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Interference: The Relationship Between Response Latency and Response Accuracy

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Two experiments using classic paired-associate paradigms were performed to look at interference effects on response latency and response accuracy. The first experiment involved a recall task and the second experiment a recognition test. It was shown that, even when interference conditions are equated to control conditions in percent recall by extra study trials, there is a reaction time deficit in the interference condition. Of the types of theories considered, the only kind compatible with these data are theories that assume probability of recall is affected by encoding and retrieval factors but reaction time is only affected by retrieval factors. Further, interference must affect retrieval more than encoding. The ACT theory (Anderson, 1976) is an instance of such a theory and it is shown that this theory is compatible with the results of these experiments both at a qualitative and a quantitative level. That theory proposes that traces are formed in an all-or-none manner but their retrieval depends on a continuous strength that is subject to interference. Probability correct reflects both the all-or-none encoding and strength-determined retrieval, whereas latency is only affected by the latter factor.

This research is concerned with the relationship between accuracy and latency in memory tests and the way in which these two measures relate to manipulations of interference. Given the prominence of these two dependent measures, of studies of interference, and the frequency with which both measures are used to study interference, such research is definitely needed. However, this research has another concern at least as important as contributing to our understanding of current experimental methodology. It provides evidence relevant to understanding the nature of the memory trace and the effect on it of interference. By way of introduction to this research I will review some facts about interference and all-or-none versus continuous memory traces and present a theoretical proposal (ACT—Anderson, 1976) of how these two traditionally separate issues might be related. Then I will show how studying the relationship between latency and accuracy can enlighten us about these general issues of memory, and describe two experiments that attempt to provide that enlightenment. I will discuss the results of these two experiments and their implications for various theoretical positions, including ACT, and present a mathematical model for the results of the experiments.

Selective Comments on the Literature

There has been a long tradition of work displaying interference phenomena within a paired-associate recall paradigm (e.g., see reviews and views by Anderson & Bower, 1973; Crowder, 1976; Greeno, James, Da Polito, & Polson, 1978; Keppel, 1968; Martin, 1971; Postman & Underwood, 1973; Wickelgren, 1976). There also has been a more recent surge of research studying interference effects (e.g., Anderson, 1974, 1976; Hayes-Roth, 1977; Perlmutter, Sorce, & Myers, 1976; Smith, Adams, & Schorr, 1978; Reder & Anderson, 1980; Thorndyke

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& Bower, 1974; Wickelgren & Corbett, 1977). These later studies have tended to use sentences rather than paired associates, and recognition paradigms rather than recall, but there are demonstrations of interference effects on latency in all combinations of materials and criterion tests. It seems a safe generalization to say that interference effects can be obtained using paired-associate or sentence material, using percent correct or latency measures and using recall or recognition tests. There has been some question about whether interference effects on probability correct can be obtained in paired-associate paradigms using a recognition test (Postman & Stark, 1969). However, the weight of the evidence indicates that such interference effects can be obtained (see reviews by Anderson & Bower, 1973; Wickelgren, 1976).

A great many theories have been proposed to account for interference effects. One major dichotomy is between theories that assume the interference is specific to traces and those that do not. For instance, it has been proposed (Postman, Stark, & Fraser, 1968) that the whole list of to-be-remembered responses is repressed. The experiments showing interference effects in mixed-list designs (see Anderson & Bower, 1973, chap. 15) gave some evidence for trace-specific interference but did not deny the more general factors. My concern is with such trace-specific factors. Trace-specific theories can be categorized into those that suppose the trace is lost versus those that propose that the trace only becomes inaccessible. The ACT theory is an instance of a theory that attributes interference to lack of accessibility.

The question of interest for this article is what the relationship might be between the measures of response accuracy and response latency. A very parsimonious assumption is that both directly reflect some single underlying measure like trace strength. This predicts that we should see a perfect correlation between the two measures. There seem to have been no experiments that directly tested this hypothesis, but incidental evidence from available experiments does not support the hypothesis. Rather, latency appears to be a more sensitive indicator of interference than recall accuracy. Postman and Kaplan (1947) found retroactive interference effects on latency after relearning had eliminated these effects on accuracy. Similarly, a number of the sentence recognition experiments from my laboratory found latency effects after attempting to train subjects to equal recall criteria on interference and noninterference material.

