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Priming and Retrieval from Short-Term Memory: A Speed Accuracy Trade-Off Analysis

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Subjects saw 16 consonants presented serially at a .5-second rate. Then following a .7-second blank interval, a test consonant was presented which subjects judged to be present or not in the preceding list. A tapping speed accuracy trade-off method was employed in which subjects pressed both "yes" and "no" keys every .4 seconds, beginning during the blank interval. Both keys are pressed simultaneously at first in this method, but as soon as possible the chosen response is to lead the other by a time interval that reflects confidence in the decision. Memory strength in storage declined over a 6-second interval containing 12 items, but priming of retrieval dynamics was found only for the last item in the memory set. Active (primary) memory under these conditions appears to be limited to the very last thought.

Any perturbation in behavior that is contingent upon some event and lasts for only a few seconds after that event may be called short-term memory. But calling different perturbations by the same name does not mean they result from the same underlying memory trace. The present paper is concerned with deciding whether two types of short-term perturbations, item strength and priming, result from the same underlying trace or different traces. The method used is to determine whether the forgetting dynamics of these two perturbations are the same or different. In brief, the question is whether the two perturbations disappear after the learning event at the same or different rates. Such comparisons of forgetting rates can be fraught with theoretical difficulties of interpretation (Gruneberg, 1970; Loftus, 1978; Wickelgren, 1973) but none of the known difficulties apply in the present case.

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Item Short-Term Recognition Memory

If one repeatedly presents lists of letters or digits with interlist intervals on the order of seconds, and presentation rates of one item per second or faster, recognition memory for these items declines rapidly. Indeed, when memory strength is assessed by a single-item probe technique and measured in d' units of discriminability from items not presented on the current trial, memory strength declines approximately exponentially at a rate such that memory for an item is virtually gone after about a dozen intervening letters or digits (Wickel-

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gren & Norman, 1966; Wickelgren, 1970). This short-term memory strength of items as measured by a recognition task is one of the two short-term perturbations we compare in the present paper.

Priming in Memory Retrieval

The other short-term perturbation, the forgetting rate of which we wish to investigate, is the *priming effect* on memory retrieval. For a short period of time after processing an item, one is faster in processing the same item or an associated item. We should distinguish between two types of priming effects; the repetition effect and the association effect. The *repetition effect* is a priming of retrieval (processing) that occurs as a result of prior processing of the same item or a component of the item. The *association effect* is a priming that results from prior processing of an associated item.

Repetition effect. The repetition effect has been observed in a large variety of choice reaction time tasks (Bertelson, 1961, 1963, 1965; Hale, 1967; Hyman, 1953; Kirby, 1976; Smith, 1968; Taylor, 1977). Gough and Rohrman (1965) and Rohrman and Gough (1967) demonstrated that the time to decide whether two words were synonymous or the time to decide whether two nonsense syllables were identical were both reduced by advance presentation of one of the words or syllables to be matched. Beller (1971) and Posner and Snyder (1975) demonstrated the same repetition effect in a single-letter, matching task. Posner and Snyder further showed that the repetition effect is an automatic, involuntary consequence of processing the prior identical item, because it occurs even in cases where the prime has very low validity as a predictor of the subsequent letters to be matched. In a more conventional choice reaction time paradigm, Taylor (1977) has confirmed the same conclusion favoring an automatic repetition priming effect.

In single-item probe recognition memory (e.g., Sternberg, 1966, 1969), immediately or recently presented or rehearsed items are recognized faster than less recently activated items both for verbal materials (e.g., Monsell, 1978; Seamon, 1976b; Seamon & Wright, 1976; see Wickelgren (1975) for a review of earlier work) and tones (Clifton & Cruse, 1977). Seamon (1976a) also showed that time to name the probe was reduced by recent rehearsal. Sometimes these priming effects are obtained only for the last item and sometimes they extend much farther back in time, suggesting the possibility of two priming effects with very different dynamics.

Priming effects have also been observed for repetition of parts or constituents of items. Collins and Quillian (1970) found partial repetition priming effects in the verification of familiar propositions (e.g., verification of "A canary can sing" is faster when it follows verification of "A canary is a bird"). Hayes-Roth and Hayes-Roth (1975) also found some constituent repetition priming effects for verification of linear order relations ($H > F$). Loftus (1973) found partial repetition priming for generation of examples of a category. This effect applied at immediate repetition, but also extended to repetition after one or two intervening trials of generating examples of other categories. Partial or constituent repetition priming is not always successful. In mental arithmetic, immediate repetition of the same two addends in the same or opposite order reduces the time required to verify a sum. However, repeating a single addend or the sum does not improve verification time (Ashcraft & Battaglia, 1978; Winkelman, 1974).

Association effect. Empirical support for the association priming effect is at least as voluminous and diverse as for the repetition effect. Processing a word shortens the time needed to process an associated word in both lexical decision and naming tasks (Fischler, 1977a, 1977b; Fischler & Goodman, 1978; Massaro, Jones, Lipscomb, & Scholz, 1978; Meyer & Schvaneveldt, 1971; Neely, 1976, 1977; Schmidt, 1976; Warren, 1977). A similar priming effect shortens naming time for the second of two associated pictures (McCauley, Weil, & Sperber, 1976). Ashcraft (1976) showed that verification of propositions in semantic memory (e.g., A sparrow has feathers) is speeded by prior verification of propositions with associated concepts (e.g., A robin has wings). Macht and Spear (1977) found that verifying a statement such as "All trees have bark" during a retention interval facilitated short-term retention of a triad of associated words such as "fir, willow, oak." Taylor and Juola (1974) found that contextual recognition memory (for which animal or body part names had occurred in a prior list) was speeded by preceding the test word with another word from the same semantic category. There is also evidence that priming some nodes may result in inhibition of other nodes (Neely, 1976; Rosch, 1975; Warren, 1972, 1974).

