A Developmental Study of the Storage and Retrieval of Information

R. A. Chechile
Tufts University

C. L. Richman
Wake Forest University

C. Topinka and K. Ehrensbeck
Tufts University

Chechile, R. A.; Richman, C. L.; Topinka, C.; and Ehrensbeck, K. *A Developmental Study of the Storage and Retrieval of Information*. Child Development, 1981, **52**, 251–259. First- and sixth-grade students as well as college-age students were examined with a procedure that generates separate measures of storage and retrieval components of the probability of correct recall. Recall performance was found to improve with each advancing age level. However, the storage measure improved in accuracy only between first-grade and sixth-grade age levels, and then it stabilized. Retrieval accuracy increased with each age level. The major conclusion of the study was that the fundamental memory processes of storage and retrieval develop at different rates.

Developmental psychologists have suggested a number of factors as being responsible for the relative difficulty in memory retention experienced by children, but these factors can all be related to either problems with the storage of information or problems with the subsequent retrieval of that information. Evidence for the development improvement in retrieval has been provided in several ways, such as by the differential effectiveness of retrieval cues (Kobasigawa 1974), by the differential rates of output interitem pauses (Belmont & Butterfield 1969), and by the differential delayed free recall rates for an item initially learned and not studied further (Buschke 1974a, 1974b). Also, there is evidence for the developmental improvement in storage, as suggested by the differential rates of interitem study times (Belmont & Butterfield 1969) and by the differential rate of initial recall shown with Buschke's selective reminding technique. In light of these findings, a question emerges as to whether storage and retrieval processes develop at different rates. This question is difficult to answer without establishing measures for storage and retrieval on a common and equally sensitive scale. Recently, Chechile and his associates (i.e., Chechile 1977, 1978; Chechile & Butler 1975; Chechile & Meyer 1976; Gerrein & Chechile 1977; Skoff & Chechile 1977), working with adult populations, have developed and used a quantitative technique for obtaining separate ratio-scale measures for storage and retrieval that can be applied to an individual subject. In the present study, the same technique is employed to investigate the rates of developmental improvement for the underlying storage and retrieval processes.

The experimental task for separating storage and retrieval is one where recall trials are randomly intermixed with yes-no recognition trials. Also on recognition trials, three-point confidence judgments are required (with a 3 rating denoting maximum confidence). For this general paradigm, there is a task analysis which involves parameters for storage, retrieval, guessing, and confidence judgments. Contingent on the fairly general assumptions of the task anal-

This research was supported in part by grant MH21288 from the United States Public Health Service of the National Institute of Mental Health. The authors would like to thank the administrators, teachers, staff, and students of the Reading, Massachusetts, school system for their cooperation in this research. This experiment was reported in part at the 18th Annual Meeting of Psychonomic Society in Washington, D.C., 1977. Requests for reprints should be sent to Dr. Richard Chechile, Department of Psychology, Tufts University, Medford, Massachusetts 02155.

[*Child Development*, 1981, **52**, 251–259. © 1981 by the Society for Research in Child Development, Inc.
0009-3920/81/5201-0029$01.00]

ysis, probabilistic measures of storage and retrieval are obtained that uniquely factor the probability of correct recall. An advantage of these probabilistic measures in comparison to other approaches that distinguish between storage and retrieval (e.g., Buschke 1973, 1974a, 1974b; Belmont & Butterfield 1969) is that both processes are measured on a standardized ratio scale. Of course, these probabilistic measures also have a disadvantage since they relate to the overall success or failure of storage and retrieval and not to subtle qualitative gradations in the underlying process. Nevertheless, with these ratio-scale measures, the relative efficiency of storage and retrieval can be examined at any age—thereby providing a detailed description of memory development in terms of fundamental memory processes.

