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Dual Trace Theory and the Consolidation of Long-Term Memory*

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Retention functions were determined for four *S*s for recognition memory of letters at 14 different delays from 3 sec to 5 min and two levels of storage load (1 and 6 letter lists), the retention interval being filled with backward counting. Memory strength retention functions were fit extremely well by assuming that two traces, short-term memory and long-term memory, are operative in this type of memory task. Only the short-term memory trace appears to be present during the first 8 or 10 sec of the retention interval, and this short-term trace decays exponentially with a time constant in the vicinity of 10 sec. Long-term memory is subject to a consolidation process which does not begin until about 10 sec after the study period and which is substantially complete at about 30 sec after the study period. Storage load has a very large effect on the degree of acquisition (learning) for both short and long-term traces, but storage load appears to have only a moderate effect or no effect on the decay rate of the short-term trace. There is some suggestion that the duration of the consolidation phase is shortened by an increase in storage load.

In a "distractor" design for the study of memory (e.g., Brown, 1958; Peterson and Peterson, 1959; Murdock, 1967), the subject is presented with one or more items to be remembered, followed by a delay (retention interval) which is filled with some activity designed to minimize rehearsal, followed by a retention test. Previous distractor studies have always employed recall as the test of retention, and, with two exceptions (Keppel and Underwood, 1967; Sheirer and Voss, 1969), have used delays less than

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or equal to 32 sec. Previous studies have also never used more than 6 different delays in the same experiment. The present study is designed to determine the form of the retention function using probe recognition tests and 14 different delays from 3 sec to 5 min for two very different amounts stored in memory, namely, one vs. six letters. The use of a probe recognition test, where the test letter is a single letter, regardless of the number in the list stored, eliminates any possible confounding between the effects of the amount stored and the amount retrieved.

Recognition also appears to provide a pure test of loss in storage (whether due to time or interference or both), independent of retrieval interference (competition). Besides this being so plausible an assumption that most workers in verbal learning assumed it to be true without proof, the assumption has been given direct experimental support in two recent studies (Bower and Bostrom, 1968; Wickelgren, 1967). Thus, recognition is preferable to recall as a test of loss in storage.

The specific decision-making assumptions of strength theory (Wickelgren and Norman, 1966; Wickelgren, 1968) provide a way to transform the probabilities of correct and incorrect recognition into an interval scale measurement of memory trace strength. Besides the direct support for the scaling assumptions of strength theory (Bower and Bostrom, 1968; Wickelgren, 1967), there is indirect support in the simple retention functions obtained using the strength scale (Wickelgren and Norman, 1966; Wickelgren, 1969, 1970 a and b). Thus, there are grounds for hoping that a quantitative analysis of strength retention functions will help answer questions regarding the number of memory traces, the presence or absence of consolidation processes, and the parameters of acquisition, consolidation, and decay.

It should be pointed out that, according to strength theory, memory strength is not necessarily linearly related to the probability of correct recognition (or recall). Furthermore, memory strength is not even monotonically related to the probability of correct recognition, unless the false recognition rate is controlled in "yes-no" recognition tasks and the number of alternatives is controlled in multiple-choice recognition or recall tasks. According to strength theory, the mathematical form of *probability-correct* retention functions and their parameters (e.g., rates of forgetting, etc.) could vary in a very chaotic manner, which is essentially what is observed.

Dual Trace Consolidation Theory

According to the present dual-trace consolidation theory, two traces are assumed to be available to mediate performance in memory tasks with delays from a few seconds to a minute, namely, short-term memory with a time constant of seconds and long-term memory with a variable time constant of minutes to years. In some situations, the contribution of either one of these components is negligible, but, in other situations, both are assumed to make substantial contributions to the total memory trace. The total memory trace strength is assumed to be the sum of the short-term and long-term components.

Both short and long-term memory are assumed to be acquired during the period of active study of an item or list of items, but what is acquired is only a potential trace, not a retrievable (usable) trace. A consolidation process converts potential traces into retrievable traces. In the case of short-term memory, consolidation is assumed to occur either simultaneously with acquisition or within a few seconds after acquisition, and is not measurable, at present. However, consolidation of long-term memory is assumed to begin to produce retrievable memory only after a delay of around 10 sec following active study, and to require 10 or more sec after this to be substantially complete. Thus, it should be possible to study the consolidation of long-term memory in behavioral memory experiments.