The term "association" should not be taken to imply a conscious voluntary process. Although some of the association effects may be conscious and voluntary, a consensus seems to have emerged that there is a very short-latency (less than 100 milliseconds) automatic (involuntary and initially unconscious or preconscious) spread of activation from directly referenced nodes to associated nodes (Quillian, 1962, 1967; Collins & Loftus, 1975).

Activation and Retrieval State

Retrieval state refers to the degree to which a memory trace has been activated (retrieved, thought of, used to affect behavior, etc.). Retrieval state is a necessary concept. At any given moment in time, some thoughts are on our mind more than others—which is to say, some memory traces are more active than others. At any given moment our behavior is controlled by memory traces that are in the active state, not by traces in the passive state.

Retrieval can be thought of as the cognitive process that converts traces from the passive to the active state. According to this view, *primary memory* (or active memory) is the persistence of a trace in the active state for a time after retrieval. *Priming* is partial activation of a trace due either to (a) partial activation in retrieval of related traces (as in diffuse attentional set due to spread of activation from a fully activated trace) or (b) decline in degree of activation after attention has shifted to another trace (decay of primary memory).

It should be noted that this theoretical framework discusses activation and priming of traces, not nodes. This is not because nodes are not presumed to be activated, but because the trace-activation framework is potentially more general since it allows activation of a subnetwork of both nodes and links—whatever subnetwork comprises the trace. Just as an example, activation of an item node can be said to be activation of the item trace, which includes at least all of the nodes that are constituents (segments, attributes, features, etc.) of the item node, and possibly some of the nodes of which the term is a constituent or linked to in some other way. The links are also an important part of the item trace. Furthermore, tying together node and link activation (retrieval) may permit an important simplification in constructing a mathematical theory of the dynamics of storage and retrieval in networks (e.g., network strength theory (Wickelgren, 1976) compared to models that separate node activation and transmission through links (e.g., neural net models such as those of Rashevsky (1960) and McCulloch & Pitts (1943) or psychological node net models such as those of Quillian (1962, 1967), Dosher (1977), and McClelland (1979)).

Primary Memory and Item Recognition

Whether priming is partial activation of nodes or of traces (nodes and links), we expect faster processing of primed items, namely, repetition and association effects. The present study is concerned with the duration of primary memory (persistence of activation) as measured by the duration of priming (repetition) effects on the retrieval of item memory in a probe memory task. Presumably, if an item has just been presented (e.g., the last item in a list) and then is immediately tested for recognition memory, its processing should be facilitated because it is still partially activated (primed). Would this priming effect hold to a lesser extent for the next to last item in the list, and so on? Would the decline in the priming effect be at the same rate as the decline in item short-term recognition memory in those cases where, by virtue of rapid presentation and repeated use of the same small set of items in different sequences on different trials, the decline of item strength is very rapid—a matter of seconds? The question is whether the short-lasting trace that mediates item memory in a memory span type task is primary memory (persistence of activation). Waugh and Norman (1965) and Wickelgren (1979, pp. 210–211) have claimed such an identity. We propose to test that claim, making the assumption that primary memory is most definitively assessed by the priming effect. If the dynamics of the priming effect and short-term item strength memory are the same, it is parsimonious to assume the same primary memory trace for both. If the dynamics are very different, then there are two different traces, and short-term item recognition memory is probably not primary memory.

Speed Accuracy Trade-Off Method

There are many reaction time studies of the duration of the priming (repetition) effect. None of these is of any value for determining the duration of primary memory and answering the primary question of this study. There is no doubt that both the speed and the accuracy of item recognition memory more or less decline together over the period of seconds that the item memory trace persists in these tasks. Reaction time (speed) is not a good measure of the persistence of priming (partial activation) because reaction time depends on the strength of the item memory trace in storage as well as on the retrieval state (degree of activation or level of primary memory) of the item trace.

If subjects wait 2 or more seconds in deciding whether a probe item was in the preceding list, they decide with a level of accuracy that is unaffected by retrieval time (above 2 seconds), but which *is* affected by retention interval (time in storage between presentation and test). If subjects are given less than about 500 milliseconds (200–800 milliseconds for different subjects) to make their yes–no decision, item recognition memory is at a chance level, $d' = 0$ (Reed, 1973, 1976). At some critical processing time, called the intercept (δ), performance begins to rise above chance performance and to approach the asymptotic level of performance. The asymptote (λ) is the strength of the item memory trace in storage. The transition period between the time intercept (around 500 milliseconds of processing) and the time at which asymptote is reached (varying from 1000 to 1500 milliseconds in different subjects) is the period of speed accuracy trade-off. In the present task, this period of speed accuracy trade-off amounts to about 700 milliseconds—a very large period of time in relation to most RT differences between conditions. A reaction time study obtains the equivalent of a single point on such an SAT function. RT is affected by the asymptotic level of strength (λ) as well as by the processing dynamics parameters, namely, intercept (δ) and rate (β) of approaching the asymptote (Corbett & Wickelgren, 1978; Dosher, 1977; Reed, 1973).