The debate between all-or-none and continuous models has somewhat subsided (but for reviews see Battig, 1968, and Restle & Greeno, 1970). The all-or-none side proposed that traces were formed in a single encoding act. Evidence for the all-or-none position came from analyses of the fate of individual items in various lists. The apparent gradual learning of a whole list was said to be the artifact of averaging. The counter from the continuous camp was that the individual item analyses were compromised by selection artifact problems. However, the near all-or-none learning of individual items remains striking. Nonetheless, there are situations in which individual items appear not to be acquired and maintained in an all-or-none manner, such as interference studies in which items are temporarily unavailable and are later retrieved. Also, relearning experiments by Nelson (1971, 1978) showed that items that apparently are not remembered still show savings advantages upon relearning. This is strong evidence for subthreshold traces. Thus, there are good demonstrations both for all-or-none theory and for the continuous theory, but the all-or-none demonstrations tend to involve original acquisition, whereas the continuous demonstrations involve retention. Rock and Heimer (1959) noted this pattern of data and suggested that trace formation may be an all-or-none matter, but that once formed, a trace may accrue strength that will affect its retention. This suggests that the interference paradigm might be a profitable one in which to reconcile these apparently contradictory results, since it can be designed to involve both original acquisition and retention.

The ACT Theory

In the ACT theory (Anderson, 1976, p. 124), it was proposed that traces are formed in an all-or-none manner with some probability. Once formed, the trace remains forever, but its strength relative to other competing traces can grow or decay with time. I do not want to imply any strong commitment to the view that a trace, once formed, is never lost. However, for the purposes of analyzing current experiments we can continue with this assumption. Each trace has an absolute strength that is used in defining its relative strength. The absolute strength of a trace grows directly with the amount of study exposure and does not decay. Again, there may be situations in which one would want to complicate this assumption, but it is adequate for current purposes.

The relative strength of a trace can only be defined with respect to various sets of competing traces. A trace connects a number of items that can variously be thought of as stimuli, concepts, or nodes in a network. A trace for a paired associate might be thought of as connecting stimulus and response. A propositional trace for a sentence connects all the content words in the sentence. Each of the items involved in a trace is connected to many other traces. Let s be the absolute strength of the target trace j attached to item i, and let S be the absolute strength of all traces involving the item i. Then the ratio s/S defines the relative strength of trace j from that item i. It is relative strength, not absolute strength, that directly governs retrieval dynamics. Activation will spread from a presented test item to all traces involving the item. The amount of activation allocated to a trace will be directly proportional to its relative strength. If more than one item is presented for retrieval of the trace (as in a recognition paradigm in which stimulus and response are presented) the activation from different items can intersect and sum. As we will see, retrieval time and retrieval probability vary as a function of the level of a trace's activation. Consequently, a manipulation that increases the trace's absolute strength will improve its recall, and a manipulation that increases the absolute strength of its competitors will decrease its recall.

Time to retrieve a trace is directly proportional to its level of activation. So, if trying to recall a trace from one item and $r = s/S$ is the relative strength of that trace to other traces involving the item, then its expected retrieval time will be

$$\mathrm{ERT} = I + \frac{1}{rA}, \tag{1}$$

where A is the total amount of activation and I is an "intercept" reflecting nonactivation factors in retrieval—for example, encoding, response generation. Although the above is the expected or mean retrieval time, it is assumed that the activation times are exponentially distributed. Moreover, if the activation time is greater than a constant T, there will be failure to recall. This leads to the following equation mapping relative strength onto probability of correct recall:

$$\mathrm{EPC} = 1 - e^{-TrA}. \tag{2}$$

More complex derivations from the model, addressed to the results of Experiments 1 and 2, are given in the Discussion section of this article.

Under this view there can be two reasons why a subject fails to recall. The first is that he has simply failed to form the trace. The second is that the trace has been formed but cannot be activated. Only the second factor is influenced by interference (i.e., by changes in relative strength). This is one of the reasons that percent recall is not expected to be as sensitive an indicator of interference as latency. This can be seen by considering what happens when a control condition and an interference condition are equated for percent recall. The interference condition requires more study, so there is a greater probability of forming the traces. Because observed probability of recall is equal, this must mean the traces formed in the interference condition have a lower probability of being activated and have lower relative strength. Since latency reflects only relative strength, we should see slower times in the interference condition.

A second reason retrieval times are more accurate reflectors of interference is that at fairly high levels of strength, activation time for all conditions might be such that almost all traces in interference and noninterference conditions are activated before the criterion time T. Still the traces in the interference condition may show significantly longer retrieval times. This point amounts to observing that ceiling effects on percent correct are expected before floor effects on reaction time.