Some time after the termination of the consolidation process, decay begins. In the case of short-term memory, this decay is assumed to be exponential and to begin immediately after acquisition and consolidation terminate, which can be assumed to be at the end of the active study period. In the case of long-term memory, decay is not assumed to be exponential over the entire span of long-term memory, which is years. However, over a period of a few minutes, long-term memory can be assumed to be decaying approximately exponentially. The time at which the decay process begins for long-term memory will be assumed to be an estimated parameter, at present.

Dual-trace theory assumes that the strength of each trace depends on the acquisition, consolidation, and decay functions and that total strength in memory is the sum of the strengths of each component trace. Thus, we can express the total strength of an item in memory by the following equation:

$$d' = s + l + X$$

$$d' = \alpha_L e^{-\beta t} + \lambda_L (1 - e^{-\psi\{t-b\}})\, e^{-\gamma\{t-c_L\}} + X, \tag{1}$$

where

d' is the total strength

s is the strength of the short-term trace

l is the strength of the long-term trace

X represents uncontrolled noise and is a random variable with zero mean and unit standard deviation.

α_L is the degree of initial acquisition in short-term memory of an item from a list of length L

β is the decay rate of short-term memory

t is the time delay in sec since the end of the study period

λ_L is the degree of initial acquisition in long-term memory of an item from a list of length L

ψ is the rate of consolidation of the long-term trace

b is the delay between the end of the study period and the onset of the production of retrievable long-term memory by the consolidation process.

γ is the decay rate of long-term memory

c_L is the delay between the end of the study period and the onset of the decay process for long-term memory, for a list of length L.

$$\{y\} = \begin{matrix} 0 & \text{for} & y \leq 0 \\ y & \text{for} & y > 0 \end{matrix}$$

The sum of the strengths of the short and long-term traces ($s + l$), in conjunction with an estimated criterion strength for a "yes-no" decision, determines the probabilities of correct and false recognition.

By using operating characteristics in the manner described by Wickelgren and Norman (1966), it is also possible to use the empirical recognition probabilities for correct and false test items in a condition to obtain an empirical estimate of the difference in total memory strength ($s + l$) for correct and false test items under that condition. Empirical strength-retention functions are derived from plotting these strength difference values as a function of delay of testing (t). An empirical strength-retention function can then be compared to a theoretical strength-retention function. If false test items are assumed to have zero mean strength, and all strength distributions are assumed to have unit variance, then Eq. (1) describes the theoretical strength-retention function for the different storage load and delay conditions of the present study.

A more complete discussion of these matters can be found in several other places (Wickelgren and Norman, 1966; Wickelgren, 1968, 1970 b, in press).

METHOD

Procedure. On each trial, subjects heard a 1 sec warning signal, followed by a 1 sec pause, followed by auditory presentation of either 1 or 6 letters presented at the rate of .5 sec/letter, followed immediately by auditory presentation of a number between 900 and 999, from which they were to begin counting backward by threes as fast as possible until the auditory presentation of a test letter. At every delay of testing (t), the probability of a correct test letter was .5. Subjects were given 3 sec to decide whether the test letter had been presented in the list for that trial and to state their confidence in that decision on a scale from 1 (least) to 6 (most). Subjects wrote "*Y*6," "*N*2," etc., on paper. For the 1-letter lists, the acquisition period was .5 sec long, and for the 6-letter lists, the acquisition period was 3 sec long. Delays were measured from the end of the list of 1 or 6 letters (the onset of the Experimenter's pronouncing the three-digit number) to the beginning of presentation of the test letter. The letters were chosen randomly without replacement from the following population of 18 consonants: *B*, *C*, *D*, *G*, *H*, *J*, *K*, *L*, *M*, *N*, *P*, *Q*, *R*, *S*, *T*, *V*, *W*, *Z*.

Subjects were instructed to refrain from rehearsing or otherwise thinking of the list of letters during the delay interval. When subjects got to zero, one, or two they continued counting backwards by threes into minus numbers. Numbers were pronounced as follows: "three twenty-nine," "oh forty-five," "minus two sixty-five." The Experimenter monitored a different subject on each trial to check that the subject was counting backwards at close to the rate of one three-digit number every .75 sec, which seemed to be as fast as these subjects could perform the counting task. Subjects did not know who was being monitored at any time. No records were kept concerning the homogeneity of backward counting at different delays, but we satisfied ourselves at the time that these subjects were quite consistently counting backwards at a rate of about .75 sec per three-digit number, at all delays and at all times since the beginning of the session.