Task analysis.—Storage is dichotomized as either sufficient or insufficient. The cases of fractional storage and no information storage are grouped and characterized as insufficient since in both cases the subjects could not have recalled the entire target item. We are not assuming that fractional storage is impossible; rather, we are just disregarding the distinction between all the incomplete representations. Incidentally, sufficient storage means more than just item information since in some tasks, order or position, information is also required for the recall of the target. Thus, on any trial, the subject either has sufficient or insufficient storage concerning the target information; and across many trials the proportion of times that the subject sufficiently stores the target information is defined as θ_s, the probability of storage.

Given that sufficient storage has occurred on a trial, then retrieval is dichotomized into successful retrieval of all of the stored information or unsuccessful retrieval. Across the trials where there is sufficient storage, the proportion of times that the subject successfully retrieves the information is defined as θ_r, the probability of retrieval. Therefore, the probability of correct recall of a complex item that is unlikely to be guessed is just $\theta_s \cdot \theta_r$, since correct recall requires both sufficient storage and successful retrieval.

The model for old recognition is shown in figure 1 as a tree diagram. It is assumed that when the subject has sufficient storage of a target, he will give a "yes 3" response. This assumption implies that there are no retrieval problems on old recognition trials if there is sufficient storage of the target. However, with insufficient storage, the subject may guess "yes" with probability θ_g. The parameters θ_1, θ_2, θ_3, and θ_4 correspond to the rating processes as illustrated in figure 1.

The distractor recognition model is shown in figure 2. The parameter θ_{dr} represents the probability of successful recognition retrieval when the target is sufficiently stored. After all, the distractor item is not as good a retrieval cue for the target encoding as is the old recognition cue. In essence, the recognition retrieval is assumed to be always successful when an old recognition probe is used, but it is successful with probability θ_{dr} when a distractor probe is used. Consequently, if there are both sufficient storage and successful recognition retrieval on distractor recognition, then the subject responds "no 3." Otherwise, the subject guesses and rates as illustrated in figure 2. For further mathematical details concerning the estimation of parameters, refer to the Appendix.

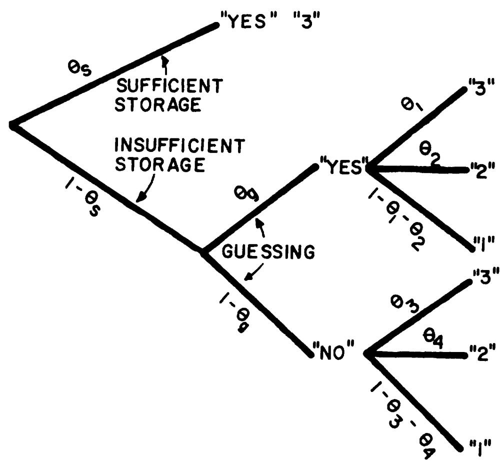

Fig. 1.—Tree diagram for the events in old recognition.

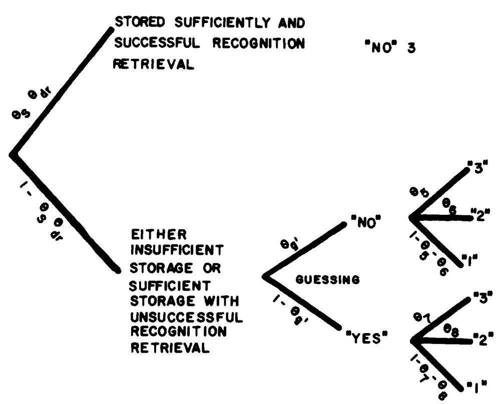

Fig. 2.—Tree diagram for the events in distractor recognition.

The model shows the same storage parameter on recall, old, and distractor recognition trials. This assumption is reasonable because the randomization procedure insures that the subjects have no clue prior to testing as to the type of test procedure used on any particular trial.