The persistence of activation (primary memory) seems best assessed by the intercept and rate parameters of a speed accuracy trade-off function. To the extent that the item trace remains activated, the dynamics of recognition memory should be facilitated. It is not mathematically necessary that the asymptotic strength of an item trace in storage covary with its retrieval (processing) dynamics parameters. Therefore, we can ask the following empirical questions: (a) Will there be any priming effect on retrieval dynamics parameters, even for the immediately prior item, when the (asymptotic) storage differences as a function of retention interval have been factored out? (b) If there is a priming effect on retrieval dynamics parameters, will the *storage* dynamics of its persistence as a function of retention interval match that of the item trace as measured by the asymptote (the level of which declines to zero in a matter of seconds under these conditions)?

A previous speed accuracy trade-off study by Dosher (Note 2) demonstrated a priming effect on retrieval dynamics for word–word paired-associate recognition memory. The rate of retrieval was faster for recognition tests of the last pair in a list of three pairs when it was tested after 3 seconds of backward counting vs about 80 seconds of time filled with the learning and testing of many word pairs. The priming effect on retrieval dynamics appeared to be largely limited to the immediately prior pair, as only very small priming effects were obtained for the first two pairs of the list of three pairs. So, while the priming of word pair retrieval survived 3 seconds of backward counting, little, if any, survived the interpolated learning of another word pair (3-second learning time). The present study simplified the item to single letters, presented the items much more quickly (two letters per second), and tested attention after only a .7-second unfilled lag following the last list item to see if primary effects could be obtained that extended to more than the last learned item.

METHOD

The present study employs a number of new SAT data collection and analysis methods, briefly summarized by Wickelgren (1978).

First, we employed two-key *time difference* as a measure of confidence in the yes–no decision. Subjects pressed both yes and no keys when they responded, but were instructed to make the leading key indicate their choice and the time difference between the two key presses reflect their confidence in the choice. Reed (Note 1) and Dosher (1977) have shown that this time difference method provides a fairly accurate measure of confidence at the time of the choice. Direct comparisons of the temporal method with other procedures are not available. By obtaining rating scale operating characteristics after each of several periods of retrieval time, we can determine the characteristics of the retrieval process more precisely than with only a binary yes–no measure obtained at each retrieval time.

Second, we have developed the *tapping method* which obtains a measure of performance at several retrieval times on each trial, instead on only one, as with previous SAT methods. In the present study, subjects tapped both keys about every .4 seconds, simultaneously, at first. As soon as any information became available they began to indicate their response and confidence according to the scheme described above. With this tapping method we obtain a performance measure every .4 seconds. By employing two conditions differing by .2 seconds in the relation between tap time and onset of the retention test time, we obtain a performance measure every .2 seconds (in two trials).

Third, we use a new analytic method, called *incremental d′ scaling,* to characterize performance accuracy at each retrieval time in a given retention interval condition. Instead of comparing a true and false condition at each retrieval time, we plot operating characteristics comparing a given true condition at zero retrieval time with the same condition at about .2 seconds retrieval time, then this .2-second retrieval time is compared to the .4-second retrieval time, and so on, out to the maximum retrieval time of about 3.1 seconds. The slope of each operating characteristic is used to adjust the unit of d' measurement for each comparison to be the standard deviation of the noise in the zero condition. Then the cumulative d' is obtained for a given retrieval time by adding up all incremental d's up to that time. This cumulative d' represents the total retrieved memory strength up to that point in the retrieval process, assuming that response bias (to press yes or no keys and to respond with any particular time difference) is not changing as a function of retrieval time.

Just in case response bias is changing, we do the same incremental scaling process for the comparable false condition, cumulate false-alarm incremental d's, and subtract the false d's from the true d's to obtain the usual bias-free d' measure of recognition memory accuracy at each retrieval time. Both true and false cumulative d's are measured in units of the standard deviation of the zero time condition and relative to a zero point which is the mean of the zero time strength distribution. Since at zero retrieval time, the strength distributions for true and false conditions are identical, we actually pool these two conditions, and it is therefore ensured that both true and false cumulative d's are being measured in the same units, relative to the same zero point. The incremental d's scaling method is an adaption to the SAT paradigm of a d' method suggested by Creelman (1967), which is itself analogous to integrating *jnd*'s.

Incremental d' scaling has several advantages over conventional d' scaling in SAT studies. First, it guarantees that d' values at all retrieval times are being measured relative to the same zero point and with the same unit of measurement, which conventional d' scaling may not. Second, it minimizes the effect of deviations from the normal distribution assumption of statistical decision theory by using the fat (middle) part of the distribution for scaling at all times. Thus, it places less weight than conventional d' scaling on the tails where deviations from the normal distribution assumption have the most severe consequences. Third, incremental scaling permits measurement of very large d' levels. With conventional d' scaling, as soon as there is no overlap in the responses between true and false distributions, one cannot assess the d' value ($\hat{d}' = \infty$). But with incremental scaling, even when subjects are perfectly accurate in their asymptotic (long retrieval time) response, a reasonable d' value can be assigned to the condition. That value will be different from the asymptotic d' for conditions in which subjects are asymptotically more or less confident, even if yes–no performance accuracy is 100% in all conditions.

Subjects

Two groups of three subjects participated in the experiment. The subjects in each group were run simultaneously in one room. Subjects were paid $2.50/hour.

Procedure

Subjects participated in two test sessions a day for 3 days. Each session consisted of 15 practice trials and 285 test trials and lasted approximately 70 minutes. A set of 16 letters was presented on each trial, followed by a test probe. Subjects then made eight separate yes–no recognition responses following onset of the test probe. Subjects were instructed to time their response to coincide with a 50-millisecond tone that sounded every 400 milliseconds. (An additional response preceded the probe to establish the response rhythm.) The tones started at one of two different times in relation to the probe, so that the initial response preceded the probe by either 100 or 300 milliseconds. In each response, subjects pressed both the yes and no response keys. The first key pressed indicated the yes–no decision and the interval between presses represented the confidence rating. Subjects were instructed to respond so that the length of the interval between the two key presses (from 0 up to 400 milliseconds) was directly related to their confidence.

