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Associative Interference and Retrieval Dynamics in Yes–No Recall and Recognition

Wayne A. Wickelgren and Albert T. Corbett
University of Oregon

Recall dynamics of an A–B paired associate were studied by a new speed–accuracy tradeoff method: Present A; wait a variable-lag time; present B, followed 200 msec later by a signal to make a yes–no decision within 200 msec. Recognition memory dynamics were studied by the method of Reed: Present an A–B pair; wait a variable lag; present a signal to make a yes–no response within 200 msec. Recall strength was about half of recognition strength, compatible with the hypothesis that recall tapped only the forward association, while recognition used both forward and backward associations. Memory retrieval dynamics in recall and recognition appeared identical. The A–B, A–C associative interference had a small retarding effect on retrieval dynamics for an A–B association, and the effect was about the same for recall and recognition. The effect was approximately half that predicted by the simplest serial search model of memory retrieval. The findings are compatible with a direct-access model for retrieval, with interference producing a modest retardation in both recognition and recall dynamics.

There appear to be two basic modes for retrieving information stored in human memory: recall and recognition. Despite a great deal of research on this topic, it is fair to say that there is no general agreement on the relation between these modes. For an introduction to this literature and a brief review of some representative theoretical positions, see Tulving and Watkins (1973). The present study does not presume to resolve this problem. However, we have invented a speed–accuracy tradeoff method for studying the dynamics of memory retrieval in recall that may be useful in studying the relationship between recall and recognition. This article describes the method and uses it to compare retrieval dynamics in recall and recognition as a function of the presence or absence of associative interference.

The present study is concerned with basic retrieval processes that underlie a single elementary act of probe recall or recognition for paired associates. We are not studying the complex combination of elementary acts of recall and recognition that produces free recall of long lists or recognition of items under conditions in which subjects have lots of time and are free to recall additional material, go back and change answers, and so forth. Theories of the relation between complex processes such as free recall and multiple-item recognition may have very little in common with theories of the relation between elementary recall and recognition.

Before proceeding to describe our method for studying recall, it is necessary to describe the speed–accuracy tradeoff method for studying recognition memory as developed by Reed (1973, 1976). For the sake of simplicity, we shall describe Reed's method as we have used it to study paired-associate recognition memory. First, subjects learned a list of A–B pairs. Recognition memory for the pairs was then tested by presenting a correct A–B or an incorrect A–D pair, followed by a variable lag ranging from .2 to 4 sec, followed by a tone which signaled the subject to make a yes–no recognition

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Requests for reprints should be sent to Wayne A. Wickelgren, Department of Psychology, University of Oregon, Eugene, Oregon 97403.

response about 200 msec after the onset of the tone. The accuracy of recognition memory performance is assessed using a d' measure of the discriminability of correct and incorrect pairs. The dynamics of the retrieval process in recognition memory are assessed by plotting this d' accuracy variable as a function of the increase in processing time for the pair. Because subjects' reaction times following the response signal (the tone) are typically not precisely constant over the different lag times, this speed–accuracy tradeoff function for recognition dynamics typically plots recognition accuracy as a function of the total processing time (lag + mean response latency at that lag).

Speed–accuracy tradeoff methods can be applied to the study of conventional recall in a reasonably straightforward way by employing verbal recall and a deadline procedure. One presents the A cue and requires subjects in some block of trials to attempt to recall the B item before a deadline of, say, .5 sec, 1 sec, or 2 sec. Both Houston (1968) and Murdock (1968) have employed essentially this type of speed–accuracy tradeoff procedure in the study of conventional recall. However, there are some disadvantages to this method.

First, the deadline method has some deficiencies compared to the response-signal method as a means of generating speed–accuracy tradeoff functions, most notably the defect that since a given deadline condition must be run in a homogeneous block of trials (or else be cued in advance of each trial), subjects may be operating with different strategies during the first 500 msec of a 500-msec deadline condition than during the first 500 msec of a 1-sec deadline condition, and so on. Furthermore, it is more difficult to get a low variance (tightly packed distribution) of reaction times using the deadline method as compared to using the response-signal method. On the other hand, the response-signal method has the disadvantages of requiring processing of an additional signal (the response cue) and possible changes in expectation of that signal as a function of lag.

Second, it is not feasible to use key-press responses for multiple-choice recall with a large number of alternative responses. Thus, one is forced to use vocal responses and a voice key for both recall and recognition memory to maximize comparability.

Third, although either probability-correct or d' can be used as an accuracy measure for both recall and recognition, the probability of a correct response is not very suitable as a measure of performance accuracy in recognition because of its sensitivity to response bias. However, the decision-making assumptions involved in computing d' for recall are different from the assumptions made for recognition. The validity of the decision-making assumptions for recall are far from being established for even small, well-defined populations of response alternatives, let alone for large, unspecified populations of alternatives (such as English words).

Fourth, when there is more than one correct response to a stimulus item (i.e., when both A–B and A–C pairs have been learned), recall of both response items is necessarily sequential due to the characteristics of the speech output process. This is true regardless of whether the earlier memory retrieval process for the B and C associates is serial or parallel. As a consequence of the serial character of the output process, most people probably assume that the retrieval process in recall is intrinsically serial. As we shall see, the results of the present study suggest that this may not be the case.

Accordingly, the following method was devised to study the retrieval process in recall. Presentation of the A item was followed after a variable lag ranging from .1 sec to 3.9 sec by presentation of the correct B item or an incorrect D item, followed after a fixed .2 sec by presentation of a tone signaling subjects to make a yes–no response as to whether the second item was or was not a correct associate of the A item. During the lag between presentation of the first (A) item and the second (B or D) item, subjects were to attempt to recall the associates of the A item so as to be able to make a fast yes–no decision about whether the second item was or was not a correct associate. As with the speed-accuracy tradeoff method for recognition, subjects were instructed to make this yes-no response about 200 msec following the response signal. The response signal occurred 200 msec after presentation of the second item so that subjects would have time to process that item and to match it to what was recalled in response to the A item.