The prior studies which used the storage-retrieval separation method have also provided some evidence concerning the validity of the measures. For example, all prior studies have shown that θ_s and θ_r are statistically independent. More specifically, the grand weighted correlation from the past studies is only $-.035$ (based on 736 pair scores). Consequently, the separation procedure has been successful in isolating two different components of the probability of correct recall. Furthermore, in experiment 2, Chechile and Meyer (1976) have shown that memory search time is exclusively related to the retrieval parameter, θ_r. In addition, Chechile (1978) showed a close relationship between θ_s and the speed of old recognition, as would be expected of a valid storage measure. Taken together, these findings support the position that θ_s and θ_r validly correspond to the respective overall success rates of storage and retrieval.

In this research, the storage-retrieval procedure is adapted to the single-trial serial probe task and used to investigate storage and retrieval differences among first-grade, sixth-grade, and college-age levels. In addition, rehearsal instructions are examined as a function of age. It is expected that the college-age subjects will perform well under all rehearsal conditions, but that the performance of the younger subjects will depend on the type of rehearsal instructions. Furthermore, with the present methodology it will be possible to tie any interaction of age with rehearsal conditions to the underlying processes of storage and retrieval.

Method

Subjects.—Forty first-grade, 40 sixth-grade, and 40 college-age introductory psychology students served as subjects. First-grade children were at least 6 years old and sixth-grade children were at least 11 years old. Exact age as to the number of months past their birthdays was not recorded for the elementary school children. The mean age of the college students was 19.68, with a standard deviation of 1.34.

For each age group, there were an equal number of males and females. Also, subjects were randomly assigned to one of two rehearsal conditions of equal size. All subjects were approximately from the same SES (middle- to upper-middle class).

Materials and apparatus.—Stimuli were 90 colored cards with pictures of common objects (e.g., fruit, furniture, etc.). Both "motive-expressive" and "association-picture" cards from the Developmental Learning Material Corporation were used as stimuli. For each stimulus, there was a duplicate.

A metronome was used to time the presentation and test phases of the experiment. Between the presentation and test phases, there was an interpolated task of shadowing tape-recorded digits.

Design.—The design consists of four factors of age (three levels), rehearsal instructions (two levels), sex (two levels), and serial position (three levels). The first three factors are between-subject factors with 10 subjects per condition, whereas the last factor is a within-subjects factor.

Each subject was tested on 18 trials. A trial consisted of presenting five sequentially spaced pictures. Care was taken to insure within each trial that the pictures presented were not related in an obvious fashion. On each trial there was one recall test, one old recognition test, and one distractor recognition test. Only the first, third, and fifth serial positions were tested. The testing order for the three serial positions and type of test trial was counterbalanced across the 18 trials.

The presentation procedure was to turn up each of five face-down pictures for 0.5 sec and then to turn the picture face down again. There was a 2-sec pause between the presentation of one picture and the next. In the overt rehearsal condition, the subjects were instructed to label verbally each picture and then to repeat the picture name three times during the interstimulus interval. In the other rehearsal condition, the subjects were instructed to verbally label each picture but then to remain silent during the balance of the interstimulus interval. Following the presentation of the five pictures, all subjects shadowed 40 random digits for 20 sec. Following the shadowing task, the subjects were given one recall test, one old recognition test, and one distractor recognition test. For the recall test, the experimenter pointed to one of the five face-down cards and asked, "What was here?" For the recognition test, the experimenter showed the subject a duplicate of one of the pictures and asked if that picture had been in a particular position (i.e., "Was this picture here?"). In old recognition tests, the duplicate was placed in the same position as in the original presentation, whereas for the distractor recognition tests, the duplicate was not in the same position. The subject was asked to respond on recognition tests with either a yes or no answer supplemented with a confidence rating of either "sure," "maybe," or "I don't know." The sure, maybe, and I don't know ratings respectively correspond to the 3, 2, and 1 ratings used in the model and shown in figures 1 and 2. Only the pictures in the first, third, and fifth serial positions were tested. The distractors were pictures from the original set of five pictures but from a different serial position (i.e., serial position 2 or 4). A position-preference test was conducted before and after the critical 18 trials to see whether the subjects were learning a strategy as to which serial positions were more likely to be memory targets. On the position-preference test, the subjects were asked to guess what position corresponded to a picture not shown to the subject. If the subjects could detect that the targets were always from the central or end positions, then a significant increase in frequency for those positions would be expected on the final preference test.