It is interesting to note here that Greeno, James, Da Polito, and Polson (1978) provide evidence that their first stage of learning (which can be interpreted as trace formation) is not longer in interference than in control conditions. The negative transfer effects all show up in a second stage that is interpreted as learning to retrieve.

To summarize, the ACT theory assumes trace formation is all-or-none but trace retrieval is a strength-governed process. Depending on the importance of trace formation versus retrieval dynamics to recall, memory will appear to be all-or-none or continuous. Thus, this theory offers a reconciliation of apparently contradictory results concerning all-or-none versus continuous learning. The theory proposes that interference only affects the strength-dependent retrieval process. Thus, its view of interference is an instance of the trace-specific availability explanations. The theory predicts that reaction time is a purer indicant of interference than percent recall, and consequently it should indicate the presence of interference even when percent recall is equated in control and interference conditions. The experiments that follow are tests of this prediction about the relationship between the two measures under manipulations of interference. If confirmed, this will support the ACT theory's attempt to relate and reconcile these different research issues in human memory.

Experiment 1

In the interest of promoting comparability to much of the traditional interference work, this experiment used a paired-associate recall task. Subjects learned two lists of 20 paired associates with eight trials on each list. This was sufficient to bring the subject population to near asymptotic performance in terms of percent recall. The treatment of the interference and control groups with respect to the first list was identical. After the eight trials on List 1, the interference subjects were moved to List 2, which had the same stimuli but different response pairings. For the control subjects, List 2 had different stimuli. I expected to see negative transfer on List 2. That is, the interference subjects should have learned List 2 less rapidly than the control.

After subjects learned List 2, I expected to see retroactive interference for List 1. Therefore, four retraining trials were given in List 1. Because of proactive interference and because of the retroactive effects of List 1 retraining trials, I expected interfering effects in List 2 retention. Therefore, I followed the four List 1 retraining trials with four List 2 retraining trials.

The general intent of the design was to pepper the experimental session with comparisons of the interference and control groups at varying levels of interference, learning, and retention. This would provide a configuration of data that would constitute a maximally demanding test of the ACT theory. In particular I was hoping to create pairs of control conditions on one trial and interference conditions on a later trial that were equal in percent correct. Then I could look for differences in reaction time.

Method

Subjects. Forty subjects were selected from the Yale undergraduate population and 20 were assigned to each of two conditions. To assure comparability and to exclude poor performers, subjects who scored 60% or less in the final Trial 8 in original learning on List 1 were replaced. To achieve the 20 subjects for the control group, 3 subjects had to be replaced, and for the interference group 2 subjects had to be replaced.

Materials. The stimuli were 40 concrete nouns selected from the norms of Paivio, Yuille, and Madigan (1968) to be high in imagery (mean rating 6.50), high in concreteness (mean rating 6.95), and high in meaningfulness (mean rating 7.27). In the interference condition the same 20 nouns were used for both lists. In the control condition 20 different nouns were used for List 1 and for List 2. The responses assigned to the nouns were the digits 0–9 on the terminal keyboard. Each digit was randomly assigned to 2 of the 20 stimuli from each list. The randomization was done separately for each subject. The second list responses in the interference condition were chosen under the constraint that they would not match the first list responses for the stimuli.

Procedure. The experiment was completely computer run using the YEPS system on a PDP 11/40 computer (Proudfoot, 1978). The material was presented to the subject on a CRT screen. Subjects were given the stimulus for 5 sec, during which they could type in the response. The 10 digits were arranged 1-9, 0 at the top of the keyboard. Subjects were requested to respond as quickly as was compatible with giving an accurate response. The time was measured from stimulus presentation until the key press. After the 5-sec stimulus presentation, subjects were given 5 sec to study the stimulus-response pairing. Subjects went through eight passes (trials) on List 1 and eight trials on List 2 in this manner. Of course, in the first presentation of each list the subjects could not know the correct response and they were instructed to just study the items. Immediately following List 2, subjects were given four retraining trials on List 1 followed by four retraining trials on List 2. The order of the stimulus-response pairs was randomized for each trial.

Results

Table 1 presents percent recall and reaction times for correct recall for Experiment 1. First trials for the two lists are omitted, as these are just learning trials. Analyses of variance were done on the two dependent measures using lists (1 vs. 2), groups (control vs. interference) and trials (seven original learning and four retraining). The standard error for the reaction time measure is 58 msec and for the percent recall measure is 2.6%. Nearly all effects and interactions are significant. The only exceptions are that the difference between lists defined on reaction times is only marginally significant, $F(1, 38) = 2.31$, $p < .15$, as is the List × Trial interaction for reaction times, $F(10, 380) = 1.43$, $p < .20$.