Based on the results of Corbett (Note 1) and Dosher (Note 2) and the present study, we know that the 400 msec that elapsed following presentation of the second (B or D) item before the subject made his yes or no response is inadequate to achieve above-chance responding using a *recognition* process applied to the A–B or A–D pair. Thus, any increase in the accuracy of yes–no recall as a function of increasing the lag between presentation of the first and second items seems likely to be based on some kind of *recall* process initiated by the A item. It is parsimonious to assume that this recall process is identical to the initial memory retrieval phase of conventional recall, that is, the period of memory retrieval prior to the decision (output) phase of conventional recall. According to this hypothesis, yes–no recall and conventional recall share an initial-recall memory retrieval process but have different decision processes, yes–no recall having a decision process comparable to yes–no recognition, but conventional recall typically requiring a choice among many alternative responses. This hypothesis is parsimonious and has considerable face validity, and we will discuss our results having made this assumption. However, one must be mindful of the possibility that yes–no recall has nothing in common with conventional recall.

In the present experiment, recognition and yes–no recall are used to study memory for A–B associations learned with and without associative interference. Associative interference was produced by having subjects learn both an A–B and an A–C association. Thus, there are four basic conditions in our study: (a) pair recognition without associative interference, (b) pair recognition with associative interference, (c) yes–no recall without associative interference, and (d) yes–no recall with associative interference.

To produce learning of the no-interference A–B associations, subjects constructed a visual image involving both the A and B words. To learn the interference A–B, A–C associations, subjects constructed a visual image uniting an A–B–C word triple into a common visual image under the instruction that memory would only be tested for the A–B or A–C (not the B–C) association. Visual-image mnemonics were employed to produce rapid learning of a large number of pairs and triples in order to allow time for a large number of test trials in each session. The reader should keep in mind that the results of the associative interference condition under either yes–no recall or recognition might have been different had subjects learned A–B and A–C as separate pairs rather than uniting them into a common image. Furthermore, although it now appears likely that much, if not all, paired-associate learning of word pairs proceeds by means of forming propositional or image chunks (Anderson & Bower, 1973), the results of the present study are relevant only for memory retrieval under conditions of learning by visual-image chunking.

Method

One basic memory retrieval experiment was run using the four conditions specified earlier. In all, six subjects were run in these four conditions. The experiment was run in two phases with three subjects in each phase and some (presumably small) differences in procedure. In addition, after running the first three subjects in the retrieval task, a useful control experiment occurred to us, so we ran the first three subjects in it. Accurate performance in the control experiment was then used as a selection criterion to choose the three subjects for the second phase of the experiment. For clarity, the experiments are described in the order Phase 1, Control Experiment, Phase 2.

Phase 1

Subjects. Three subjects (P.B., E.C., and S.S.) were paid $2 per hour to participate in the experiment.

Materials. A list of 1,200 high-imagery words was compiled from the Paivio, Yuille, and Madigan (1968) norms, the Kučera and Francis (1967) norms, and the American College Dictionary. In compiling the list, synonyms of words already in the list were not included. Synonymity and imagery decisions were based on the experimenter's judgment.

Procedure. Subjects participated in two sessions a day, one in the morning and one in the afternoon, each approximately 75 min. long. Each session was divided into a learning session and a test session. Stimuli were presented on a cathode-ray tube in both learning and testing. The experiment was controlled by a PDP-15 computer. All three subjects were run simultaneously on one station.

Learning. At the beginning of each session, subjects were presented with a list of 13 word pairs and 13 word triples. The pairs and triples were randomly selected from the list of 1,200 words. No word appeared in more than one pair or triple across the entire experiment. One pair and one triple were displayed at the beginning of each session. These were employed as practice stimuli in the test session. They were followed by the remaining pairs and triples randomly intermixed. A tone was sounded each time a new pair or triple appeared. One element (A) appeared on the left side of the display screen. The second element of a pair (B) appeared on the right side. The second (B) and third (C) elements of the triples appeared on the right side of the screen, one above the other. Subjects were told that in the test session the A item would appear on the screen and that they would be asked to recognize or recall the B (and C) items. Each pair and triple remained on the screen for 3 sec in the learning phase. Subjects were instructed to use visual-image mnemonics to learn the pairs and triples and were given instructions in imaging.

Test. The test phase was initiated shortly after learning (within 5 min.). The test session consisted of 396 trials divided into six blocks of 66 trials each. The first 12 trials in each session were practice trials and were not included in the analysis. Each test session consisted entirely of recognition or entirely of recall trials. On each day there was one recognition and one recall session (in random order). Subjects were informed of the nature of the test after learning and before the test phase. There were three preliminary practice sessions in recognition and three in recall followed by six recognition sessions and six recall sessions that comprised the experiment.