Results

The position-preference results show no significant shifts in frequency for any age group, that is, $\chi^2(1) = 1.09$ for first graders, $\chi^2(1) = 0.08$ for sixth graders, and $\chi^2(1) = 1.79$ for the college students. Consequently there is no support for the hypothesis that subjects of any age were developing a shortcut strategy of studying the materials.

Means for correct recall, recognition hit and false alarm rates, and the modal estimates for storage θ_s; retrieval, θ_r; and the guessing parameters θ_g and $\theta_{g'}$ are shown in table 1 as a function of age, rehearsal instructions, and serial position.

The summary results of five separate four-way analyses of variance (ANOVA) performed on the proportion of correct recall, θ_s, θ_r, θ_g, and $\theta_{g'}$, are displayed in table 2. There is a significant age effect for the proportion correctly recalled, as well as for θ_s, θ_r, and $\theta_{g'}$. For the proportion correctly recalled, the age effect is significant between the first- and sixth-grade ages, $t(78) = 5.05$, $p < .00002$, as well as significant between the sixth graders and the college students, $t(78) = 2.37$, $p < .03$. The retrieval component of recall, θ_r, shows a similar pattern (i.e., $t[78] = 3.24$, $p < .001$ for the difference between the first and sixth graders and $t[78] = 3.40$, $p < .001$ for the difference between the sixth graders and the college students). However, the storage component of recall, θ_s, shows a significant difference only between the first and sixth graders, $t(78) = 3.29$, $p < .001$. Thus the change in correct recall between the first and sixth graders is due to both storage and retrieval processes, but the change between the sixth graders and college students is due to retrieval alone.

Serial position has a significant effect on all of the measures shown in table 2. For the proportion correctly recalled, the third serial position is suppressed as compared with either the first or fifth serial positions, smallest $t(119) = 4.27$, $p < .00005$. Also, there is a greater primacy effect than a recency effect, $t(119) = 8.84$, $p < .0000001$. For the storage parameter, there are both primacy and recency effects, smallest $t(119) = 13.70$, $p < .0000001$; however, there is no significant difference in the magnitudes of the primacy and recency effects. For the retrieval parameter, there is only a significant primacy effect, $t(119) = 7.13$, $p < .0000001$. Consequently, the primacy effect is due to enhanced storage and retrieval, but the recency effect is due only to enhanced storage.

While there is no main effect for rehearsal conditions, the rehearsal instruction nevertheless did significantly interact with age and with age $\times$ serial position for the storage measure (see table 2). The presence of these interactions demonstrates that the age effect for storage is dependent on the serial position and the type of rehearsal condition. Dunn multiple comparisons on the age $\times$ rehearsal condition interaction show that the sixth graders improve their storage over that of the first graders under silent rehearsal, but the sixth graders and the college students do not differ significantly. However, under conditions of rote vocal rehearsal, the sixth graders are no longer significantly different from the first graders, but the college students still maintain an improvement in storage in comparison to the first graders. Further Dunn multiple comparisons show that the interaction of rehearsal with age and serial position is due to the fact that the age $\times$ rehearsal interaction holds for the central serial position but not for the extreme serial positions, most likely because of a ceiling effect for the end serial positions. Unlike the storage measure, no interactions are significant for the retrieval measure. Furthermore, since the overall level of θ_s is high and that of θ_r is low, the probability of correct recall is thus influenced