The experiment was controlled by a PDP-15 computer and the memory set and test probe were presented on a separate cathode ray tube for each subject. The subjects in a group received the same stimuli on each trial. A plus sign (+) appeared at the beginning of each session for 500 milliseconds and served as a warning signal. Then, following a 500-millisecond blank interval the 16 letters in the memory set were presented, one letter at a time for 500 milliseconds each. The test probe was presented after a 700-millisecond blank interval and remained on the screen until the subjects finished responding.

The response tones were presented over earphones. The first tone was presented either immediately at offset of the last letter of the learning set or 200 milliseconds later. Subjects were instructed to begin responding at the second tone which then occurred either 300 or 100 milliseconds prior to the test probe. For this initial response, subjects pressed the two keys simultaneously (no confidence) since there was no information on which to base a decision. Subjects then made eight more responses (at either 100, 500, 900, 1300, 1700, 2100, 2500, and 2900 or 300, 700, 1100, 1500, 1900, 2300, 2700, and 3100 milliseconds after the probe). A 1-second blank interval followed the last response, and then the next trial began. Subjects became familiar with the procedure in four practice sessions that preceded the six test sessions.

Design

Nineteen consonants were employed in this experiment (W and Y were excluded). Sixteen consonants were presented on each trial with no repetitions within a trial. There were 14 experimental conditions, six positive conditions and a negative condition crossed with the two starting times for the response tone. The position of the test probe in the memory set varied across the six positive conditions. The positions for the six conditions were as follows: (1) final (16th), (2) 15th, (3) 14th, (4) 11th through 13th, (5) 6th through 10th, (6) 3rd through 5th. Positions 1 and 2 were not probed in the test trials.

There were a total of 1710 test trials across the six sessions, with 95 trials in each of the 12 positive conditions (position crossed with tone condition) and 285 trials in each of the two negative conditions. In conditions with multiple possible probe positions, each position was tested equally often (± 1). The 1710 test trials were divided into five consecutive blocks of 342 trials each. Each letter appeared once in each of the 12 positive conditions and three times in the two negative conditions in each block. In addition each letter appeared once in each serial position in the memory set in each block. There were 15 practice trials at the beginning of each session. In these trials the first position in the memory set was tested three times, the second position was tested three times, three other positions were randomly selected to be tested, and there were six negative tests. Finally, the same test probe did not appear on successive trials. Two such stimulus sets were generated, one for each group of three subjects.

RESULTS AND DISCUSSION

True and False Recognition Rates

The average (over the six subjects) true and false recognition rates for each of the seven serial positions tested (six positive and one negative) at each of 16 test latencies are shown in Table 1. The latencies shown in Table 1 are the average times at which subjects pressed the first key (yes or no) in each condition. The latency to press the first key is the best available measure of the time at which the decision is made because the latency of the second key press reflects confidence in the decision.

Lag-Latency Functions

Before or shortly after the onset of the test item, subjects are tapping both keys at virtually the same time and the average discrepancy between the time of the tone (lag time) and the time of the first tap (or pair of taps) is -9 milliseconds (the first tap anticipates the tone by an average of 9 milliseconds over the six subjects). As processing time (from the onset of the test item) lengthens, the average degree of anticipation increases slightly to around 45 mil-

TABLE 1
RECOGNITION MEMORY TRUE AND FALSE RECOGNITION RATES

Test latency (msec)	Probe item position 16	15	14	11–13	6–10	3–5	New
91	22	20	18	22	17	22	22
294	21	24	23	21	21	23	22
484	61	44	42	39	39	37	34
691	78	59	52	45	41	40	36
876	93	74	66	59	50	45	36
1086	94	82	73	62	54	49	38
1271	96	84	78	72	62	56	40
1481	97	87	81	69	60	57	43
1665	97	86	79	73	64	56	41
1879	98	88	82	72	63	58	44
2060	98	85	80	73	65	57	41
2274	98	88	82	73	64	59	44
2455	98	86	81	74	65	57	41
2658	98	88	82	74	64	58	43
2853	98	86	82	74	65	56	41
3054	98	89	82	76	64	59	44

Note. P ("old") in % averaged across subjects.

liseconds. Thus, the latency of the first tap (of a pair) in relation to the tone goes from −9 to −45 milliseconds on the average. There are differences in absolute latency across individuals, with some subjects' taps following the tones, especially at short lags. However, all subjects show the same trend toward earlier responses with increasing lag.

Most impressive, all subjects show virtually no difference in the lag-latency functions for different serial positions of the test item (average standard deviation of 2 milliseconds). Since d' values differ enormously with the serial position of the test item, it is impressive that subjects execute their responses at the same time for these different test item positions. The average lag-latency function pooling over subjects and serial positions of the test item is shown in Table 2.