Recognition. At the beginning of each trial READY appeared on the display screen for 1,000 msec, then was immediately replaced by a test pair with one word displayed above the other. The top word was an A item and the bottom word was a B, C, or D item. The test stimulus was always a pair, regardless of whether the A item was from a pair or a triple. There was no indication in the display of whether a pair or a triple was being tested. Subjects were to decide if the two items had occurred in the same pair or triple. At a variable interval, or lag, after the onset of the test pair, the test pair was shut off and a 1,000-Hz auditory response signal was presented for 50 msec. Subjects were instructed to make a yes–no recognition response by pushing one of two keys immediately after the tone onset (about 200 msec). They were instructed to respond quickly even if they had not finished deciding whether the two words had occurred together. In the practice sessions, subjects were encouraged to respond within 200–300 msec of the tone, and eventually to reduce their latencies to around 200 msec. When all the subjects had responded, RATE appeared on the screen, and the subjects had 3,000 msec to rate their confidence on a scale from 1 to 4. The subject was instructed to think back and rate his confidence in his yes–no decision at the time that decision was made, not his confidence at the time of the confidence rating itself. After the confidence rating, each subject was given feedback on his latency from tone onset. This feedback remained on the screen for 2,000 msec, then READY appeared and a new trial began. The

Table 1
Time Course of the Recognition and Yes–No Recall Task

Recognition sequence	Time in msec	Recall sequence	Time in msec
READY	1,000	READY	1,000
Present A–B, A–C, or A–D	200–4,000	Present A	100–3,900
Tone	50	Present B, C, or D	200
Tone onset to response	200 (approximately)	Tone	50
RATE	3,000	Tone onset to response	200 (approximately)
Feedback	2,000	RATE	3,000
		Feedback	2,000

lags employed in the recognition task (i.e., the time between stimulus and response cue onset) were 200, 300, 400, 600, 900, 1,200, 2,500, and 4,000 msec. A diagram of the procedures for both recognition and yes-no recall is shown in Table 1.

Recall. As in recognition, READY appeared on the screen for 1,000 msec at the beginning of each trial. It was then replaced by a single word, an A item, on the left-hand side of the screen. Subjects were instructed to attempt to recall the word(s) which occurred in the same pair or triple as the A member in learning. Again, there was no indication in the display of whether the A item occurred in a pair or in a triple in learning. At a variable interval after the onset of the A item, the A item was removed and a second item (a B, C, or D item) appeared directly below where the first word had appeared. Subjects were to decide if this second item matched the item(s) that the subject had recalled in response to the A item. Two-hundred msec after the second item appeared, that item was removed and the 50-msec response cue was presented. Again, subjects were to respond immediately (about 200 msec) after the response-cue onset. As in recognition, a yes-no response was required. The trial then proceeded exactly as a trial did in the recognition task: The subjects rated their confidence in their decision and were given feedback concerning their response latency from the response cue. The lags employed in recall (the times from onset of the A item to response-cue onset) were 300, 400, 500, 700, 1,000, 1,300, 2,600, and 4,100 msec. The intervals from the A item to the second item were, of course, 200 msec shorter. The lag times from presentation of A to the response signal were increased by 100 msec from the recognition conditions because it was thought (incorrectly) that yes-no recall dynamics would be slower than recognition dynamics.

Design. In both recognition and recall, each pair and triple was tested eight times with correct items and eight times with incorrect items, once at each lag. In testing triples correctly, the B item and C item were each employed four times. In testing a given triple or pair, the incorrect test item (D) was randomly selected from the B and C members of the four pairs and triples which occurred just before or just after the A-B or A-B-C unit in learning, with the constraint that each of the eight pairs and triples contributed a B or C item for one of the eight incorrect testings of the A unit.

Matching Control Experiment

In the yes-no recall design, subjects were allowed 400 msec in which to match the second word to the words they had retrieved in response to the first word. A second study was run to determine how accurately subjects can match two words in 400 msec independent of memory retrieval. An estimate of this accuracy is necessary to evaluate the results of the yes-no recall study.

Subjects. The same three subjects as in Experiment 1 were paid $2 per hour to participate in this experiment.

Materials. The stimuli in this experiment consisted of a subset of the B and C items from the six yes-no recall sessions of Experiment 1.

Procedure. This study was controlled by the PDP-15 as in Experiment 1. Subjects participated in two sessions a day, one in the morning and one in the afternoon. At the beginning of each session, subjects were presented with a list of 52 words. The words were presented 1 at a time, each for 3 sec. The onset of each word was accompanied by a tone. The first 2 words served as practice words in the session. Subjects were instructed just to look at the words, not to attempt to learn them. The words were presented to familiarize the subjects with the words and to increase the similarity of this control study to the yes-no recall task. Following the presentation of the list the subjects participated in a test session.

Test. The test trials were very similar to those in the yes-no recall task. At the beginning of each trial READY appeared on the screen for 1,000 msec, then was immediately replaced by a single word on the left-hand side of the display screen. At a variable interval after the onset of this first item (A), the item disappeared and a second item (B) appeared on the screen directly below where the A item had appeared. In this task subjects were asked to decide if the B item matched the A item, that is, if the two words were identical. Two-hundred msec after onset of the B item, that item was removed and a 50-msec tone sounded. Subjects were instructed to respond with latencies of about 200 msec from the tone. After making this yes-no response, subjects rated their confidence in their decision at the time that the yes-no decision was made, on a scale from 1 to 4. After rating confidence, the subjects were given feedback concerning their response latency. There were four lags between the A item and tone in this experiment: 300, 700, 1,300, and 4,100 msec.

There were 408 test trials in each session. The first 8 trials were practice and were not included in the analysis. Each of the 50 test words was tested once positively and once negatively at each of the four lags. Subjects participated in four practice sessions and then in two test sessions.

Phase 2

We felt that the results from the first three subjects required replication, especially with subjects who were known to be able to perform at a high level of accuracy in the matching control task. Accordingly, two additional groups of three subjects each participated in the matching control experiment. These subjects practiced in eight sessions, then were tested in two sessions. Of the six subjects, the three most accurate in this control study (C.L., C.M., and S.J.) then participated in the recognition and yes-no recall tasks. The procedures described in Experiment 1 were followed exactly, with the following exceptions. The two sessions each day were run in the afternoon and evening. Subjects were instructed to respond about 200 msec after the response cue (rather than being instructed to respond immediately after the cue). The study time per pair and triple in learning was gradually reduced across days from 3,000 msec to 1,500 msec. Study time was always constant for the two sessions in one day. Study time was decreased so that accuracy remained measurable (finite d') as subjects improved with practice.