TABLE 1

Group Means for Correct Recall, Hit Rate, False Alarm Rate, Storage, Retrieval, and the Recognition Guessing Measures

	First-Grade Rehearsal					
	Vocal (SP)			Silent (SP)		
	1	3	5	1	3	5
Correct recall	.383	.100	.175	.350	.167	.183
Hit rate	.908	.775	.950	.950	.775	.942
False alarm rate	.092	.450	.142	.050	.483	.150
Storage (θ_s)	.822	.490	.871	.857	.482	.825
Retrieval (θ_r)	.567	.116	.258	.462	.360	.316
Old recognition guessing (θ_0)	.596	.553	.850	.829	.594	.805
Distractor recognition guessing (θ_0')	.780	.413	.717	.864	.374	.693

	Sixth-Grade Rehearsal					
	Vocal (SP)			Silent (SP)		
	1	3	5	1	3	5
Correct recall	.550	.150	.333	.608	.283	.308
Hit rate	.933	.842	.942	.975	.925	.983
False alarm rate	.058	.275	.092	.100	.317	.058
Storage (θ_s)	.899	.514	.917	.959	.763	.962
Retrieval (θ_r)	.697	.352	.402	.703	.429	.404
Old recognition guessing (θ_0)	.833	.658	.777	.843	.773	.892
Distractor recognition guessing (θ_0')	.785	.505	.733	.845	.425	.892

	College Rehearsal					
	Vocal (SP)			Silent (SP)		
	1	3	5	1	3	5
Correct recall	.617	.308	.450	.642	.300	.433
Hit rate	.950	.800	.975	.983	.792	.958
False alarm rate	.058	.192	.108	.008	.242	.033
Storage (θ_s)	.924	.689	.938	.934	.542	.941
Retrieval (θ_r)	.761	.577	.547	.808	.646	.533
Old recognition guessing (θ_0)	.850	.568	.878	.931	.565	.794
Distractor recognition guessing (θ_0')	.924	.637	.735	.941	.563	.878

Note.—SP refers to serial position.

TABLE 2

Summary of Five Separate Analyses of Variance

Source	df	Correct Recall MSE	Correct Recall F	Storage MSE	Storage F	Retrieval MSE	Retrieval F	θ_g MSE	θ_g F	$\theta_{g'}$ MSE	$\theta_{g'}$ F
Between subjects:											
Age (A)	2	...	25.28**	...	7.91**	...	21.92**	...	1.95	...	3.89*
Rehearsal instructions (B)	1	...	1.82	...	1.14	...	1.76	...	1.70	...	.61
Sex (C)	1	...	8.28**	...	.01	...	4.43*	...	2.11	...	2.56
A × B	2	...	.27	...	3.63*	...	.13	...	.53	...	.07
A × C	2	...	.49	...	.28	...	1.33	...	.19	...	.07
B × C	1	...	.31	...	.24	...	.34	...	1.44	...	.45
A × B × C	2	...	1.49	...	.32	...	1.53	...	.96	...	.34
Error	108	356	...	366	...	609	...	878	...	960	...
Within subjects:											
Serial position (D)	2	...	77.51**	...	183.85**	...	40.92**	...	14.90**	...	52.61**
A × D	4	...	1.54	...	.34	...	1.31	...	1.50	...	.85
B × D	2	...	1.28	...	.68	...	2.15	...	.73	...	2.56
C × D	2	...	.00	...	.33	...	.38	...	1.30	...	1.08
A × B × D	4	...	.76	...	4.25**	...	.92	...	.89	...	.57
A × C × D	4	...	.67	...	3.33*	...	1.31	...	.41	...	.76
B × C × D	2	...	.21	...	.14	...	.12	...	.79	...	2.29
A × B × C × D	4	...	1.41	...	1.02	...	1.86	...	.77	...	.33
Error	216	213	...	135	...	339	...	784	...	560	...