There are a number of noteworthy general features in the data. In the control data, note the improved learning performance for the second list relative to the first. This reflects a learning-to-learn phenomenon. Also note that there is little change in overall performance from last trial of original learning to first trial of relearning. For both lists the percentage recall increases slightly and the reaction time slows slightly, but neither effect is significant.

The interference group is remarkably similar to the control group for the learning of List 1. However, it is substantially worse in the learning of List 2, showing the negative transfer from List 1. When subjects returned to List 1 for relearning, they were considerably worse than the control subjects, showing retroactive interference from List 2. Similarly, interference subjects showed a big drop-off from the last trial on List 2 in original learning to the first relearning trial, reflecting either proactive interference from the original learning of List 1 or retroactive interference from the relearning of List 1. In summary, the interference effects are large and highly significant for both dependent variables.

This experiment was performed to test the major qualitative prediction of the ACT theory that equating for percent recall there would be reaction time differences between control and interference conditions. There are some direct comparisons. Percent recall is approximately equal on the following pairs of List 2 learning trials: Control 2 and Interference 3, Control 3 and Interference 6, Control 4 and Interference 7, Control 5 and Interference 8. The average accuracy for the four control trials is 85.9% and for the four interference trials is 86.0%. However, the average control retrieval time is 1,620 msec, and the average interference retrieval time is 1,879 msec. With the standard error of these averages of reaction times 30 msec, there can be no doubt that there are highly significant interference deficits in reaction time even after equating for percent recall. There appear to be similar effects in the relearning data, but nowhere does percent recall in the interference condition for relearning get as high as percent recall for control, so direct tests are not possible.

Figure 1 illustrates a more systematic attempt to test this hypothesis. Here I have plotted the data from List 2 and the relearning data for both lists. All points are included for which percent recall is greater than 70%. This figure plots percent recall against reaction time. Each point on the figure reflects a condition from Table 1. As can be seen, over the range 70%-100%, reaction time and percent correct vary in an approximately linear fashion, but the interference points are above (slower than) the control points. I tried to fit separate but parallel functions to the interference and control conditions of the form $RT_i = T - bP_i$ for control and $RT_i = T - bP_i + a$ for interference, where RT_i is the reaction time in a particular condition, P_i the proportion recall, T the intercept of the function, b the slope relating reaction time to proportion recall, and a the amount the interference function is shifted above the

Table 1
Results from Experiment 1

	Control				Interference			
	List 1		List 2		List 1		List 2	
Trial	Percent correct	Time (sec)	Percent correct	Time (sec)	Percent correct	Time (sec)	Percent correct	Time (sec)
	Original learning							
2	.520	2.189	.722	1.882	.532	2.121	.552	2.408
3	.687	2.012	.857	1.632	.647	1.921	.710	2.258
4	.797	1.711	.917	1.531	.800	1.813	.767	2.070
5	.882	1.702	.940	1.434	.892	1.654	.797	1.898
6	.920	1.568	.960	1.381	.927	1.536	.875	1.787
7	.960	1.459	.980	1.398	.957	1.475	.910	1.770
8	.952	1.380	.967	1.335	.955	1.424	.945	1.699
	Relearning							
9	.965	1.422	.975	1.370	.830	1.983	.860	2.058
10	.975	1.305	.977	1.353	.885	1.929	.872	1.955
11	.975	1.292	.987	1.358	.907	1.826	.932	1.847
12	.982	1.272	.987	1.326	.952	1.747	.960	1.778

control function. The values of the best fitting parameters are $T = 3.190$ sec, $b = 1.875$ sec, and $a = .338$ sec.[1] The two straight lines in Figure 1 are derived from these parameters. The functions in Figure 1 account for 97.2% of the variance in the reaction times. The amount of additional variance accounted for by adding the a parameter was highly significant, $F(1, 836) = 51.28$, $p < .001$. Thus, it is both clearly and significantly the case that subjects are slower in the interference condition, equating for percent correct.

These results show that equating for percent recall, interference subjects show a disadvantage with respect to reaction time. Stated another way, equating for reaction time, interference subjects show an *advantage* with respect to percent recall. But either way, it is clear that reaction time is more sensitive to the detrimental effects of interference and that the two measures do not reflect exactly the same properties of the memory trace. I consider the theoretical implications of this data more after the second experiment.