Results

The d_T measure was used to assess accuracy in the matching, yes–no recall, and recognition tasks. The d_T measure is a d'-type score based on two probabilities: (a) a yes response under a hit condition and (b) its comparable false-alarm condition, but adjusted for the effects of non-unit slope as indicated by the confidence judgment data. Computation of the d_T accuracy measure is described in detail by Reed (1973). For statistical comparisons we adopted a significance level of .01.

Matching Control Task

Table 2 presents the mean latencies and d_T accuracy levels at each lag condition in the matching control task. All three subjects used in Experiment 2 and Subject P.B. from Experiment 1 achieved very high accuracy on the matching control task. Thus, for these four subjects it is quite reasonable to assume that the process of matching the test item to an internally recalled item posed no great problem and did not have a significant depressing effect on the d_T accuracy score obtained for yes–no recall at any lag. For subjects E.C. and S.S. in Experiment 1, it is possible that the accuracy level in the yes–no recall task somewhat underestimates the true value as a result of these two subjects' difficulties in performing the matching output task. However, to the extent that the underestimation is a constant proportion across the different lags, it need not affect the time intercept or rate parameters of the yes–no recall retrieval functions. Although, as indicated in Table 2, the underestimation for Subjects E.C. and S.S. appears to be slightly greater for short than for long lags, it seems best to consider the data from all six subjects. However, it should be kept in mind that the results for Subjects E.C. and S.S. in the yes–no recall task may be biased by their difficulty in performing the output or decision phase of the yes–no recall task in the brief time permitted.

Lag–Latency Functions

The average latency for all six subjects in each of the four conditions in the experiment at each of the eight possible lags is shown in Table 3. There were some small individual differences in the form of the lag–latency function across individual subjects, but, on the whole, the average function reflects individual functions rather well.

There are two interesting points to make concerning the lag–latency functions. First, while recognition showed a modest decline in latency of about 60 or 70 msec, from the shortest lag of 200 msec to the longest lag of 4 sec, yes–no recall latencies were almost

Table 2
Matching Control Task

Lag (msec)	Subject											
	P.B.		E.C.		S.S.		C.L.		C.M.		S.J.	
	d_T	t	d_T	t	d_T	t	d_T	t	d_T	t	d_T	t
300	4.7	175	1.0	154	1.2	147	2.8	144	3.7	224	3.2	204
700	11.2	164	1.7	151	1.5	170	3.7	129	3.9	196	4.3	211
1,300	6.6	174	1.8	173	1.4	182	4.4	140	3.6	222	3.5	197
4,100	7.7	181	2.7	169	1.6	191	3.4	144	3.0	225	3.6	176

Note. t = mean latency (msec) of yes and no responses for both match and nonmatch conditions.

completely invariant as a function of lag. In part this may be because the shortest lag for yes-no recall was 300 msec, while the shortest lag for recognition was 200 msec. However, only about 20 msec of the drop in recognition memory can be accounted for in this way. Second, there was virtually no difference in the lag-latency function for pairs and triples in recognition memory and only a rather small (average 16 msec) difference between the pairs and triples conditions in yes–no recall. In both recall and recognition, there was no difference in the form of the lag–latency functions for pairs versus triples.

There may be some deep theoretical reasons why recall and recognition show slightly different lag–latency functions and why recognition latencies show a small decline as a function of lag. However, at this stage in our understanding of the speed–accuracy tradeoff method, we assume that latency differences merely reflect strategy differences in when to respond. In any event, the small differences in latency for different conditions and lags do not obscure the fact that a remarkable degree of invariance in latency as a function of lag can be achieved using the response-signal method. It seems entirely reasonable at this point to assume that small differences that remain in latency for different lags are satisfactorily incorporated into speed–accuracy functions by adding the mean latency to the lag time and plotting accuracy as a function of this total processing time. Accordingly, the independent retrieval-time variables in the speed–accuracy tradeoff functions reported in the following section are the sum of lag plus mean latency for the individual subject at that lag.

Individual Speed–Accuracy Tradeoff Functions

The hit and false-alarm rates in each condition of the experiment are shown in Table 4. These were transformed to d_T accuracy scores to eliminate differences in response bias. A 2 × 2 × 8 × 6 analysis of variance on the d_T scores demonstrated significant main effects of retrieval lag, $F(7, 35) =$

Table 3
Average Lag Latency Functions

Recognition latencies (msec)			Yes–No recall latencies (msec)		
Lag (msec)	Pairs	Triples	Lag (msec)	Pairs	Triples
200	234	236	300	177	189
300	213	220	400	174	183
400	195	202	500	176	185
600	176	184	700	172	189
900	170	178	1,000	165	188
1,200	173	174	1,300	173	196
2,500	173	176	2,600	181	200
4,000	165	171	4,100	178	198
Average	187	193	Average	175	191

22.6, $MS_e = 1.338$; associative interference, $F(1, 5) = 36.3$, $MS_e = 1.328$; and recognition versus recall, $F(1, 5) = 18.0$, $MS_e = 4.011$. The interaction between lag and interference was significant, $F(7, 35) = 6.4$, $MS_e = .213$, as was the interaction between lag and recognition versus recall, $F(7, 35) = 10.2$, $MS_e = .813$, showing that the effects of interference and recognition versus recall are primarily on the asymptotes (at long lags). No other interactions were significant.