However, it should be pointed out that since subjects always began counting backwards with a number between 900 and 999, short delays of testing (t) featured numbers with 9 or 8 as the first digit, whereas longer delays included numbers with lower first digits. In addition, subjects received greater practice in the backward counting task at the higher numbers. It is possible that the effects of this task upon retention were not homogeneous at all delays for these reasons. If this is a serious problem, it could distort the form of the empirical retention function.

Design. There were two levels of storage load (1 vs. 6 letters), two types of test letters (correct and false), and 14 delays (3, 4, 5, 6, 7, 8, 10, 15, 20, 30, 45, 90, 180, and 300 sec), for a total of 56 conditions. The conditions were randomized in blocks of 56 trials, with one block given in a one-hour session. There was 1 practice session, followed by 50 regular sessions, yielding an *N* of 50 trials per condition. Each session was preceded by 5 practice trials. In the 6-letter conditions, serial positions 1, 2, 5, and 6 were each tested 8 times and serial positions 3 and 4 were each tested 9 times.

Subjects. The subjects were 4 M.I.T. undergraduates who were paid for their services. The subjects were usually run together, with each subject whispering the numbers as he counted backwards.

Results and Discussion

Recognition Probabilities

The raw data consisted of the frequencies of using each rating category on the ordered scale from "*Y*6" to "*N*6" in each condition for each subject. The data were pooled for all serial positions in the 6-letter conditions. These data were converted to the cumulative probabilities of each subject's selecting a rating response which was at least as affirmative as "*Y*6," "*Y*5,"..., "*Y*1," "*N*1," "*N*2,"..., "*N*6" in both correct and false recognition test conditions, at each delay, for each level of storage load. Let the 12 rating categories be labeled $i = 1, \ldots, 12$ from "*Y*6" to "*N*6." Let $p_k = \Pr\{i \leqslant k\}$, $k = 1, 2, \ldots, 11$ for a correct test letter, for a given subject, and let $q_k = \Pr\{i \leqslant k\}$, $k = 1, 2, \ldots, 11$ for a false test letter. The pairs of (p_k, q_k) probabilities for each subject for each condition whose sum was closest to 1.00 are shown in Table 1.

TABLE 1

Correct and False Recognition Probabilities

Storage Load	Delay (sec)	MM		RC		DC		PS	
		p	q	p	q	p	q	p	q
1	3	.96	.04	1.0	.04	1.00	.04	.98	.04
	4	.92	.04	1.0	.04	1.00	.02	.98	.06
	5	.92	.08	1.0	.16	.98	.02	.94	.06
	6	.92	.06	1.0	.02	.96	.02	.98	.02
	7	.92	.08	1.0	.02	.94	.06	.92	.04
	8	.84	.12	1.0	.02	.92	.06	.94	.06
	10	.82	.10	.98	.02	.94	.04	.92	.12
	15	.86	.12	.96	.06	.90	.12	.78	.16
	20	.90	.20	.98	.08	.96	.10	.90	.18
	30	.80	.08	.94	.08	.82	.12	.82	.20
	45	.78	.28	.94	.08	.88	.22	.80	.22
	90	.82	.32	.82	.20	.84	.18	.74	.26
	180	.70	.26	.76	.28	.56	.14	.80	.26
	300	.60	.28	.68	.30	.46	.22	.54	.24
6	3	.78	.32	.96	.04	.94	.08	.82	.12
	4	.72	.40	.96	.04	.88	.16	.78	.22
	5	.80	.32	.94	.02	.86	.16	.76	.16
	6	.76	.34	.96	.10	.68	.20	.76	.22
	7	.58	.20	.86	.10	.76	.20	.70	.28
	8	.66	.32	.94	.06	.78	.24	.68	.30
	10	.70	.40	.90	.10	.70	.28	.76	.26
	15	.66	.38	.80	.22	.64	.30	.66	.32
	20	.54	.54	.86	.22	.72	.28	.54	.44
	30	.64	.44	.72	.28	.70	.30	.70	.32
	45	.60	.34	.70	.38	.72	.44	.46	.46
	90	.26	.34	.64	.36	.50	.44	.44	.36
	180	.40	.42	.48	.34	.42	.34	.46	.40
	300	.58	.42	.52	.56	.38	.44	.54	.48