SAT Functions and Priming

The empirical item recognition memory functions for individual subject for each serial position in the memory set are given in Table 3. A few representative SAT functions (the last two serial positions for subjects S1 and S5) are shown in Figures 1 and 2. As was true for previous SAT studies of memory retrieval dynamics (e.g., Corbett, 1977; Corbett & Wickelgren, 1978; Dosher, 1976; Wickelgren & Corbett, 1977) these SAT functions are closely approximated by an exponential approach to a limit, namely,

$$d' = \lambda\,(1 - e^{-\beta\,\{T\,-\,\delta\}}),$$

where λ is the asymptote, δ is the intercept, β is the rate parameter, T is the retrieval time in milliseconds, d' is the measure of memory strength at time T, and $\{T - \delta\} = T - \delta$ for $T \geqslant \delta$ and 0 for $T < 0$. Thus, the more elegant incremental d' scaling method appears to confirm the exponential approach to a limit as a good approximation to the form of the retrieval function. No other functions were fit to the data, so nothing in this discussion should be taken to imply that another theoretical function might not fit equally well, or better. A time will come (soon we hope) when SAT methods are refined enough to justify more precise comparative testing of different theoretical functions to see if some other function fits better than the simple exponential. However, the exponential fits too well and the major deviations from the function are too unsystematic to make such comparative testing useful at this time.

TABLE 2
LAG-LATENCY FUNCTIONS (msec)

Tone lag	100	300	500	700	900	1100	1300	1500
Response latency	91	294	484	691	876	1086	1271	1481
Tone lag	1700	1900	2100	2300	2500	2700	2900	3100
Response latency	1665	1879	2060	2274	2455	2658	2853	3054

Note. Averaged over six subjects.

What is of some value is to use the exponential function as a good approximation to the data for each condition and search for invariances or systematic differences in the parameters of the exponential function for different conditions.

In the present experiment, we expect the asymptote parameter (stored memory strength) to decrease systematically from the last item in the list to earlier items, reflecting the fact that item recognition memory is declining rapidly as a function of the number of intervening items. Of course, this was observed, and all models tested allowed the asymptote parameter (λ) to vary for each serial position. Also, there are individual differences, so parameters were estimated separately for each subject.

The controversial issue is whether retrieval dynamics (measured here by the intercept (δ) and rate (β) parameters) changes with serial position. Our method for answering this question was to compare the fit of different models that assumed various types of variation or invariance across serial position of the δ and β dynamics parameters.

Of course, in general, the more parameters one estimates in order to fit a set of data, the better the fit will be. To permit a rough comparison of the fit of models with different numbers of parameters, we employed the standard measure:

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (d_i - \hat{d}_i)^2/(N - k)}{\sum_{i=1}^{N} (d_i - \bar{d})^2/(N - 1)},$$

where N is the number of empirical points d_i, k is the number of parameters in the model, $\hat{d}_i$ is the theoretical d' value for condition i, and $\bar{d}$ is the grand mean of all the d_i values (Reed, 1976). R^2 is essentially the percentage of variance accounted for by the theory, but adjusted for the number of estimated parameters. The term $(d_i - \bar{d})^2$ is the total squared variation about the mean. Dividing this total variation by $(N - 1)$ gives the average variance per free point, on the assumption that using the data to estimate a single mean parameter is equivalent to reducing the number of free points in the data by 1. The term $(d_i - \hat{d}_i)^2/(N - k)$ is completely analogous, representing the remaining unexplained variation per free point of the data about the predicted values, on the assumption that using the data to estimate k parameters is equivalent to reducing the number of free points in the data by k.

In all, we evaluated the fit to the SAT data of 15 different models.[1] Their goodness of fit values ranged from a low of $R^2 = .814$ for the model which estimated δ, β, and λ separately for each serial position to a high of $R^2 = .935$ for the model which assumed separate λ values for each serial position, but only two values for each of the two dynamics parameters (δ and β). In this best-fitting model, the average intercept parameter was very slightly higher for the last item than for earlier items in the list ($\delta_0 =$ 485 milliseconds vs $\delta = 438$ milliseconds), but the rate of retrieval averaged almost three times higher for the last item vs earlier items ($\beta_0 = .0100$ vs $\beta = .0034$). Because of one extreme parameter estimate (β_0 for S2), the actual difference in the retrieval rates is probably better estimated by the medians, $\beta_0 = .0048$ vs $\beta = .0031$, which indicate about 50% greater retrieval rate for the last vs earlier items. The estimated parameter values and R^2 values for each subject are shown in Table 4.

In evaluating the fit of a model, it is at least as important to look at the internal consistency of parameter estimates across subjects as to look at the R^2 values. In the best-fitting $2\delta - 2\beta$ model, there is only one case (β_0 for S2) where the rate parameter varied excessively over subjects, and that

[1] The last two points for S6 were much higher than the other points on the asymptote of the SAT functions for S6 and were excluded from all goodness of fit analysis. This may be some second-guess phenomenon, an unknown flaw in the tapping method, or some other artifact.