The speed–accuracy tradeoff functions for each of the four conditions for each of the six subjects in the experiment are shown in Figure 1. The theoretical lines for each condition shown in Figure 1 were obtained by assuming that speed-accuracy tradeoff functions have the form of an exponential approach to a limit following a period of chance accuracy from 0 sec of retrieval time up to some time intercept (δ), that is to say, an equation of the form

$$d_T = \lambda(1 - e^{-\beta[T-\delta]}), \qquad (1)$$

where $[T - \delta] = T - \delta$ for $T > \delta$ and 0 elsewhere. No theoretical significance attaches to the choice of the exponential approach to a limit as the form of the retrieval function. The choice is based on the fact that the exponential approach to a limit has provided rather good fit to speed–accuracy tradeoff functions in this study and previous studies of retrieval dynamics, with no systematic deviations across all studies (Corbett, Note 1; Dosher, 1976).

Table 4
Hit and False-Alarm (FA) Rates

Lag (msec)	P.B. % hit	P.B. % FA	E.C. % hit	E.C. % FA	S.S. % hit	S.S. % FA	C.L. % hit	C.L. % FA	C.M. % hit	C.M. % FA	S.J. % hit	S.J. % FA
					Recognition pairs							
200	76	61	49	69	82	83	69	58	44	43	85	64
300	78	49	67	58	88	85	88	30	71	43	65	54
400	86	33	71	46	83	67	89	18	78	22	75	29
600	93	7	88	15	90	26	96	7	92	8	86	12
900	100	1	97	4	96	15	94	8	100	3	89	8
1,200	99	0	97	6	100	11	96	8	96	3	96	6
2,500	100	0	100	6	99	1	97	3	100	3	89	10
4,000	99	0	100	3	97	4	97	4	99	1	92	8
					Recognition triples							
200	68	68	58	58	83	89	64	57	40	44	78	62
300	68	43	50	53	81	68	57	40	40	40	61	43
400	72	40	35	40	82	57	65	26	35	25	58	33
600	81	11	56	22	85	31	75	15	54	15	76	19
900	97	6	81	14	89	22	85	22	75	19	81	17
1,200	99	3	72	17	85	17	79	15	89	6	83	12
2,500	99	0	82	8	92	19	79	8	83	6	89	11
4,000	100	0	89	19	89	10	88	3	81	4	89	7
					Recall pairs							
300	89	76	67	69	79	71	68	47	53	33	79	72
400	86	49	67	67	81	69	79	22	49	25	78	50
500	94	36	75	51	78	58	82	28	63	17	88	39
700	90	22	74	26	90	38	78	13	78	12	81	26
1,000	94	22	72	28	76	47	83	22	88	12	83	32
1,300	96	19	85	25	72	35	85	8	82	6	88	21
2,600	90	14	69	12	74	44	81	15	82	3	79	19
4,100	93	22	79	8	89	24	90	24	86	7	85	15
					Recall triples							
300	82	69	61	60	86	76	61	51	33	30	69	62
400	69	47	53	65	74	76	44	32	32	40	64	60
500	78	50	50	49	75	74	64	28	40	21	57	42
700	78	32	54	40	82	57	64	15	42	15	65	38
1,000	79	39	60	40	83	65	67	19	57	22	62	25
1,300	75	29	58	31	82	46	60	26	46	26	57	28
2,600	88	19	53	26	79	50	71	26	49	10	53	28
4,100	71	14	50	17	72	42	64	31	44	17	54	15

With the three-parameter exponential function, the theoretical fit with minimum predictive error is obtained by allowing all three parameters (intercept, rate, and asymptote) to be different in each condition and for each subject. The asymptote parameter (λ) represents the difference between the mean strength of correct A–B associations and incorrect A–D associations in memory storage, given unlimited retrieval time. It is obvious from Figure 1 that λ must in general be assumed to be different for each of the four conditions, with recognition conditions having λ values approximately twice that of comparable recall conditions and with λ values for pairs (no interference) being somewhat greater than that for triples (interference).

However, simple inspection of the results in Figure 1 suggests the possibility that the time-intercept and rate parameters for the four different conditions may not be different. To determine whether there were any systematic differences in the intercept (δ)

