory traces. This raises the question of compensation. Can older adults always compensate the decline in memory accuracy by taking more time to complete the task? The data presented suggest that this is the case when 15 of 30 words must be recalled. It is possible, however, that with higher accuracy demands, for example, if we determine the presentation time needed to recall 100% of the words, with different material, or memory tasks with high interference, this would no longer hold true. A task difference that cannot be compensated for with longer study time might lead to important aging-related constraints on cognitive processing. If old adults can compensate for the decline in memory accuracy with more presentation time, then the questions are whether or not age differences in CRPTs increase in a proportional fashion with the difficulty of the memory task, and whether or not this increase is comparable to the slowing observed in other domains of cognitive functioning. Both questions relate to the *correspondence assumption of cognitive aging* (Cerella, 1990); that is, the assumption that young and old adults (or young adults and children) do not differ in the kind and sequence of mental operations, but only in a general characteristic of the cognitive system (such as slowing or susceptibility to internal processing errors).

CRPTs are available from 4 experiments with a total of 10 different conditions. A simple graphical way to check the possibility that age differences increase with the difficulty of the experimental condition is to plot CRPTs of old adults against those of young adults of corresponding conditions (Brinley, 1965; see also Kail, this volume; Salthouse, this volume). In Fig. 5.6, the regression line represents young and old adults' time demands for equal accuracy. For example, the triangle in the lower left gives the time that was needed by both age groups when they had to recall 12 of 16 words (75% accuracy); the triangle in the upper right gives the

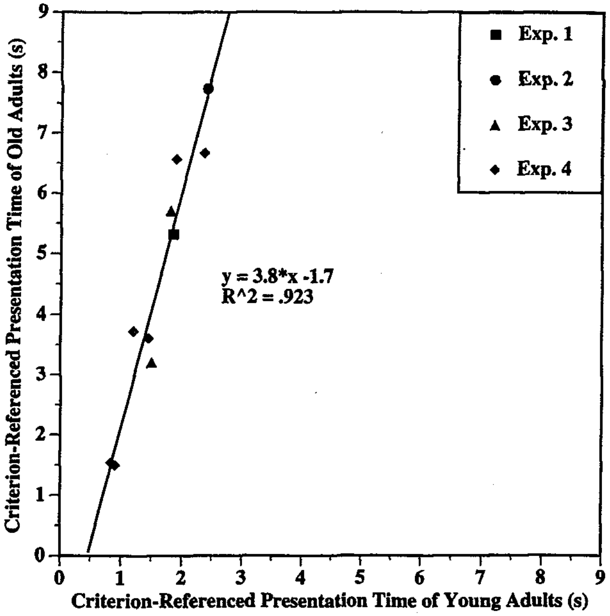

FIG. 5.6. Meta-analysis of age differences in criterion-referenced presentation times (equal-accuracy young–old function) based on four experiments (Kliegl & Lindenberger, 1993; Baltes & Kliegl, 1992, second training phase; Thompson & Kliegl, 1991; Kliegl, Mayr, & Krampe, 1994).

values for 16 out of 16 words (100% accuracy) in the same experiment. The slope of the regression of old on young adults' CRPTs was 3.8; the amount of variance explained by the linear regression was 87%. This highly systematic relation was obtained despite the fact that the experiments were quite different in their design. For example, they differed in the length of the lists, which ranged from 16 to 30 words. They also differed in the criterion; we used values between 50% and 100%. The common feature across all experiments was that they required the generation of memory traces on the basis of a mnemonic technique. Manipulations of the difficulty of the memory task affected young and old adults in a similar way when we look at proportionate age differences in CRPTs. Whatever manipulation increased the presentation time required by young adults by 1 sec, increased the presentation time required by old adults by an additional 3.8 sec.