Memory Operating Characteristics

Rating-scale operating characteristics were plotted using the rating scale data for the correct and the false recognition conditions at each delay for each of the two storage loads, separately for each subject. See Wickelgren and Norman (1966) for a discussion of memory operating characteristics. The operating characteristics showed no systematic deviation from (visually-fitted) straight lines on normal-normal probability coordinates, consistent with the assumption that the noise in the strength values for both correct and false recognition conditions was approximately normally distributed. Slopes were measured in degrees (actually $\tan^{-1}$ slope) to reduce the variability introduced by a few operating characteristics which were nearly vertical. The slopes (in degrees) of the operating characteristics were not correlated with the intercepts (d's or strength-difference values). Pooling over subjects, the correlation was .07 for the 1-letter conditions and .03 for the 6-letter conditions, both very insignificant by a t-test. In addition, the average slope was very close to unity (45°), being 41.4° for the 1-letter conditions and 42.3° for the 6-letter conditions. Due to substantially lower variance in the slopes for 6-letter conditions, the deviation of the 42.3° average slope from 45° just reached significance at the .05 level, but the 41.4° slope was not significantly different from 45°. Because slope was not correlated with d', the intersection of the operating characteristic with the negative diagonal was used to determine the d' value (strength difference between correct and false test items) for each condition of delay and storage load. Each d' value was estimated by using the estimates of correct and false recognition probabilities associated with the point of intersection in conjunction with Table 1 of Elliott (in Swets, 1964).

Strength Retention Functions

To determine how total memory strength changed over time for each of the two levels of storage load, the empirical strength (d') values were plotted as a function of delay for each level of storage load for each subject. These empirical strength retention functions are shown in Fig. 1 on a semilog plot.

If the total memory strength consisted of a single exponentially decaying trace ($d = \alpha_L e^{-\beta_L t}$), then the plot of log strength against time would be a straight line. Best-fitting straight lines were obtained by a minimum chi-square procedure separately for each of the two storage-load conditions for each of the four subjects. This minimum chi-square procedure used the original probability data shown in Table 1, including the conditions with unmeasurable d's. The unmeasurability of d' has no effect on the ability to do a chi-square goodness-of-fit test on the original probability data. The estimates of the acquisition parameters (α_1 and α_6), the estimates of the decay parameters (β_1 and β_6), and the goodness-of-fit of the single-trace theory for each of the four subjects are shown in Table 2.

Inspection of Fig. 1 indicates that the memory strength retention functions for each of the four subjects deviate systematically from that predicted by a single-trace theory with exponential decay. This is confirmed by the rather poor fit of this theory to the data as indicated by the large χ^2 values in Table 2. In general, the decay is more rapid at the short delays and/or slower at the longer delays than that predicted by a simple exponential decay theory. Furthermore, there is generally too little forgetting in the region from 10 to 30 sec delays.

On the other hand, the dual-trace consolidation theory fit the retention functions extremely well. The parameter estimates for the dual-trace consolidation theory