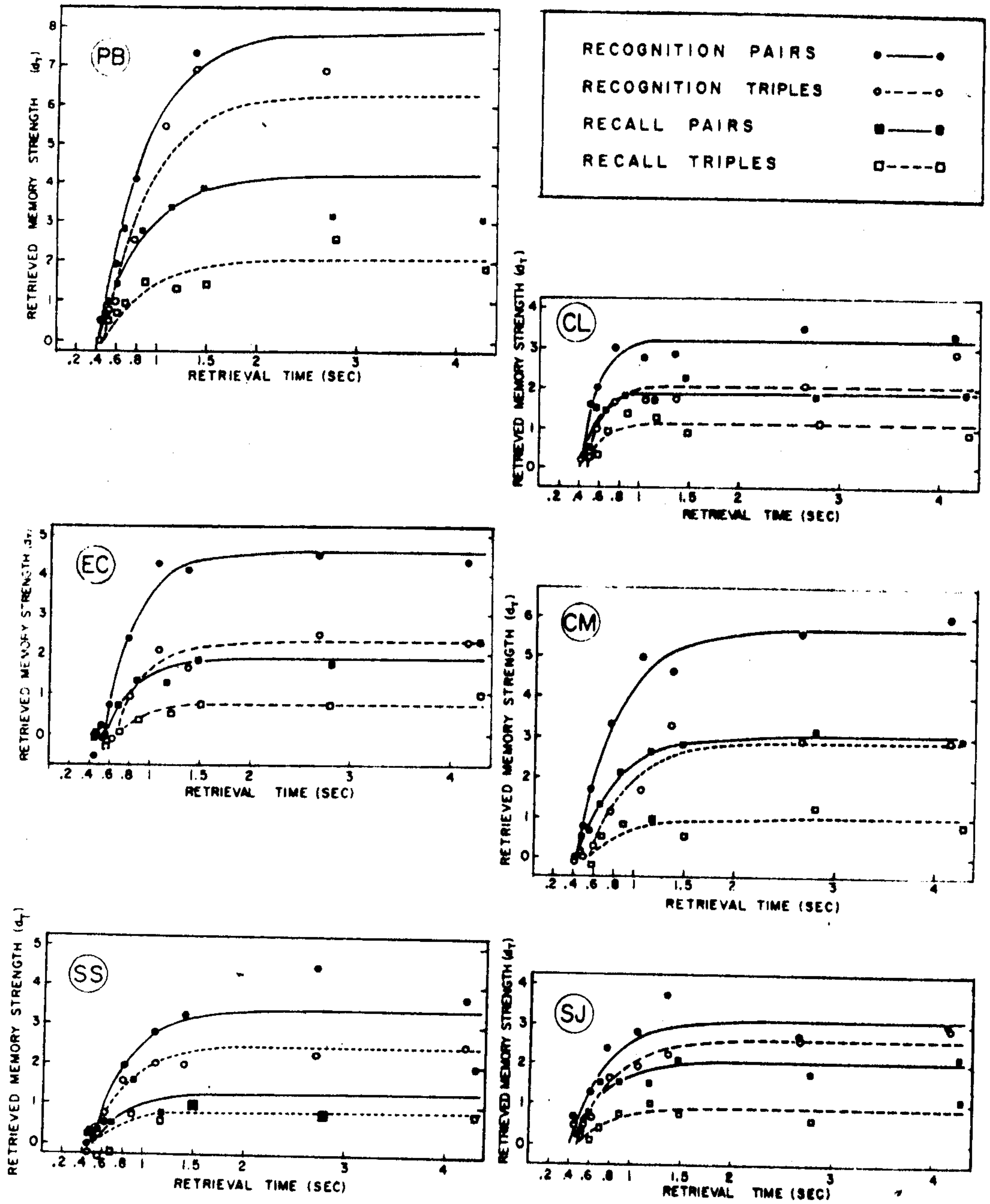

Figure 1. Speed–accuracy tradeoff functions for the recognition pairs (no interference), recognition triples (A–B, A–C interference), recall pairs (no interference), and recall triples (A–B, A–C interference) conditions.

or rate (β) parameters for the various conditions, we performed a variety of goodness-of-fit tests, making different assumptions concerning the values of the δ and β parameters across the four conditions.

At the opposite extreme of assuming four different δ values and four different β values for the four different conditions, we might assume a single δ parameter and a single β parameter for all four conditions. Accordingly, both the 4-δ, 4-β model and the 1-δ, 1-β model were fitted to the d_T data for each subject. A variety of other models were also fitted to the data, including 1-δ, 4-β; 4-δ, 1-β; 2-δ pairs versus triples, 1-β; 1-δ, 2-β pairs versus triples; 2-δ pairs versus triples, 2-β pairs versus triples; and 2-δ pairs versus triples, 2-β recall versus recognition. The goodness-of-fit procedure was basically the same as that described by Reed (1976), namely, varying the parameters of any given model and using an iterative hillclimbing algorithm which minimized the squared error between the theoretical and empirical d_T values. To be able to make a fair comparison of models having a different number of free parameters, the goodness-of-fit statistic was R^2, the percentage of variance accounted for, but adjusted for the number of free parameters using the following formula:

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

where N is the number of empirical points d_i, k is the number of free parameters in the theoretical function, d_i is the empirical d_T value for condition i, $\hat{d}_i$ is the theoretical d_T value for condition i, and $\bar{d}$ is the grand mean of d_i.

Using this measure to compare goodness of fit for different models, it does not appear necessary to assume four different time intercepts and four different rates for the four different conditions. Actually, a reasonably good fit is obtained by assuming a single time-intercept and rate parameter for all four conditions for any given subject. The average R^2 (over subjects) for the 1-δ, 1-β model is .72, while the average R^2 for the 4-δ, 4-β model is only .68. The model providing the best fit was 2-δ(pairs vs. triples), 1-β, with an average $\beta = .0033$ (averaged over the six subjects), an average pairs $\delta = 455$ msec, and an average triples $\delta = 524$ msec. This model is the one used to draw the theoretical lines in Figure 1. The best-fitting parameter values for each subject for this model, along with the R^2, values are shown in Table 5.

The 2-δ (pairs vs. triples), 1-β model had an average $R^2 = .76$, which was only marginally superior to the average $R^2 = .75$ for the 1-δ, 2-β (pairs vs. triples) model, with an average $\beta = .0044$ for pairs and an average $\beta = .0028$ for triples. The fit was not improved by assuming that both δ and β were different for pairs and triples. Obviously, we cannot decide whether the time intercept is increased or the rate of retrieval is decreased from pairs to triples, but it is clear that retrieval dynamics is somewhat slower in both recall and recognition in the

Table 5
Parameter Estimates and Goodness of Fit for the 2-δ (pairs vs. triples), 1-β Model[a]

Subject	Recognition		Yes-No recall			
	Pairs	Triples	Pairs	Triples	β	R^2
P.B.						
λ	7.9	6.3	4.2	2.1	.0021	.85
δ	420	479	420	479		
E.C.						
λ	4.6	2.3	1.9	.8	.0033	.87
δ	557	657	557	657		
S.S.						
λ	3.4	2.5	1.3	.9	.0028	.66
δ	499	499	499	499		
C.L.						
λ	3.2	2.1	1.9	1.1	.0062	.79
δ	408	475	408	475		
C.M.						
λ	5.7	3.0	3.1	1.0	.0025	.91
δ	438	560	438	560		
S.J.						
λ	3.2	2.6	2.1	.9	.0027	.47
δ	405	476	405	476		
Average						
λ	4.7	3.1	2.4	1.1	.0033	.76
δ	455	524	455	524		

[a] Using the equation $d_T = \lambda(1 - e^{-\beta(T-\delta)})$.

triples condition. However, it should also be noted that the effect on retrieval dynamics is not too large in either recall or recognition.