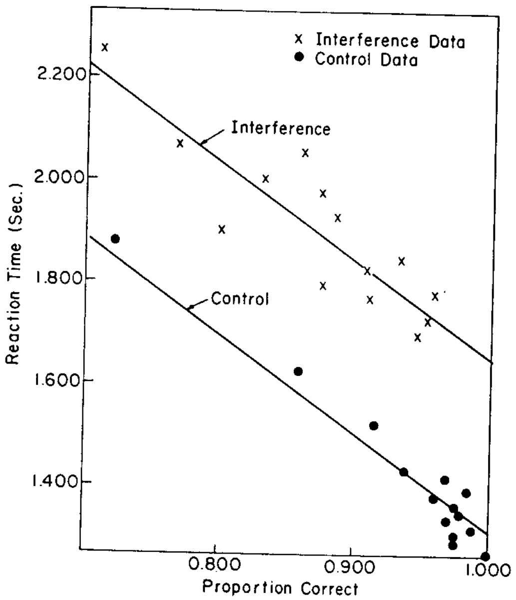

Figure 1. Plot of reaction time as a function of proportion correct. (The best fitting function for the interference data is RT = 3.528 − 1.875*P*, and for the control data it is RT = 3.190 − 1.875*P*, where *P* is proportion correct.)

[1] In fitting these data I also used a data point that falls outside of the space represented in Figure 1. This is the first interference trial, with a .552 proportion correct and a reaction time of 2.408 sec. The predicted reaction time by the interference function is 2.493 sec.

Experiment 2

An alternate interpretation of reaction time's greater sensitivity to interference would be that the extra interference in reaction time measure reflected the competition from the responses for the two lists. Given the prominence of response competition in the interference literature this might seem a reasonable conjecture. The basic idea is that subjects' emission of the response from one list is interfered with by a competing tendency to emit the response from the other list. This is a much more peripheral process than the strength-determined retrieval dynamics.

One way to deal with this is to use a recognition paradigm in which the subjects' task is to recognize whether particular pairs were studied or not. Then a particular test stimulus (a recognition pair) will not be associated to competing responses. The second experiment used such a recognition paradigm with noun-noun pairs. In the control condition the nouns used for the first and second lists were distinct. For the interference condition, the second list used the same first and second nouns as the first lists, but the nouns were re-paired. Note that we chose an A–B, A–Br paradigm because it typically shows more interference in a recognition test than an A–B, A–C paradigm.

Method

Subjects. Forty subjects were selected from the Yale undergraduate population; 20 were assigned to the control condition and 20 to the experimental condition. To assure comparability and to exclude poor performers, subjects who scored less than 80% on the final Trial 5 in original learning of List 1 were excluded. By this criterion two subjects were dropped from the control condition.

Materials. The stimuli were constructed from 80 concrete nouns from the Paivio, et al. (1968) norms selected to have properties similar to the 40 nouns used in Experiment 1 (mean imagibility = 6.52; mean concreteness = 6.93; mean meaningfulness = 7.34). In the interference condition half of the nouns were randomly selected for both lists. In the control condition the 80 nouns were randomly divided between the two lists. The 40 nouns for the two lists were randomly paired to yield 20 pairs for each list. In the interference condition 20 different pairs were created for the second list.

Procedure. The experiment was completely computer run using the same YEPS system as in the first experiment. The material was presented to the subjects at the rate of 3 sec per pair. The first trial on each list simply consisted of presentation of the 20 pairs for study. Subsequent trials involved a test-study sequence. Twenty foil pairs were randomly created for each trial by repairing the stimulus and response nouns that formed the target pairs. In no case did a foil pair for one list correspond to a target pair for the other list. These 20 foil pairs were intermixed with the 20 target pairs. A pair (target or foil) was presented on the screen for 3 sec, in which time the subject had to recognize the item. If it was a foil, he was then given 1-sec feedback as to whether his response was correct and then advanced to the next item. If it was a target, the subject was given 3 sec more to study the pair, along with a message indicating whether his response had been correct.

The subject went through one study trial and then five test-study trials for List 1. This was followed by a similar set of six trials for List 2, then three more test-study relearning trials for List 1, and finally three more like trials for List 2. The order of the pairs was randomized on each trial.