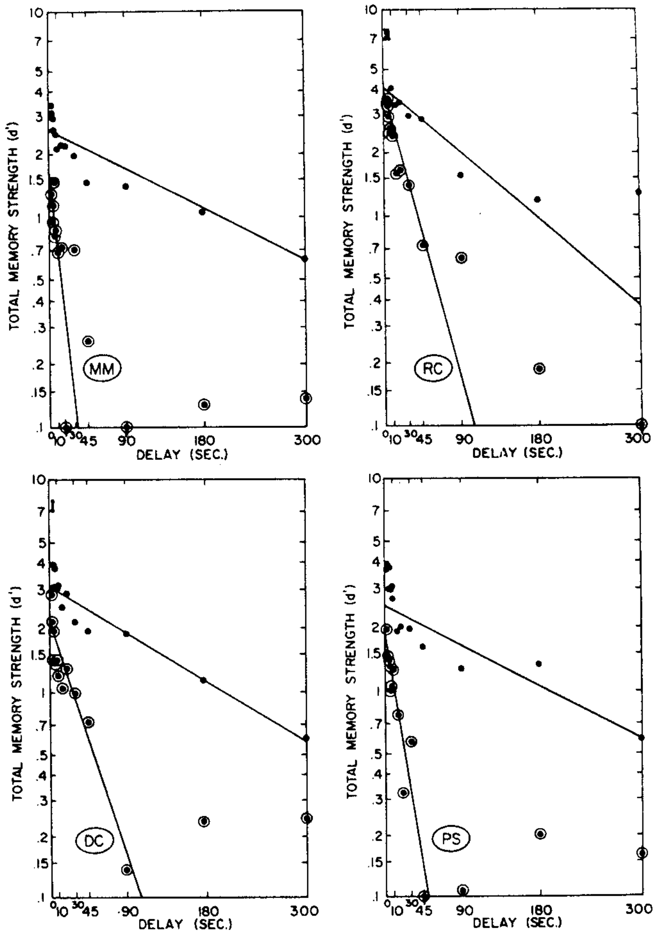

FIG. 1. Strength retention functions on semilog plots for each of four subjects in recognition memory for single letters from lists of one or six letters. The straight lines are the least squares predictions of a single-trace theory with exponential decay and both acquisition and decay rate variable across storage load conditions. Points plotted at $d' = 7$ with upward arrows had an unmeasurable d' due to no overlap in the rating scale data. Points plotted at $d' = .1$ with a downward arrow had a $d' < .10$.

TABLE 2

Parameter Estimates and Goodness-of-Fit for the Single-Trace Theory

	α_1	α_6	β_1	β_6	χ^2	*df*	*p*
MM	2.6	1.6	.0045	.080	43	24	.01
PS	2.5	1.9	.0045	.060	65	24	.001
DC	3.2	2.2	.0058	.030	47	24	.01
RC	4.1	3.8	.0080	.035	34	24	.10

TABLE 3

Parameter Esimates and Goodness-of-Fit for the Dual-Trace Consolidation Theory

	α_1	α_6	$\beta(\text{sec}^{-1})$	λ_1	λ_6	$\psi(\text{sec}^{-1})$	b(sec)	$\gamma(\text{sec}^{-1})$	c_1(sec)	c_6(sec)	χ^2	*df*	*p*
MM	4.1	1.5	.07	1.4	.4	.18	11	.0037	90	30	21	18	.3
PS	5.0	1.9	.06	1.3	.0	.25	17	.0067	180	—	21	18	.3
DC	7.5	3.5	.12	1.9	.8	.20	8	.0053	90	30	15	18	.5
RC	7.9	4.3	.06	2.0	.6	.13	14	.0032	45	30	11	18	.8

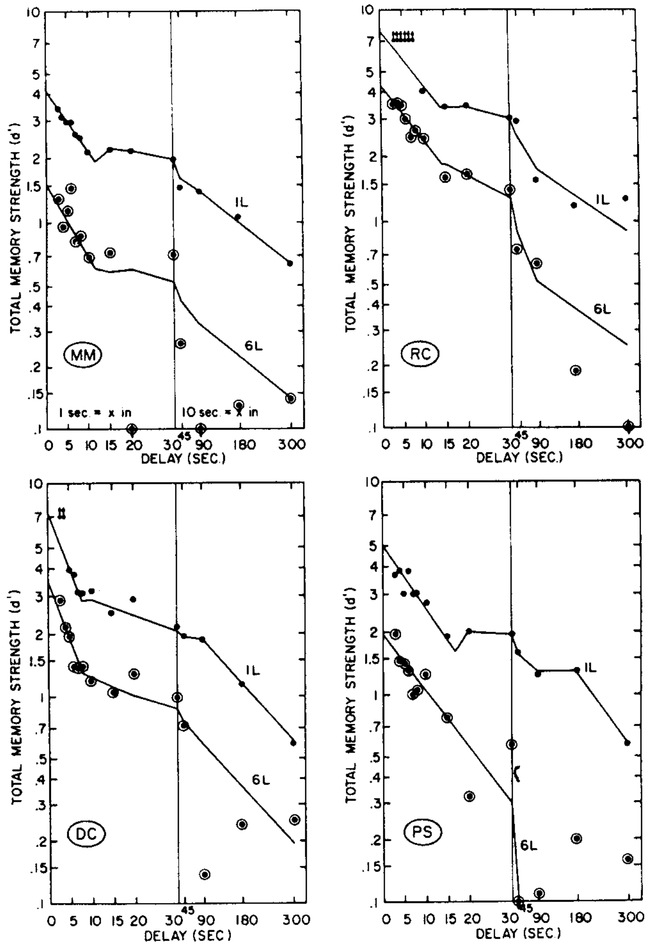

FIG. 2. Strength retention functions on "split" semilog plots for each of four subjects in recognition memory for single letters from lists of one or six letters. The straight line segments connect the predictions of dual-trace consolidation theory with the parameter estimates from Table 3. Note the scale change on the delay axis at 30 sec.

as applied to the present experiment in Eq. (1) are presented in Table 3, along with the χ^2 goodness-of-fit measure, for each subject. The parameter estimates were obtained by a combination of informal graphical and more formal least-squares procedures on different sections of the strength retention functions. However, the χ^2 goodness-of-fit measure was made using the probability data in Table 1. All of the data were used in the goodness of fit test, including the points with unmeasurable d's. Although minimum chi-square estimation methods would undoubtedly have produced a somewhat better fit, the obtained fits are so good that little would be gained.