Tests of the 4-δ, 1-β model indicated quite clearly that the intercepts are either identical or close to identical for recall and recognition. Tests of the 1-δ, 4-β model also indicated little or no difference in retrieval rate (β) for recall and recognition. The 2-δ (pairs vs. triples), 2-β (recall vs. recognition) model had an average $R^2 = .76$, no better than the fit of the simpler 2-δ, 1-β model. Furthermore, the average recognition β was .0030 and the average recall β was .0038, a rather small difference. There would appear to be little or no support in the present data for any difference in retrieval dynamics for yes–no recall as compared to recognition.

Another rather surprising finding deserves comment: In the triples condition for yes–no recall, subjects had to recall *both* the B and C associates of the A item during the lag time. One might expect memory retrieval to be much slower in this condition, on the hypothesis that one can recall only one item at a time. The results gave little support to this hypothesis. Instead, we obtained approximately the same form and retrieval rate (β) in the speed–accuracy tradeoff function for this condition as in the other three conditions. In the 4-δ, 1-β model, there was a somewhat greater difference in intercept (δ) between recall pairs and triples (averaging 98 msec) than between recognition pairs and triples (averaging 54 msec). However, this difference is small compared to the time course of retrieval dynamics and assuming this difference in δ values for recall versus recognition did not improve the goodness of fit when adjusted for the increase in the number of free parameters.

There is approximately a 2:1 difference in the asymptotic strength (λ values) for the recognition conditions as compared to the recall conditions, with the difference being slightly less than 2:1 for recognition versus recall pairs and greater than 2:1 for recognition versus recall triples. The reduction in asymptote (λ) for the recall triples condition is perhaps the most striking difference between this condition and the other three.

Group Speed–Accuracy Tradeoff Functions

Because the speed–accuracy tradeoff functions in each condition were not very different for different individuals, it is possible to pool the data across subjects and obtain group functions that do not substantially distort the results obtained for individual subjects. This allows us to assess the effect of a confounding that occurred in the comparison of pairs and triples for individual subjects. In the design of the experiment, each pair and each triple were tested correctly eight times in a session. Since each triple had two tested associations, A–B and A–C, each individual association was tested only four times in the triples condition as against eight times in the pairs condition. Hence, the somewhat faster retrieval dynamics obtained in the pairs condition may have resulted from greater frequency of testing each association in that condition than in the triples condition. There are not enough data to subdivide the pairs condition into the first four versus the second four tests and get reasonable speed–accuracy tradeoff functions for individual subjects, but this can be done with the pooled group data. Making this subdivision, we now have six conditions derived from two factors: recognition versus recall and first pairs versus second pairs versus triples.

An exponential approach to a limit provided an even better fit to the pooled data than to the individual data, confirming the absence of systematic deviations from this form of retrieval function for individual subjects. Once again, the 1-δ, 1-β model provided the poorest fit ($R^2 = .86$). The best fits ($R^2 = .92$ to $.93$) were obtained for models that assumed a reduction in the intercept parameter (δ) as a function of repeated testing (first pairs and triples vs. second pairs). Thus, repeated retrieval of the same association over the course of an hour appears to produce a reduction in the intercept amounting in this case to a difference of about 60 msec ($\delta = 483$ msec for first pairs and triples vs. $\delta = 419$ msec for second pairs).

When the differential effects of repeated retrieval were eliminated by comparing first pairs and triples, there was still some remaining difference in the direction of either a greater intercept for the triples condition ($\delta = 496$ msec for triples vs. $\delta = 478$ msec for first pairs) or a slower rate parameter for triples ($\beta = .0025$ for triples vs. $\beta = .0031$ for pairs). Thus, there was some evidence for a small slowing of retrieval dynamics (20 msec reduction in the intercept or a 20% reduction in the rate parameter) when there were two competing associations (A–B and A–C) versus no associative interference (A–B only). A small effect of associative interference on retrieval dynamics of almost exactly the same magnitude was also obtained by Dosher (Note 2). Thus, there does appear to be an associative interference effect in retrieval dynamics, but it is a very small effect—considerably smaller than the effect of repeated retrieval.

In the group functions, there was also an indication of a modest difference between recall and recognition in retrieval dynamics in the direction of *faster* rate of retrieval in recall ($\beta = .0038$) than in recognition ($\beta = .0026$). However, the assumption of a difference in rate between recall and recognition in addition to the effects of repeated retrieval and associative interference did not produce any significant improvement in fit ($R^2 = .931$ vs. .930), just as it did not improve the fit in the individual analyses. However, it is possible that retrieval of a (presumably) unidirectional association in yes–no recall is faster than retrieval of (presumably) bidirectional associations in recognition.

Discussion

Recall and Recognition Asymptotes

It is often assumed that recognition of an A–B pair is based on both the forward association from A to B and the backward association from B to A, while recall of B given A is based on only the forward association and recall of A given B is based on only the backward association (Merryman, 1971; Wickelgren, 1974; Wolford, 1971). Backward recall of A given B was not assessed in the present experiment, but Murdock (1974, p. 127) notes that forward and backward recall are often nearly equivalent for word–word pairs, which is what we used. If such associative symmetry was obtained in the present study, then the 2:1 difference in asymptotic strength for recognition as compared to recall is exactly what would be predicted on the hypothesis that recognition is based on the sum of the forward and backward associations while recall is based on the strength of a unidirectional association.