The slope of 3.8 suggests that the effects of age on episodic memory are more than twice as large as one would expect from much of the other cognitive aging research, in particular from research based on tasks with response latencies as a dependent variable. When performances of old adults are plotted against those of young adults in a similar way, the slope of the best fitting linear function is about 1.5 to 1.8 (for a review, see Cerella, 1990). Thus, the determination of CRPTs reveals larger age differences in cognitive processing time for memory than do traditional measures of cognitive aging. There is a confound between type of task and method of assessment: Perhaps the steeper slope in episodic memory compared to search tasks is not the inherently greater complexity of the former, but is due to the format of assessment—that is, CRPTs instead of response times. Therefore, we determined the slope of search tasks also with CRPTs—the amount of presentation time required to achieve various levels of accuracy in searching for words and figural objects. The slope obtained for episodic memory tasks was significantly steeper than the slope based on CRPTs without demands on episodic memory, such as simple visual and word search tasks (Kliegl, Mayr, & Krampe, 1994; Mayr & Kliegl, 1993). Proportional models adequately describe the age difference; there is not much support for models postulating a power or quadratic function for the shape of the equal-accuracy young–old function (Cerella, 1990; Myerson, Hale, Wagstaff, Poon, & Smith, 1990).

TIME-ACCURACY FUNCTIONS

Determining More Than One CRPT

The determination of criterion-referenced presentation times we used to provide practice conditions of intermediate difficulty for each participant triggered a new line of research (Kliegl et al., 1994). Obviously, if we can determine the amount of time required to reach a specific level of accuracy, we should also be able to determine the amount of time required for any level of accuracy. Indeed, the data collected to determine CRPTs for three different accuracy criteria were sufficient to determine complete time-accuracy functions covering the entire range between chance and asymptotically perfect performance. Most importantly, as shown in Fig. 5.7a, condition-specific functions of this kind could be determined for individual subjects.

The graphs illustrate, for a word scanning and a memory task, how presentation time relates to performance accuracy in one young and one old adult. In word scanning, we measured the time demand for reading four words; in the

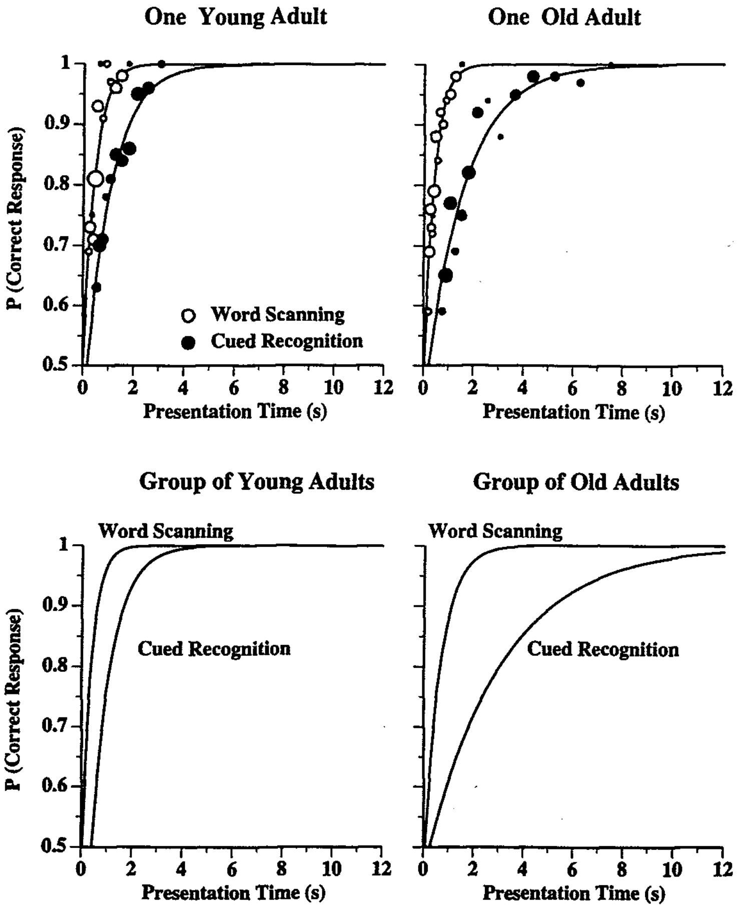

FIG. 5.7. (a) Individual time-accuracy functions for one young and one old adult in word scanning and cued recognition. (b) Corresponding functions for groups of young and old adults. Curves are based on the means of two parameters (x-intercept, slope) estimated for each person in each condition (Kliegl, Mayr, & Krampe, 1994).

memory task, we measured the time demand for reading and remembering a word pair. Procedural details about how one obtains enough information at the level of experimental conditions for individual subjects were described in Kliegl et al. (1994). Briefly, the adaptive determination of CRPTs selectively samples for each experimental condition and each subject the segment of the presentation-time dimension that corresponds to the specified accuracy criterion. By combining data for different criteria, scatterplots can be produced with mean accuracy as a function of presentation time. The size of the symbols in Fig. 5.7a codes the number of times the particular presentation time was sampled for this person. The number and sizes of these symbols differed across tasks and between persons because of the adaptive testing procedure. The continuous lines show the best fitting exponential functions for one subject. Group curves can be computed by averaging the free parameters (intercept and slope) for young and old adults (Fig. 5.7b).