The theoretical predictions of the dual-trace theory are shown in Fig. 2 along with a replot of the data points from Fig. 1. Each retention function in Fig. 2 is really being shown on two semilog plots, with the delay times under 30 sec enlarged by a factor of ten (in comparison to delay times above 30 sec) to permit closer inspection of the fit of the theory to the data in this region.

Prior to the onset of the production of retrievable long-term memory (i.e., for $t \leqslant b$), only short-term memory is available to mediate recognition memory decisions. As indicated in Table 3, b is estimated to be in the vicinity of 10 sec for this task, with individual estimates ranging from 8 sec for *DC* to 17 sec for *PS*. Examination of the strength retention functions for $t \leqslant b$ shows no systematic deviation from the prediction of a simple exponentially decaying short-term memory trace for these short retention intervals.

However, starting at a delay of about 10 sec, the empirical retention functions decelerate sharply in their rate of decay. This is accounted for in dual-trace consolidation theory by the onset of the consolidation of potential long-term memory into retrievable long-term memory.

According to the model, decay of short-term memory continues at the same rate for $t > b$ as for $t \leqslant b$, but this is counterbalanced by the consolidation of long-term memory over retention intervals from about 10 to 30 sec. Indeed, if the amount of long-term memory and the rate of consolidation are high enough in relation to the amount of short-term memory and its rate of decay, then one can get a temporary increase in the total strength of the memory (reminiscence) at delays between 10 and 30 sec.

No substantial or systematic reminiscence was obtained in the present study, but a few previous distractor studies have found reminiscence at around a 20 sec delay by comparison to shorter delays (Keppel and Underwood, 1967; Peterson, 1966; Scheirer and Voss, 1969). Furthermore, all the studies of Ward-Hovland reminiscence in the recall of serial list were concerned with reminiscence occurring over the period from around 6 sec to around 2 min (e.g., Hovland, 1938; Ward, 1937). Many studies do not find reminiscence occurring over these delays, but strength retention functions plotted for all the studies I know about show at least a substantial deceleration of the decay rate occurring at a delay of around 10 sec, in agreement with the results of the present study (e.g., Hellyer, 1962; Melton, 1963; Murdock, 1961; Peterson and Peterson, 1959).

With the estimates of the rate of consolidation (ψ) given in Table 3 (time constants between 4 and 8 sec), consolidation of long-term memory is essentially completed by around 30 sec. However, according to the dual-trace theory, the onset time (c_1 or c_6) of the decay of long-term memory may be delayed for many tens of seconds beyond 30 sec. Nevertheless, according to the theory, there may be a moderate decline in the total strength between 30 sec and 1 minute due to the decay of the remaining short-term memory trace. After about a minute, short-term memory is no longer a factor, and one observes either the slower decay of the long-term memory trace or a flat section of the retention function during the end of the consolidation process followed by the onset of the decay process for the long-term trace.

As can be seen in Fig. 2 and Table 3, the dual-trace theory with consolidation fits details of the rather complex empirical strength retention-functions very well. Many parameters were estimated, but the parameters all appear quite naturally from the properties of the different phases of the memory traces in what is really quite a simple theory. The good fits were obtained with most of the parameter estimates for a given subject assumed to be the same for the 1-letter and 6-letter storage load conditions. The degrees of acquisition in short-term and long-term memory were assumed to be different for the two storage-load conditions. However, it seems reasonable for acquisition to be poorer for each item when there are more items to learn, even though study time per item is held constant. This can be considered to be an acquisition "fatigue" effect. The only *ad hoc* parameter estimate which was made separately for the two storage load conditions was the onset delay for the decay of the long-term memory trace (c). This seemed to produce a better fit in the present experiment, but obviously no great significance should be attached to this finding, given the small density of delays in the relevant interval. It should be noted that the 3 parameters assumed to vary from the 1-letter to the 6-letter storage load conditions all vary in a modest and consistent manner across the four subjects.