When the number of B alternatives is considerably smaller than it was in the present experiment and when subjects have more time in the recall task, then it would not be surprising to find d' values for recall considerably more than half those for recognition, even to the point of obtaining equality for recall and recognition. However, when subjects are operating under time pressure that largely restricts memory to a single elementary act of retrieval, then recognition performance may indeed be the simple sum of recall performance in the forward and backward directions.

Although our data do give some support to this simple hypothesis, we have some reservations. First, there is consistently less than a 2:1 difference in the pairs condition between the asymptotic strengths for recognition (average $\lambda = 4.97$) and recall (average $\lambda = 2.82$) for the four most trustworthy subjects (those who performed very accurately on the matching control task). Second, for all subjects there was a greater than 2:1 difference between recognition and recall in the triples condition. Finally, the relation between yes–no recall and conventional recall is not established, so the application of these results to conventional recall is uncertain.

Recall and Recognition Dynamics

Perhaps the most surprising conclusion of the present study is that the form of the speed–accuracy tradeoff function and the rate and intercept parameters for these functions are not substantially different for yes–no recall and recognition. This is true even in the associative interference (triples) condition in which the subjects must be retrieving two associations simultaneously in the recall condition, whereas they need only to retrieve one association in the recognition condition. (If anything, retrieval is faster for recall than for recognition.) Thus, recall and recognition may have the same basic type of memory-retrieval process, though what associations are retrieved may differ, as discussed in the preceding section. The output of the memory retrieval process feeds into a decision and output process that necessarily must differ for yes–no recognition and conventional recall. By using the yes–no recall task, we appear to have funneled the output of the retrieval process in recall into the same kind of decision and output process as in recognition, facilitating the comparison of the earlier memory retrieval processes. These retrieval processes for recall and recognition appear to be identical. Certainly they appear to have the same dynamics, at least for pairs and triples learned under imagery instructions.

Learning Differences: Pairs versus Triples

The fact that the A–B, A–C interference (triples) condition had a somewhat lower asymptote than the A–B no interference (pairs) condition in both yes–no recall and recognition is of little theoretical significance, since the same total study time was given to learning triples as to learning pairs and there was more repeated testing of pairs than of triples.

It is somewhat more interesting that the ratio of the λ parameter in the triples condition to the λ parameter in the pairs condition was substantially greater for recognition (average $\lambda = .67$) than for yes–no recall (average $\lambda = .46$). This difference in the asymptotic strength of the memory trace is the only way in which the recall triples condition was substantially inferior to the other three conditions. It is possible that this discrepancy is due to forward (A–B) associations' being weaker relative to backward (B–A) associations in the triples condition as compared to the pairs condition. For example, the forward associations may have been somewhat stronger than the backward associations in the pairs condition, but in the triples condition, the ordering of the A–B and A–C pairs completely lost significance, and associative symmetry prevailed. It is even possible that because of the instruction that only A–B and A–C pairs would be tested in the triples condition, the backward associations (B–A and C–A) actually acquired greater strength than the forward associations (A–B and A–C). One reason for this might be greater storage interference between the forward A–B and A–C associations than between the backward B–A and C–A associations.

Retrieval Dynamics in Recognition and Recall

The results of the present study suggest that the same basic retrieval process operates in recognition of a pair of items as in yes–no recall of one member of a pair, given the other as a cue. Certainly yes–no recall is not slower than recognition, even when two associations must be retrieved as opposed to one. In fact, it is possible that yes–no recall of a (presumably) unidirectional association is somewhat faster than recognition of a (presumably) bidirectional association. The relation between yes–no recall and conventional recall is unknown.

Effects of Repeated Retrieval

The largest effect in our study was actually the reduction in the intercept of memory retrieval dynamics due to repeated retrieval of the same association. Whether this is a long-term facilitation of the retrieval dynamics for an A–B association (automatization) or a relatively short-term (priming) effect cannot be decided by this study.

Associative Interference and Retrieval Dynamics

The results of the present study indicate that the presence of associative interference has a modest but consistent effect in retarding the dynamics of memory retrieval in both recognition and yes–no recall of materials learned by visual imagery. It is not possible to decide on the basis of the present findings whether the effect is in the intercept or the rate parameter of the memory retrieval function. It is also not possible to use these data to decide between serial search and parallel search or direct-access models of memory retrieval.

For example, Anderson and Bower (1973) proposed that two associations diverging from a common node must be retrieved in strict sequential order. In the triples condition, this means that half of the time the correct association would be retrieved first and half of the time it would be retrieved second. Applying this model to predict speed–accuracy tradeoff functions is complicated and has a number of options. In many versions, the intercept for the triples condition is the same as for the pairs condition, but since twice as much time is required to achieve asymptotic accuracy in the triples condition, the rate parameter for triples is about half the rate parameter for pairs. Using the group data, $\beta = .0025$ for triples versus $\beta = .0031$ for pairs (effects of repeated retrieval having been eliminated). This is a rate decrease from pairs to triples of about 20% rather than 50%, as predicted by this simple serial retrieval model. There is no doubt that some kinds of serial models could provide a reasonable fit to the present results. For example, one could assume that when two associations branch from a single node, there is a delay of τ milliseconds between the initiation of retrieval of each association. For a suitably small value of τ, this model would probably provide a reasonable fit to the present data, but note that it would be assuming essentially a mixture of serial and parallel processing. It does seem difficult to reconcile the very small effect of associative interference obtained in this study with the simplest serial search models.

However, the results are also incompatible with the simplest direct-access model in which any one or all of the diverging associations from a common node can be retrieved in parallel with no loss in efficiency. The results are compatible with a direct-access model of memory retrieval in which associative interference produces a modest retardation in retrieval dynamics in both recall and recognition.

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