Results

Table 2 presents the percent recall and reaction time for correct recall in Experiment 2. Data are shown separately for targets and foils. Analysis of variance was performed for these two dependent measures using as factors lists (1 vs. 2), groups (control vs. interference), trials (original and relearning), and response type (target vs. foil). The standard error for the reaction time measure is 27 msec and for the percent recall 2.0%. All effects and interactions not involving response type are significant with the exception of the main effect of group on percent correct where there was only a nonsignificant, $F(1, 36) = 1.63$, advantage for the control group. Since response type did not enter into any significant interaction, all further analyses were averaged over target and foil. On original learning of List 1, the two groups are essentially identical (control = 85.7%, 1.155 sec; interference = 86.3%, 1.171 sec), but the groups separated on List 2 original learning (94.0%, 1.032 sec vs. 89.0%, 1.174 sec) and on the relearning trials (95.4%, .994 sec vs 92.1%, 1.115 sec).

In general, effects are smaller for this recognition experiment than in Experiment 1, which involved a recall measure, but the trends are similar. For the control group, performance improved in going from List 1 to List 2, showing a learning-to-learn effect. The interference group showed little difference in their initial learning of the two lists. The negative transfer for List 2 only shows

Table 2
Results from Experiment 2

	Control				Test			
	List 1		List 2		List 1		List 2	
Trial	Percent correct	Time (sec)	Percent correct	Time (sec)	Percent correct	Time (sec)	Percent correct	Time (sec)
				Original learning				
1								
Target	.794	1.270	.853	1.117	.802	1.326	.790	1.293
Foil	.756	1.401	.894	1.195	.802	1.471	.835	1.435
2								
Târget	.811	1.143	.942	1.022	.797	1.223	.807	1.154
Foil	.817	1.272	.958	1.079	.810	1.284	.912	1.262
3								
Target	.858	1.083	.939	.948	.812	1.081	.867	1.085
Foil	.867	1.178	.967	1.035	.885	1.182	.942	1.188
4								
Target	.925	1.034	.956	.963	.907	1.022	.912	1.025
Foil	.875	1.102	.972	1.030	.935	1.102	.945	1.139
5								
Target	.931	.979	.947	.923	.945	.973	.937	1.007
Foil	.933	1.086	.969	1.005	.932	1.049	.952	1.155
				Relearning				
6								
Target	.939	.951	.964	.931	.840	1.239	.895	1.155
Foil	.933	1.062	.964	1.063	.900	1.267	.932	1.206
7								
Target	.944	.923	.958	.931	.892	1.046	.925	1.013
Foil	.944	1.024	.961	1.027	.942	1.128	.932	1.139
8								
Target	.967	.970	.967	.928	.930	1.004	.950	.994
Foil	.950	1.056	.950	1.057	.975	1.085	.947	1.108

up in comparison with the control group. Interference subjects also showed a drop-off from the last trial of original learning to the first trial of relearning, whereas the control subjects did not.

The experiment was performed to test the qualitative prediction that, equating for percent correct, subjects would be slower in the interference condition than the control condition. To provide some spot comparisons, percent correct is approximately equal for the following pairs of trials: control–List 2–Trial 1–learning and interference–List 2–Trial 2–learning; control–List 2–Trial 2–learning and interference–List 2–Trial 5–learning; control–List 1–Trial 2–relearning and interference–List 1–Trial 3–relearning; control–List 2–Trial 1–relearning and interference–List 2–Trial 3–relearning. The average percent correct for control is 93.2% and for interference, 92.6%. The reaction times are 1,045 msec for control and 1,096 msec for interference. The difference in accuracy is only .50 SD and is not significant, whereas the reaction time difference is 5.34 SD and is highly significant, $t(1, 152) = 3.78$, $p < .001$.

Figure 2 reports a more systematic attempt to assess this issue, comparable to Figure 1 for Experiment 1. Here I have plotted reaction time against percent correct for the List 2 learning trials and all relearning

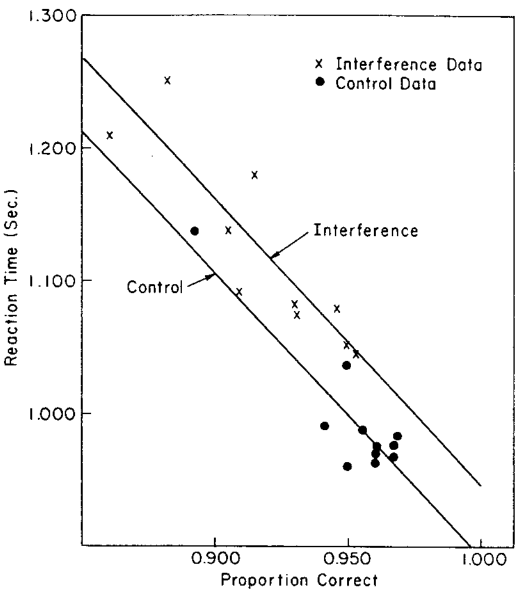

Figure 2. Plot of reaction time as a function of proportion correct. (The best fitting function for the interference data is RT = 3.088 − 2.144*P*, and for the control data it is RT = 3.035 − 2.144*P*, where *P* is the proportion correct.)