Finally, the range of individual variation in the parameter estimates across the four subjects is small. The differences in the empirical strength retention functions are being fit with modest variations in the parameter estimates. Thus, the good fit for each subject is being obtained in essentially the same way, not by wildly different mixtures of parameters in different cases.

Effects of Storage Load

Extremely good fits were obtained with the dual-trace theory under the assumption that the rates of decay for both traces, the rate of consolidation for the long-term trace, and the onset time for the consolidation of the long-term trace were constant for the two storage-load conditions. Because such good fits were obtained, there is some support from this study for assuming these parameters to be invariant with respect to storage load and for assuming that the degree of acquisition of both traces is decreased by increases in storage load. However, only large differences in many of the parameters would have been detected by the present experiment. Even though the present study used a very large number of delays by comparison to previous studies, an even larger number of delays would be desirable for efficient determination of these parameter invariance questions within the context of the dual-trace consolidation theory.

The parameter invariance question which the present study is most suited to answer is the dependence of the rate of decay in short-term memory on storage load. This question was examined by means of least squares fits of simple exponential decay functions to the early sections of the retention functions (under 8 or 10 sec) separately for each of the two storage-load conditions. In order to avoid possible contamination from the consolidation of LTM, only delays up to 10 sec were used for subjects MM and PS and only delays up to 8 sec were used for subject DC. Only the points with measurable *d*'s were used for this analysis. Thus, RC could not be used at all for this analysis because his d' scores were unmeasurable for all delays under 10 sec in the 1-letter condition. For the other three subjects, the least-squares analysis (on the logs of the d' values) gave estimated decay rates for the 1-letter and 6-letter conditions of .066 and .081 for MM, .045 and .069 for PS, and .094 and .15 for DC. None of these differences between the estimated decay rates for the two storage load conditions approached statistical significance (using t tests for the differences of the regression coefficients), and none of the differences in decay rate was very large. Combining all three significance tests using Fisher's (1938) method yielded an insignificant $\chi^2 = 8.67$ ($p = .2$ on 6 d.f.), even when 1-tail probabilities were used for each of the three subjects.

Certainly one does not find decay rate in STM being proportional to storage load or anything remotely approaching it. The small differences that do exist might be entirely due to differences in the effect of rehearsal in the two conditions. That is, if the subject does rehearse on a few occasions (contrary to instructions), it is much more likely to aid his recall (and perhaps decrease decay rate) in the 1-letter condition than in the 6-letter condition. This is because in the 6-letter condition, it is likely that the letter he rehearsed will not be tested, even if the test letter was one of the six letters in the list. However, it should be clear that the present results do not contradict the possibility of a small or moderate increase in the decay rate of the short-term trace with increases in storage load as suggested by Melton (1963) and Murdock (1967).

What has really been discovered about the possible dependence of decay in short-term memory on storage load is that this dependence is either nonexistent or else too small to account for the large difference between the short-term decay rate of .045 to .15 found for distractor-probe designs and of .17 to .87 found for single-list probe designs (e.g., Waugh and Norman, 1965; Norman, 1966; Wickelgren and Norman, 1966; Wickelgren, 1967; Wickelgren, 1970 a). Since the single-list probe studies have always had memory storage loads substantially larger than the distractor studies, it was possible that this accounted for the difference in decay rate in short-term memory.

The present results indicate that the effect of storage load on short-term decay rate is too small to account for the difference between the distractor-probe and single-list probe designs.

The theory described in Wickelgren (1970 a) accounted for the differences in short-term decay rates across different studies by differences in the rate at which new items had to be learned in the retention interval. In most distractor designs (including that in the present study), no new items have to be learned in the retention interval. According to the theory in Wickelgren (1970 a), it is the use of a nonlearning task in the retention interval which produces the slower short-term memory decay in the commonly used distractor designs as compared to the single-list designs. This theory receives some indirect support from the results of the present study because the present study shows that a plausible alternative theory will not work.

Homogeneity Questions

However, inhomogeneity in the form of the retention functions or the parameters of these functions could have critical distorting effects on the conclusions based on the present data for the following reason: These data are pooled over different letters, different serial positions of tested letters in the six-letter list, different contexts of presentation (other items in the list, nature of the items and retention intervals used on nearby trials, etc.), different states of the subject (degree of arousal, attention, etc.), and levels of practice (early vs. late in the session, early vs. late sessions).