TABLE 3
INDIVIDUAL SAT FUNCTIONS

Latency (msec)	S1 accuracy (d′) Average test delay (items)						Latency (msec)	S2 accuracy (d′) Average test delay (items)					
	0	1	2	4	8	12		0	1	2	4	8	12
164	−.01	−.08	.09	.01	.07	.02	131	.06	−.01	.15	.20	.00	.01
372	−.01	−.17	−.17	−.08	.11	−.07	324	.13	.01	.08	−.01	−.05	−.04
561	.31	−.04	.21	−.03	.13	−.02	511	2.70	.44	.14	.20	.35	−.15
769	2.00	−.05	.40	−.17	.40	−.12	710	4.39	1.59	.81	.56	.51	−.06
955	3.40	.82	1.20	.13	.38	.10	894	4.44	.96	.50	.34	.33	.00
1158	3.00	1.04	1.49	.24	.54	−.05	1099	4.35	1.72	1.04	.46	.63	.03
1351	3.02	1.34	1.69	.51	.64	.23	1282	3.70	1.55	1.26	.99	1.04	.40
1556	2.94	1.18	1.68	.28	.60	.04	1487	4.15	2.19	1.30	.98	.68	.40
1746	3.12	1.28	1.71	.55	.66	.08	1684	3.79	1.64	1.18	.84	.96	.35
1955	2.88	1.10	1.59	.26	.66	−.01	1895	3.99	2.20	1.20	.86	.74	.26
2143	3.18	1.25	1.69	.56	.67	.05	2080	3.80	1.67	1.27	.82	.96	.36
2348	3.41	1.21	1.69	.26	.63	−.03	2293	4.09	2.29	1.11	.89	.66	.27
2540	4.14	1.38	1.77	.58	.67	.06	2473	3.39	1.74	1.16	.82	.93	.28
2741	4.07	1.30	1.72	.30	.64	−.03	2679	3.72	2.09	.95	.81	.64	.15
2936	4.10	1.39	1.80	.60	.72	.10	2868	2.77	1.46	.94	.69	.95	.28
3138	4.15	1.35	1.74	.32	.68	−.03	3065	2.93	1.63	.72	.73	.66	.05

Latency (msec)	S3 accuracy (d') Average test delay (items)						Latency (msec)	S4 accuracy (d') Average test delay (items)					
	0	1	2	4	8	12		0	1	2	4	8	12
28	.05	.02	−.20	.17	.06	.14	161	−.18	−.04	−.24	.04	−.01	.13
232	.32	.23	.45	.33	.24	.23	350	−.30	−.10	.23	−.14	−.02	−.14
417	7.15	.27	.60	.32	.71	.10	565	.52	.31	.41	.39	.12	.11
628	7.76	.87	1.05	1.09	.92	.33	760	.93	.37	.58	.43	.25	.20
803	9.44	1.26	1.53	1.10	1.44	.62	951	1.62	.79	.73	.71	.26	.39
1016	10.94	1.45	1.62	1.57	1.12	.51	1151	1.68	.62	.68	.32	.28	.28
1207	9.55	1.39	1.54	1.34	1.46	.74	1340	2.04	.83	.80	.87	.23	.39
1421	10.64	1.50	1.66	1.57	1.13	.50	1545	2.19	1.00	.96	.42	.34	.26
1608	9.13	1.32	1.60	1.36	1.54	.70	1727	2.38	1.03	.85	.75	.28	.32
1824	10.74	1.47	1.62	1.65	1.14	.47	1936	2.33	1.21	1.12	.59	.34	.29
2007	10.47	1.45	1.57	1.52	1.56	.68	2114	2.59	1.07	1.05	.92	.30	.38
2223	10.83	1.56	1.55	1.73	1.16	.47	2327	2.16	1.07	1.12	.54	.28	.16
2406	10.43	1.41	1.61	1.58	1.62	.69	2507	2.23	.95	.82	.91	.27	.31
2604	10.56	1.71	1.58	1.78	1.20	.41	2717	1.90	.90	1.11	.61	.35	.06
2807	14.73	1.98	2.36	1.86	1.94	.87	2907	1.45	.78	.82	.89	.27	.22
2997	13.04	1.98	1.96	2.04	1.47	.58	3116	1.46	.65	.88	.46	.24	−.02

TABLE 3—*Continued*

Latency (msec)	S5 accuracy (d') Average test delay (items)						Latency (msec)	S6 accuracy (d') Average test delay (items)					
	0	1	2	4	8	12		0	1	2	4	8	12
50	.58	.44	.10	.17	.37	.43	13	−.11	−.18	−.09	−.05	−.23	−.13
259	.42	.40	.23	.30	.31	.40	227	.07	.25	−.17	−.20	.09	.07
456	3.06	1.77	.92	1.58	.75	.99	393	−.32	.06	−.26	.01	−.18	−.12
661	4.35	2.79	1.40	1.70	.76	1.28	617	.00	.23	−.20	−.16	−.27	−.05
863	4.61	3.48	2.00	2.31	1.21	1.36	790	2.45	3.30	1.74	1.90	.45	.56
1077	4.05	3.98	2.16	2.52	1.23	1.45	1013	2.71	3.62	1.89	1.99	.83	.62
1259	4.49	3.56	2.21	2.46	1.26	1.38	1187	3.35	4.08	2.68	2.35	.87	.68
1467	4.28	4.03	2.19	2.67	1.30	1.54	1411	3.40	4.20	2.40	2.40	.97	.84
1646	5.12	3.56	2.32	2.56	1.33	1.44	1581	3.47	4.56	2.75	2.81	.98	.86
1855	4.81	4.36	2.35	2.71	1.29	1.57	1809	3.76	4.41	2.65	2.46	1.15	.97
2039	6.05	3.91	2.35	2.46	1.33	1.44	1976	3.62	4.85	2.70	2.98	1.01	.85
2251	5.15	4.31	2.30	2.76	1.27	1.66	2201	3.99	5.13	2.97	2.81	1.27	1.03
2436	5.07	3.67	2.28	2.53	1.28	1.39	2369	3.32	4.68	2.91	3.07	1.00	.87
2640	4.74	4.29	2.22	2.72	1.20	1.61	2568	3.54	4.79	2.70	2.83	1.22	.96
2835	3.49	3.17	1.88	2.07	1.21	1.29	2765	8.73	8.89	4.92	4.11	1.57	.97
3039	3.65	3.62	1.74	2.22	1.09	1.52	2967	8.17	8.10	4.63	4.51	1.59	1.16