Note.—The dependent measures are the proportion of correct recall; the storage measure, θ_s; the retrieval measure, θ_r; and the guessing measures, θ_g and $\theta_{g'}$. All ANOVAS are based on the standard arcsine transformation of the proportions.

* $p < .05$.

** $p < .01$.

to a much greater degree by θ_r, thereby resulting in no interactions being significant for the recall measure.

The gender of the subject is involved essentially with two effects. First, there is a main effect for correct recall with females recalling more than males (i.e., .387 vs. .318). This main effect is due entirely to the retrieval component of recall, θ_r (i.e., .535 vs. .464 for females and males, respectively), as shown in table 2. Second, there is a significant interaction of gender with age and serial position for the storage measure. Dunn multiple comparisons show that this interaction occurs because the age effect between the first and sixth grades holds for males and for the central serial position, but not for females or for the end serial positions.

One potential retrieval mechanism for the age effect is differential proactive interference (PI) from interlist items. However, given the experimental design, it is not possible to examine directly how θ_r varies across the 18 trials. Nevertheless, the recall measure is a good measure of retrieval for the two older groups since θ_s is equivalent for those groups. To explore the PI hypothesis further, a two-way ANOVA was performed for the correct recall measure with age (two levels) and blocks of three trials (six levels) as factors. The blocking of three trials is required in order to offset the effect of serial position. The analysis shows significant effects for age, $F(1, 78) = 5.93$, $p < .02$, MSE $= 1.393$, and blocks, $F(5,390) = 18.82$, $p < .0001$, MSE $= 0.533$, but not for the age × blocks interaction, $F(5,390) = 1.69$, N.S., as would be expected if there were greater PI for the sixth graders. The block effect is due to a greater recall rate for the first two blocks.

In order to insure that spurious effects were not detected as a consequence of performing separate univariate analyses, both θ_s and θ_r were included in a single five-way split-plot ANOVA, with the factors being age, rehearsal instructions, gender, serial position, and process (i.e., storage vs. retrieval). Furthermore, Geisser-Greenhouse conservative F tests were used to insure the robustness of the analysis in regard to possible violations of assumptions concerning the variance-covariance matrix. Significant conservative F ratios were found for age, $F(2,108) = 31.25$, $p < .0001$, MSE $=$ 0.076, serial position, $F(1,108) = 128.24$, $p <$ .0001, MSE $= 0.037$, process, $F(1,108) =$ 162.94, $p < .0001$, MSE $= 0.097$, the age × process interaction, $F(2,108) = 6.19$, $p < .003$, MSE $= 0.097$, and the serial position × process interaction, $F(1,108) = 41.05$, $p < .0001$, MSE $= 0.037$. The interpretations of all of these robust effects are the same as reported for the univariate analyses. Furthermore, the product-moment correlation between θ_s and θ_r is 0.055, which is nonsignificant, thus replicating the independence of these measures found in the previously cited studies.

Both guessing measures changed with respect to serial position, and this effect is due to poorer guessing for the central serial position. Guessing is assumed to occur in recognition testing when there is insufficient storage. However, insufficient storage can include both the case where there is no information stored and the case where there is fractional storage. Fractional (but insufficient) information can aid the subject to give an educated guess above a chance level. Consequently, the changes in the guessing measures could be due to differences in the amount of fractionally stored information. An example of fractional storage might be typified by a subject who is familiar with the target picture but does not know, among a few adjacent positions, where the picture belongs. To test for the presence of fractional storage, an additional analysis of variance was performed on $\theta_{g'} - (1 - \theta_g)$, which is the difference in the probability to answer no between the two types of recognition tests when there is insufficient storage. If there is fractional storage, then there would be a greater tendency for the subject to say no in distractor recognition than in old recognition since no would be the correct response for distractor recognition but the incorrect response for old recognition. Furthermore, the statistic $\theta_{g'} - (1 - \theta_g)$ is equal to $\theta_g - (1 - \theta_{g'})$ which is the difference in the yes response between old and distractor recognition when there is insufficient information. The analysis shows a significant effect for age, $F(2,108) = 5.38$, MSE $= 0.239$, $p < .006$, and for serial position, $F(2,216) = 52.99$, MSE $= 0.218$, $p < .0000001$, thus indicating the presence of differential amounts of fractional storage. Orthogonal contrasts of the age variation in the measure of fractional storage, that is, $\theta_{g'} - (1 - \theta_g)$, show no significant differences between older age groups, but the first-grade students show significantly less fractional storage compared with the older students, $F(1,108) = 10.19$, MSE $= .239$, $p < .002$. Consequently, the fractional storage measure shows a pattern similar to the sufficient storage measure.