The difficulty of interpreting interactions related to presentation time and experimental condition were already touched upon (see Fig. 5.1). Problems are exacerbated if, in addition, an organismic variable (such as age group) must be considered. Fortunately, if a specific functional relation between presentation time and accuracy is compatible with the data (e.g., if negative exponentials such as those shown in Figs. 5.1 and 5.7 yield acceptable goodness-of-fit statistics), the effect of age with respect to the implemented experimental manipulations can be addressed in a way that is compatible with the line of reasoning advanced thus far: If we plot old adults' time demands over those for young adults for corresponding levels of accuracy, we obtain a young–old function for each experimental condition that, for negative exponential time-accuracy functions, turns out to be linear (see Fig. 5.8a). Moreover, a repeated-measures analysis of variance of the logarithm of parameter estimates for slopes of the exponential functions (estimated for each subject in each condition) provides a test of whether or not the slopes of the young–old functions are significantly different from each other (Kliegl et al., 1994). The set of data displayed in Fig. 5.8 passed this test. Therefore, proportional age differences in CRPTs for word scanning are significantly smaller than those for episodic memory.

An alternative presentation of the data, plotting for equal accuracy time demands of the memory task over the time demand for word scanning, yields state traces for young and old adults (see Fig. 5.8b; Bamber, 1979; Kliegl et al., 1994). The significant difference between young–old functions implies a significant difference between state traces. The significant difference between state traces implies an interaction between age group and word scanning for predicting criterion-referenced presentation times in the complex memory task with criterion-referenced presentation times from the simple word scanning task. Thus, the approach implicitly provides a statistical test of the significance of unique age-related variance in the complex task—that is, of age-related variance that cannot be accounted for by interindividual differences in the simple task (see

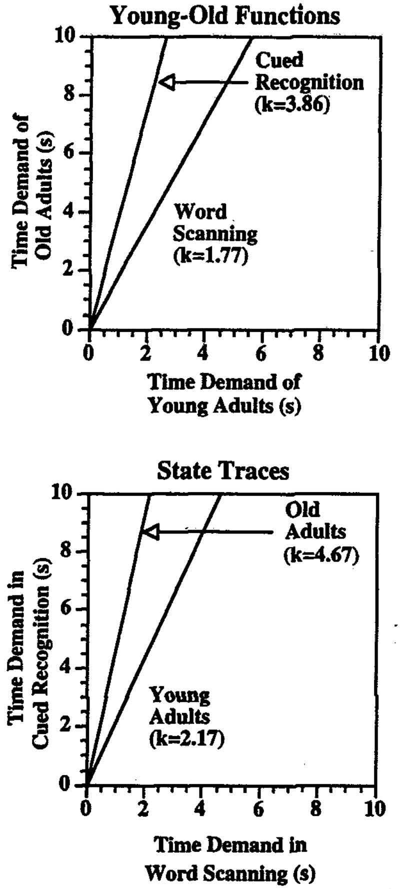

FIG. 5.8. Time demands for equal accuracy. (a) Time demand of old adults as a function of time demand of young adults. (b) Time demand in complex task as a function of time demand in the simple task.

Salthouse, 1991, 1993, this volume). Frequently, in hierarchical regression analyses, only the incremental r^2 due to age is determined. Such an effect does not imply a difference in slope, but a difference in the intercept for the two age groups; within each age group the slopes relating the complex to the simple task could still be parallel. The difference in slopes reported here corresponds to a significant effect of the multiplicative interaction term of age and simple task, rather than the main effect of age by itself. Only the latter provides evidence for task-specific age-related slowing factors.