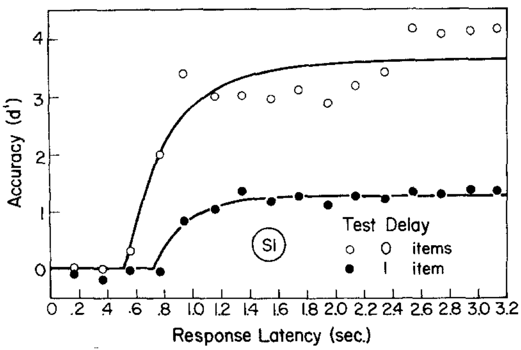

FIG. 1. Speed accuracy trade-off (SAT) functions for S1 for the last and next to last items in the list of 16 items. The last item has zero items intervening between learning and the probe recognition test. The next to last has one intervening item. Recognition accuracy is measured in d' units of discriminability from a new probe item.

was just an exaggeration of the rate difference expected by the model. More important, five of the six subjects had the rate parameter for the last item greater than for earlier items, and the one reversal is the smallest relative difference measured as a percentage change of β_0 from β.

Furthermore, in the $2\delta - 2\beta$ model, the subject with the reversal in rates (S1) also had a gigantic reversal of almost 200 milliseconds, in the δ vs δ_0 parameters from the pattern showed by the other subjects. In the model where δ was held constant for all serial positions, S1 had a very large rate difference in the same direction as the other subjects, namely, faster retrieval rate when the test item matched the immediately preceding item than when it matched an earlier

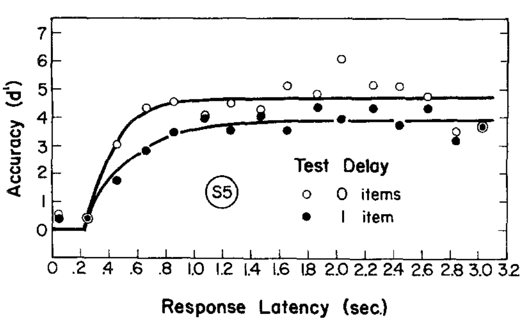

FIG. 2. Same SAT functions as in Figure 1, but for subject S5.

item. Considered as a whole, the SAT functions strongly support the hypothesis that memory retrieval rate is faster for the last item attended to than for earlier items.

There is some evidence to support the hypothesis that the intercept parameter differs for the last item compared to earlier items, but it is weak and the intercept differences are not consistent across subjects. In the best-fitting $2\delta - 2\beta$ model the intercept actually averages 20 milliseconds slower for the last item than earlier items, but only four of the six subjects show this effect, and two show reversals, one of which (for S1) is very large. The fit of the $1\delta - 2\beta$ model is only a little worse than the fit of the $2\delta - 2\beta$ model by the R^2 criterion ($R^2 = .933$ vs .935). Nevertheless, the slightly better fit is some evidence that δ is indeed different for the last item vs earlier items since R^2 adjusts for the number of parameters. Another source of support for the $2\delta - 2\beta$ model over the $1\delta - 2\beta$ model is that the intercept parameter actually has greater internal consistency in the $2\delta - 2\beta$ model than in the $1\delta - 2\beta$ model. This is true despite greater opportunity for error variation due to parameter trade-off between the two dynamics parameters, δ and β, in the $2\delta - 2\beta$ model.

The $1\beta - 2\delta$ model, in which we try to account for the retrieval dynamics difference between the last item and earlier items entirely by means of an intercept difference with constant retrieval rate, also has a somewhat poorer fit by the R^2 criterion ($R^2 = .933$) and less consistency for the parameter estimates than the best-fitting $2\delta - 2\beta$ model. In the $1\beta - 2\delta$ model, δ_0 averages 34 milliseconds less than δ, but there are two reversals of some size.

Another model that fits less well than the $2\delta - 2\beta$ model is the $1\delta - 1\beta$ model which assumes no retrieval dynamics differences as a function of how recently the item was in active memory. The $1\delta - 1\beta$ model had an R^2 fit value of .929 vs .935 for the $2\delta - 2\beta$ model. More important, however, the consistent differences between the last item

TABLE 4
PARAMETER ESTIMATES AND GOODNESS OF FIT OF THE 2δ-2β-6λ MODEL: $d' = \lambda_i\,(1 - e^{-\beta_i(T - \delta_i)})$

	Test delay					
Subject	0	1	2	4	8	12
	λ_0	λ_1	λ_2	λ_4	λ_8	λ_{12}
1	3.59	1.28	1.73	.40	.66	.06
2	3.80	1.87	1.11	.81	.81	.24
3	10.09	1.61	1.77	1.68	1.47	.63
4	2.08	.95	.97	.71	.31	.26
5	4.66	3.89	2.19	2.55	1.27	1.52
6	3.61	4.68	2.73	2.75	1.06	.89
Mean	4.64	2.38	1.75	1.48	.93	.69
	β_0	β	δ_0	δ		R^2
1	.0033	.0046	524	731		.966
2	.0374	.0030	477	416		.952
3	.0044	.0026	214	280		.853
4	.0032	.0024	495	368		.913
5	.0052	.0032	243	221		.943
6	.0064	.0045	793	610		.983
Mean	.0100	.0034	458	438		.935

and earlier items argues strongly that the last item has different retrieval dynamics than earlier items. Further support derives from the 1δ − 6β model where the average β_0 parameter is .0091, but the averages for the other 5β parameters (proceeding from the end of the list to the front) are .0034, .0035, .0033, .0040, and .0041.