Discussion

Any conclusions concerning storage and retrieval are dependent on the validity of the model of those processes. However, the finding of highly significant effects for the processing factor, the processing $\times$ age interaction and the processing $\times$ serial position interaction, even with conservative F ratios, provide justification that the model is successful in separating two different components of the probability of correct recall. This conclusion is further supported by the lack of a significant correlation between θ_s and θ_r. Thus the θ_s and θ_r measures show evidence of internal validation.

Like several previous studies (e.g., Belmont & Butterfield 1969; Buschke 1974a, 1974b), the current experiment shows that both storage and retrieval processes undergo developmental change. Unlike the prior research, however, the present study employs ratio measurement scales equally sensitive to changes in storage and retrieval. The major new finding of this approach is that storage and retrieval processes develop at different rates. For storage, the overall level is high and the developmental improvements reach apparent stability by the sixth grade. For retrieval, there is an overall lower level of performance, and there is a more persistent improvement that occurs with age.

The rehearsal condition $\times$ age interaction found for storage has some important implications regarding the development of encoding strategies. It seems reasonable to assume that the rote vocal rehearsal condition is a form of "maintenance" rehearsal as opposed to an "elaborative" rehearsal (cf. Craik & Watkins 1973). In the silent rehearsal condition there is greater opportunity for elaborative rehearsal, and it is expected, with delayed memory testing, that an elaborative coding strategy will lead to improved performance. Nevertheless, the first graders do no better in silent rehearsal condition than they do in the vocal rehearsal condition, indicating that first-grade children used a maintenance type of rehearsal even when given the opportunity for elaborative rehearsal. Sixth-grade children, however, do show improved storage under silent rehearsal conditions. College students show good storage under both vocal and silent rehearsal conditions, presumably because by college age even a vocal rehearsal can lead to an enrichment of the memory encoding.

The same developmental pattern was found for fractional storage as was found for sufficient storage. By definition, fractional storage cannot contribute to correct recall, but nevertheless it is important for the rate of learning since the missing features can be added on subsequent relearning trials. Consequently, it is expected that the youngest children would not increase their knowledge of the list as rapidly as the older children if there were a second presentation of the target material.

Finally, the failure to retrieve stored items could be either a result of interlist interference from previously stored items or a result of intralist interference. Hence the developmental effect for retrieval could have been produced by age-dependent interference. In this experiment, a test for age-dependent interlist interference failed, thereby suggesting, by default, that the retrieval changes with age are a result of age-dependent intralist interference. There is no direct support for such a hypothesis, although the hypothesis seems reasonable in light of the finding by Cole, Frankel, and Sharp (1971) that the number of clusters in the first trial of a free-recall task significantly increases with age. If the total number of stored items are the same, then it stands to reason that there should be fewer items within each cluster for the older subjects. If the subjects can restrict the search set to a cluster, then the success rate of retrieval would be inversely related with cluster size since there is greater response competition for larger clusters.