trials. I tried to fit separate functions to interference and control of the form $RT_i = T - bP_i$ for control, and $RT_i = T - bP_i + a$ for interference, where RT_i is the reaction time in a particular condition, P_i is the proportion recall, b is the slope of the function relating RT to proportion correct, T is the intercept of the function, and a reflects the amount the interference function is shifted above the control function. The parameter a reflects the amount (equating for percent correct) of greater recognition time in the interference condition. The values of the parameters are $T = 3.035$ sec; $b = 2.144$ (relating RT in seconds to proportion recalled), and $a = 53$ msec. Figure 3 illustrates the fit of these functions based on these parameters to the data.[2] As a conservative way of testing whether the 53 msec was significant I asked if the improvement in the fit obtained by adding the a parameter over a fit without it was significant. It does lead to a very significant improvement: $F(1, 1152) = 24.7$, $p < .001$. Thus, subjects are slower in the interference condition equating for reaction time.

General Discussion

These experiments demonstrated some clear-cut relationships between reaction time and percent recall under manipulations of interference. These data are incompatible with all theories that claim that both probability of recall and reaction time are direct functions of a single-dimensional property like strength. If this were the case, equating for probability of recall would equate for strength and so reaction time should be equal. Clearly, traces must vary in more than one relevant way to yield the current pattern of data. Although there may well be other analyses possible, the ACT claim is that traces have both an all-or-none property of formation and a continuous property of strength. Probability of recall reflects both attributes, whereas reaction time only reflects strength.

Just as these data are incompatible with the pure strength models so are they incompatible with many of the pure all-or-none models. The simplest all-or-none theory would make no prediction about reaction time, but it is possible to construct extensions of the theory that would. It is possible that multiple copies of the trace accumulate over time and that reaction time is an inverse function of the number of copies. This, for instance, is the model developed by Restle and Greeno (1970). As more traces accumulate, reaction time is predicted to go down as trace availability increases. In this model, if the probability of trace formation is p, the probability of correct recall on trial n is $1 - (1 - p)^n$, and the mean number of traces formed by trial n is pn. It can be shown in this model that if we assume a lower value of p in the interference case, then equating for probability of correct recall means that there are more traces in the interference case; thus there is a faster expected reaction time.[3] So this model predicts just the wrong

[2] One data point is off the space plotted here. That is an interference point with .813 proportion correct and 1.364 sec recognition time (predicted to be 1.345 sec).

[3] Observe that the function $-p/\ln(1 - p)$ is a decreasing function of p over the interval 0–1. This implies that if $p_1 < p_2$,

relationship between reaction time and percent recall. There are other versions of the multiple copy model that might predict that interference lies in the retrieval of a copy and not in formation. This type of model might prove indistinguishable from the ACT model that I will describe. In any case, it does not have the claim of the simple all-or-none models that a trace, if formed, is necessarily retrievable.

Another view of the relationship between reaction time and percent recall is contained in the speed-accuracy analysis of memory offered by Wickelgren (1976; Wickelgren & Corbett, 1977). Wickelgren's analysis proposes that the degree of memory for a trace grows continuously from presentation to some asymptotic value, and this degree of memory[4] maps onto probability correct. In situations in which the subject is free to choose when to respond, as in this experiment, it is assumed that the subject takes some arbitrary point on the speed–accuracy curve and his accuracy reflects that point. The fact that subjects in the control condition respond more quickly than interference subjects with the same accuracy is simply to be shrugged off as an uninteresting observation about how subjects trade off speed for accuracy in the two conditions. So basically such a theory says nothing about the interesting and systematic patterns of data obtained in these experiments. Although this does not disconfirm the theory, it must be counted against it.