Examination of the rate and intercept values as a function of serial positions gives no support at all for any other difference in retrieval dynamics except for the very last item in the list. Even the next to last item shows no systematic tendency for faster retrieval dynamics than earlier items. Indeed, in the 3β − 1δ model, the average β_0 for the last item is .0090, while that for the next to last item is .0034, just slightly *lower* than that for the other items, .0036.

Short-Term Forgetting Dynamics

Clearly, the priming effect on retrieval dynamics, in this task at least, is limited to the case where the test item is identical to the item that the subject was thinking about at the exact time the test item was presented. However, item recognition memory lasts for at least 6 seconds (12 intervening items) in this task. A conventional short-term memory forgetting function is obtained by plotting the asymptotic strength values (λ) in Table 4 as a function of delay, measured in elapsed time or by the number of intervening items. The delay conditions were 0, 1, 2, 3−5, 6−10, and 11−13 intervening items. Since the test probe was presented .7 seconds after the offset of the last list item, the time delays (averaged as necessary) were 0, 1.2, 1.7, 2.7, 4.7, and 6.7 seconds, on the assumption that subjects continued to rehearse the last item throughout the .7-second blank delay, as they were instructed to do. A semilog plot of the average λ value (over the six subjects) as a function of the retention interval is shown in Figure 3.

Previous studies of probe short-term recognition forgetting dynamics (Wickelgren & Norman, 1966; Wickelgren, 1970), have found exponential decay. This predicts that the retention function in Figure 3 should be a straight line. As is apparent in Figure 3, a straight line closely fits the retention function, if one excludes the first point (last list item). The first point lies above the extrapolation of the best-fitting line drawn

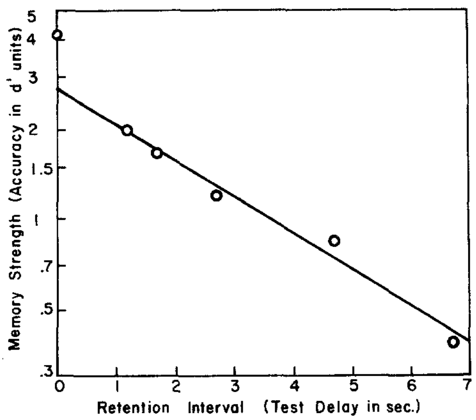

FIG. 3. Semilog plot of the average probe item short-term recognition memory retention function using the estimated λ values from Table 4. The average d' values (over the six subjects) are the logarithmic averages, not the arithmetic mean values shown in Table 4, because logarithmic averaging does not distort the shape of an exponential decay function in going from individual to group data. Delay between 0 and .7 seconds is blank time spent rehearsing the last list item. The rest of the retention interval is filled with list items to be learned, presented visually at a two-letter/second rate. Note that the last list item lies above the exponential decay function through the other points, regardless of where in the 0- to .7-second delay interval one plots that point.

through the other points. (It would be even farther above this line if we plotted the first point at a .7-second delay, on the assumption that subjects stopped rehearsing the last item during the .7-second second blank interval before the test probe.)

Formal goodness of fit tests demonstrate that better fit is achieved by estimating the λ value of the last list item separately and using the exponential decay hypothesis,

$$\lambda(t) = \alpha e^{-\phi t},$$

to predict the other five λ values from two underlying short-term memory parameters: α (degree of learning) and ϕ (decay rate in storage). Moreover, the best-fitting decay rate parameters for the six subjects within the $2\delta - 2\beta$ model were .38, .32, .12, .27, .20, and .35. These values overlap extensively with the probe short-term recognition memory decay rates (ranging from .18 to .60) found in the most comparable prior study which did not use SAT methods (Wickelgren, 1970). The decay rates found in this SAT study averaged at $\phi = .3$ whereas the previous ones averaged at $\phi = .4$, but this difference is very small in relation to possible variation in decay rates. Thus, it seems safe to conclude that the SAT technique for studying retrieval dynamics did not substantially perturb probe item retention functions in this task. Exponential decay rate in this experiment was comparable to rates obtained in earlier non-SAT experiments. Furthermore, using the more precise incremental methods of d' estimation, we can see that the memory trace for the immediately preceding item does not lie on the retention function for the preceding items.

This storage dynamics evidence is in complete agreement with the retrieval dynamics evidence that the memory trace for the item currently on one's mind is different from the memory trace for earlier items. The evidence of the present study indicates that there is good reason to distinguish primary or active memory for the thought currently on one's mind from short-term memory for other recently activated thoughts. Furthermore the present study indicates that this active memory is strictly limited to the very last item activated, even when the item is as simple as a single letter presented for .55 seconds (or 1.2 counting the blank delay). It is conceivable that there would have been some active memory for the next to last item had the probe test immediately followed the last item instead of .7 seconds later, but the present results certainly indicate that active memory decays very rapidly—within 1.2 seconds or less of thinking of just one new letter.

CONCLUSION

We do not know whether "short-term" probe item recognition memory is distinct from associative long-term memory (Wickelgren, 1973). However, the present study indicates that there is good reason to distinguish active (primary) memory for the last thought from memory for preceding thoughts. Whether active memory is always strictly limited to the last thought is open to question, but the present results suggest that it survives less than a second in the presence of an intervening thought. Passive memory persists through the intervening thoughts and appears to be responsible for most of what we call short-term memory. Such passive memory may be rapidly declining in strength, as under present conditions, but, apparently, whatever trace strength remains is retrieved with dynamics which are invariant over the lifetime of the memory trace. Further studies are necessary to establish the generality of this result.

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