Relation of Single CRPT to Time-Accuracy Function

Depending on the complexity of the tasks examined, it may be time consuming to determine CRPTs for several levels of accuracy. What is the additional information gained from complete time-accuracy functions? The relation between

CRPTs (interpreted to yield estimates of processing time) and processing-time estimates based on the slope parameter of the time-accuracy function are as follows: CRPTs are indicators of elaboration times required to achieve a specified level of accuracy with all the interpretational qualifications mentioned earlier in the chapter. Thus, each point on the time-accuracy curve represents a specific CRPT. If we assume (a) that the negative exponential is the correct specification for all persons, young and old, and (b) that differences between persons are restricted to the fundamental processing time—that is, the slope of the function, then any single CRPT specifies the correct ranking of individuals for the entire functional range of performance on a task (see Fig. 5.9a).

Unfortunately, there are alternative possibilities. As illustrated in Fig. 5.9b, for example, group differences in the minimum amount of time required for the function to get better than chance performance, that is the x-intercept of the curve (parameter a), could also yield a ranking of individuals compatible with a single CRPT, although no difference was assumed for slope (parameter b) and asymptotic level of performance (parameter c). Similarly, differences in the asymptote (parameter c) could generate a ranking of individuals compatible with the ranking on a single CRPT (Fig. 5.9c). Thus, whereas in most cases a single CRPT will probably work well as a proxy of processing time, the complete function is necessary to correctly delineate the contributions of parameters other than processing time.

PERSPECTIVES AND FUTURE DIRECTIONS

An important goal of cognitive aging research—and of developmental research in general—is an operationalization of concepts such as cognitive potential and limits (Baltes, 1993) or processing capacities and resources (Salthouse, 1985, 1991). For the case of episodic memory, it was shown how a move from assessing experimental effects by manipulations of presentation time to assessing them via the determination of criterion-referenced presentation times can yield estimates of a general parameter of cognitive efficiency—that is, the processing time required for comparable reductions of error probability across experimental conditions and age groups. Also determining several CRPTs per experimental condition per person will lead to complete time-accuracy functions. These can be used to assess interactions between age and experimental condition in terms of proportional differences.

We applied this procedure in different contexts. In one recent study, the goal was to examine age differences in proactive interference with this paradigm. In the tradition of verbal learning, we contrasted time-accuracy functions for (A-B, A-C)- and (A-B, A-Br)-paradigm. Initial results indicate that the critical age difference appears to be in the asymptote of the functions. Old adults, even with generous allotments of presentation time and after much practice, appear to be

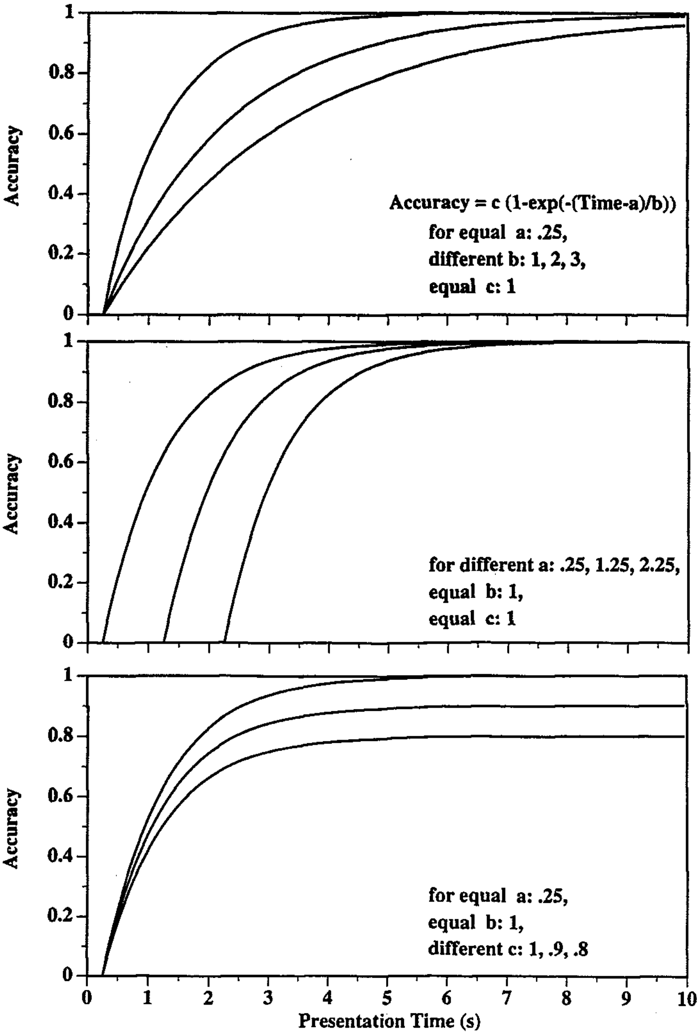

FIG. 5.9. Influence of three parameters of a negative exponential function on horizontal ordering of time-accuracy relations (a: intercept with x-axis; b: slope; c: asymptote).

unable to achieve maximum accuracy. There were no age differences in the ratios of processing time for the two episodic time-accuracy functions (Kliegl, Krampe, & Mayr, 1993).