Appendix

Chechile and Meyer (1976) discuss in detail the issue of estimating model parameters for storage and retrieval. The most general model developed by Chechile and Meyer separates retrieval into true components, θ_{dr} (distractor recognition retrieval), and θ_{rr} (the remainder of the total retrieval, that is, $\theta_r = \theta_{dr} \cdot \theta_{rr}$). Furthermore, they show that a Bayesian procedure can be used to estimate the model parameters. In general, a Bayesian inference generates a posterior distribution, given the sample data. The notation for the data is n_1 and n_2 for the respective number of correct and incorrect recalls and $n_{i1}, n_{i2}, \ldots, n_{i6}$ for the number of yes 1, yes 2, yes 3, no 1, no 2, and no 3 responses in a type of recognition trial where $i = 1$ for old recognition and $i = 2$ for distractor recognition. The posterior distributions for θ_s, θ_{dr}, θ_{rr}, θ_g, and $\theta_{g'}$ are computed in accordance to the following equations:

$$P(\theta_s \mid \{n_i\}, \{n_{ij}\}) = K_1 P_1 \int_0^1 I P_2 d\theta_{dr}$$

$$P(\theta_{dr} \mid \{n_i\}, \{n_{ij}\}) = K_2 \int_0^1 I P_1 P_2 d\theta_s$$

$$P(\theta_{rr} \mid \{n_i\}, \{n_{ij}\}) = K_3 \int_0^1 \int_0^1 (\theta_s\theta_{dr}\theta_{rr})^{n_1}(1 - \theta_s\theta_{dr}\theta_{rr})^{n_2} P_1 P_2 d\theta_{dr} d\theta_s$$

$$P(\theta_g \mid \{n_i\}, \{n_{ij}\}) = K_4 \int_0^1 \int_0^1 I P_2 G_1 \, d\theta_{dr} d\theta_s$$

$$P(\theta_{g'} \mid \{n_i\}, \{n_{ij}\}) = K_5 \int_0^1 \int_0^1 I P_1 G_2 d\theta_{dr} d\theta_s \, ,$$

where K_1 to K_5 are constants and

$$I = (\theta_s\theta_{dr})^{-1} \int_0^{\theta_s\theta_{dr}} x^{n_1}(1 - x)^{n_2} dx$$

$$P_1 = (1 - \theta_s)^{n_0 - n_{13}} \theta_s^{n_{13}} \sum_{i=0}^{n_{13}} \frac{C(n_0 + 1, n_{13} - i)(1 - \theta_s/\theta_s)^i}{C(n_{11} + n_{12} + i + 2, 2)}$$

$$P_2 = (1 - \theta_s\theta_{dr})^{n_d - n_{26}} (\theta_s\theta_{dr})^{n_{26}} \sum_{j=0}^{n_{26}} \frac{C(n_d + 1, n_{26} - j)(1 - \theta_s\theta_{dr}/\theta_s\theta_{dr})^j}{C(n_{24} + n_{25} + j + 2, 2)} \, ,$$

$$G_1 = \theta_s^{n_{13}}(1 - \theta_s)^{n_0 - n_{13}} \sum_{i=0}^{n_{13}} \frac{([1 - \theta_s]/\theta_s)^i \theta_g^{n_{11}+n_{12}+i}(1 - \theta_g)^{n_{14}+n_{15}+n_{16}}}{(n_{13} - i)!\,(n_{11} + n_{12} + i + 2)!} \, ,$$

$$G_2 = (\theta_s\theta_{dr})^{n_{26}}(1 - \theta_s\theta_{dr})^{n_d - n_{26}} \sum_{j=0}^{n_{26}} \frac{([1 - \theta_s\theta_{dr}]/\theta_s\theta_{dr})^j \theta_{g'}^{n_{24}+n_{25}+j}(1 - \theta_{g'})^{n_{21}+n_{22}+n_{23}}}{(n_{26} - j)!\,(n_{24} + n_{25} + j + 2)!} .$$

The $C(n, m)$ is the standard combinatorial of n and m. Modes of the distributions are used as point estimates.

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