Very little is definitely established concerning these homogeneity questions, but there are a few encouraging results. In the present study, the same deviation from simple exponential decay was found for the one-letter lists as for the six-letter lists, and the decay rates for the short-term components were not too different. This indicates that pooling over serail positions is not responsible for the deviation from simple exponential decay. Strength analysis of previous distractor studies (e.g., Hellyer, 1962; Murdock, 1961; Peterson and Peterson, 1959, etc.) yields short-term memory decay rates for unpracticed subjects (pooled over subjects) which are not very different from the decay rates obtained for individual subjects in the present study (pooled over different stages of practice). But these are just straws in the wind. Many more studies showing invariance of the number of memory traces and the forms and parameters of their retention functions are necessary in order definitely to establish consolidation and the dual trace theory developed in the present paper.

REFERENCES

Bower, G. H., and Bostrom, A. Absence of within-list *PI* and *RI* in short-term recognition memory. *Psychonomic Science*, 1968, **10**, 211–212.

Brown, J. Some tests of the decay theory of immediate memory. *Quarterly Journal of Experimental Psychology*, 1958, **10**, 12–21.

ELLIOTT, P. B. Tables of *d′*. In J. A. Swets (Ed.), *Signal detection and recognition by human observers*. New York: Wiley, 1964. Pp. 651–684.

FISHER, R. A. *Statistical methods for research workers*. (7th Ed.). London: Oliver & Boyd, 1938.

HELLYER, S. Supplementary report: Frequency of stimulus presentation and short-term decrement in recall. *Journal of Experimental Psychology*, 1962, **64**, 650.

HOVLAND, C. I. Experimental studies in rote-learning theory. I. Reminiscence following learning by massed and by distributed practice. *Journal of Experimental Psychology*, 1938, **22**, 201–224.

KEPPEL, G., AND UNDERWOOD, B. J. Reminiscence in the short-term retention of paired-associate lists. *Journal of Verbal Learning and Verbal Behavior*, 1967, **6**, 375–382.

MELTON, A. W. Implications of short-term memory for a general theory of memory. *Journal of Verbal Learning and Verbal Behavior*, 1963, **2**, 1–21.

MURDOCK, B. B., JR. The retention of individual items. *Journal of Experimental Psychology*, 1961, **62**, 618–625.

MURDOCK, B. B., JR. Distractor and probe techniques in short-term memory. *Canadian Journal of Psychology*, 1967, **21**, 25–36.

NORMAN, D. A. Acquisition and retention in short-term memory. *Journal of Experimental Psychology*, 1966, **72**, 369–381.

PETERSON, L. R. Reminiscence in short-term retention. *Journal of Experimental Psychology*, 1966, **71**, 115–118.

PETERSON, L. R., AND PETERSON, M. J. Short-term retention of individual verbal items. *Journal of Experimental Psychology*, 1959, **58**, 193–198.

SCHEIRER, C. J., AND VOSS, J. F. Reminiscence in short-term memory. *Journal of Experimental Psychology*, 1969, **80**, 262–270.

WARD, L. B. Reminiscence and rote learning. *Psychological Monographs*, 1937, **49**, No. 220.

WAUGH, N. C., AND NORMAN, D. A. Primary memory. *Psychological Review*, 1965, **72**, 89–104.

WICKELGREN, W. A. Exponential decay and independence from irrelevant associations in short-term recognition memory for serial order. *Journal of Experimental Psychology*, 1967, **73**, 165–171.

WICKELGREN, W. A. Unidimensional strength theory and component analysis of noise in absolute and comparative judgments. *Journal of Mathematical Psychology*, 1968, **5**, 102–122.

WICKELGREN, W. A. Associative strength theory of recognition memory for pitch. *Journal of Mathematical Psychology*, 1969, **6**, 13–61.

WICKELGREN, W. A. Time, interference, and rate of presentation in short-term recognition memory for items. *Journal of Mathematical Psychology*, 1970, **7**, 219–235. (a)

WICKELGREN, W. A. Multitrace strength theory. In D. A. Norman (Ed.), *Models of Human Memory*. New York: Academic Press, 1970. Pp. 65–102. (b)

WICKELGREN, W. A. Coding, retrieval, and dynamics of multitrace associative memory. In Lee Gregg (Ed.), *Cognition in Learning and Memory*. New York: Wiley, in press.

WICKELGREN, W. A., AND NORMAN, D. A. Strength models and serial position in short-term recognition memory. *Journal of Mathematical Psychology*, 1966, **3**, 316–347.

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