The determination of time-accuracy functions is not limited to episodic memory processes. Indeed, focusing on the time demand to achieve various levels of accuracy can help bridge task domains that, in the past, were primarily separated by their choice of dependent measures. For example, in simple search tasks the typical measure is the reaction time, in complex reasoning (or episodic memory), accuracy is used more frequently. The determination of CRPTs and time-accuracy functions for representative tasks of both domains allowed us to isolate two proportional slowing factors for tasks characterized by the presence or absence of coordinative demands on working memory (Kliegl et al., 1994; Mayr & Kliegl, 1993). In a recent study, this approach was also used to contrast information-processing dynamics in children, young adults, and old adults. Children were less affected by coordinative demands than old adults (Mayr, Kliegl, & Krampe, 1993).

Time-accuracy functions are linked to models of information accumulation. For many tasks, the expectation is that this function takes a negatively accelerated course. The negative exponential is but one possibility; power, hyperbolic, and logistic functions are alternatives. With a high density of observations it may be possible to empirically rule out one or the other function (Kliegl et al., 1994). Such exclusion of functions constrains models of information integration. Moreover, there are task domains for which the time-accuracy relation may follow a very different course. For example, in ongoing research, we showed that both very short and very long time intervals render it more difficult to reproduce a specific rhythm (Krampe, Kliegl, & Mayr, 1993). The accuracy to reproduce a rhythmic sequence of strokes on the piano will be lower for very short time intervals because of biomechanical constraints; it will also be lower relative to an optimum for very long intervals due to an increase in cognitive coordination. Again, such time-accuracy functions vary according to experimental condition (e.g., isochrone rhythms vs. polyrhythms) and group characteristics (e.g., amateur vs. professional pianists). Thus, although the functions may initially appear to be largely descriptive in character—because they generate a vector of dependent variables—their inherent linkage to different assumptions about cognitive processing dynamics implies strong theoretical propositions.

Two limitations of the research carried out thus far relate to the specificity of the processing dynamics. First, we need to become more precise about the component processes generating such time-accuracy functions. Time-accuracy functions are basically cumulative probability functions; that is, for any random presentation time they tell us the probability that the cognitive process completed at a time less than or equal to this time. If we differentiate the cumulative probability function we obtain the probability density function that gives us the completion probability for any particular presentation time. Almost always, this probability density function is the result of summing process durations associated with two or more cognitive component processes—the total time is the result of a convolution of component times (e.g., McClelland, 1979; Townsend & Ashby, 1983). The determination of condition-specific time-accuracy functions at the individual level is bound to facilitate such deconvolutions of complex cognitive processes and the identification of process-specific developmental differences.

The second limitation concerns the assumption of homogeneity of processing within individuals across presentation times. The examples presented assume that the same type of cognitive processing occurs irrespective of whether performance is close to chance or close to perfect. This is unlikely to be true. At least for episodic memory tasks, there are shifts in retrieval strategies that depend on the overall level of available information. The negative exponential (or a continuous alternative function) is a preliminary platform from which shifts in cognitive strategy can be documented and examined in greater detail. The success of such microgenetic work will depend greatly on the observational density one is willing to realize for individuals. Ideally, we should trace the developmental course of shifts in cognitive strategies within individual time-accuracy functions, thus linking microgenetic processing dynamics with ontogenesis (see also Siegler, 1987, 1991, this volume).

In adopting the time-accuracy function approach, one sacrifices experimental equivalence in presentation times for functional equivalence in terms of performance accuracy. The problems one encounters when experimental equivalence is enforced were illustrated. Of course, functional equivalence incurs problems of comparability across groups and conditions. The tolerance of this inequivalence will depend on the coherence that the determination of processing times from time-accuracy functions brings to developmental and cognitive issues.

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