One class of theories that can be shown compatible with the current results are those that make a clear distinction between factors affecting the encoding process and factors affecting the retrieval process. In such a theory, probability of recall is a product of probability of encoding and probability of retrieval, whereas reaction time only reflects retrieval factors:

$$\text{EPC} = f_1(\text{E})\cdot f_2(\text{R}) \qquad (3)$$

$$\text{ERT} = f_3(\text{R}), \qquad (4)$$

where EPC is expected probability of recall, ERT is expected reaction time, E is the encoding history, R is the retrieval state, f_1 maps encoding history into probability of forming a trace, f_2 maps retrieval state into probability of retrieving the state, and f_3 maps retrieval state into reaction time. If we make the following assumption, we can derive some interesting qualitative implications from our data:

$$f_2(\text{R}_1) = f_2(\text{R}_2) \Leftrightarrow f_3(\text{R}_1) = f_3(\text{R}_2); \qquad (5)$$

that is, if two retrieval states yield the same probability of retrieval, they will yield the same reaction time and vice versa.

Let us consider a trial n for the control and a trial m for the interference condition such that there is the same probability of recall. Clearly, $n < m$. Let $\text{E}_{c,n}$ and $\text{E}_{I,m}$ be the control and interference encoding histories and $\text{R}_{c,n}$ and $\text{R}_{I,m}$ be the control and interference retrieval states. Then,

$$f_1(\text{E}_{c,n})\cdot f_2(\text{R}_{c,n}) = f_1(\text{E}_{I,m})\cdot f_2(\text{R}_{I,m}). \qquad (6)$$

Since the reaction times are longer in the interference condition, this implies that the probability of retrieving a trace in the interference conditions, $f_2(\text{R}_{I,m})$, is lower than the corresponding probability, $f_2(\text{R}_{c,n})$, in the control condition. This means that it

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$$\frac{-p_1}{\ln(1-p_1)} > \frac{-p_2}{\ln(1-p_2)}, \qquad \text{(a)}$$

and hence

$$\frac{\ln(1-p_2)}{\ln(1-p_1)} > \frac{p_2}{p_1}. \qquad \text{(b)}$$

If we equate the groups for probability recall under the all-or-none model,

$$1-(1-p_1)^m = 1-(1-p_2)^n, \qquad \text{(c)}$$

where m and n are the numbers of trials in the interference and control conditions. From this we may derive

$$m = \frac{\ln(1-p_2)n}{\ln(1-p_1)}, \qquad \text{(d)}$$

and using Equation b,

$$m > \frac{p_2}{p_1}n, \qquad \text{(e)}$$

and hence

$$p_1 m > p_2 n. \qquad \text{(f)}$$

Therefore, the expected number of traces is greater in the interference condition.

[4] Wickelgren's term is *strength*, but I am using "degree of memory" here to avoid confusion with my use of the term *strength*. In ACT strength is a more or less permanent property of a link, not something that grows upon presentation of a memory probe.

takes more than n trials in the interference condition to compensate for any interference on retrieval. In contrast, $f_1(E_{I,m})$, the probability for encoding in the interference condition, is greater than the corresponding probability, $f_1(E_{c,n})$, for the control. Thus, it takes less than n trials to compensate for any interference in encoding. There is a precise sense in this framework in which we can say that there is a greater interfering effect on retrieval than on encoding. That is, it takes more than n interference trials to equate retrieval with m control trials but less than n trials to equate encoding with m control trials. Note that the ACT model predicts that there is no interference on encoding but only on retrieval. The preceding analysis is consistent with this claim but does not establish it. To test this claim it will be necessary to develop a detailed mathematical model of the application of ACT to the current situation.

A Mathematical Model

For simplicity let us assume that the strength of a trace is just a multiple of the number of times it has been studied, and let us set the strength scale so that each study is worth one unit of strength. This means that the strength of a trace studied for i trials is i. We let $r(i, j)$ denote the relative strength of a trace whose strength is i (that is, it has been studied i trials since its formation) and whose competitor's strength is j. Accordingly, we have

$$r(i, j) = \frac{i}{i + j + K}, \qquad (7)$$

where K is the strength of prior competing links.

The memory situation is schematized in Figure 3. Here we have the trace connected to the stimulus, response, and contextual elements. The relative strength of the connections will determine the amount of activation converging on the trace. In the recall case, activation will converge from stimulus and context, and in the recognition case, activation will converge from the response as well. The $r(i, j)$ factor as given previously will determine the amount of activation from stimulus and response, but it remains to define the $C(n)$ factor determining the contextual input.

The effects due to context can be complex because the context is not a single element and it will change from trial to trial. However, the following is a simple characterization of the temporal changes due to context. They can be seen as reflecting the temporal changes in trace availability that have been suggested in such theories as those of McGovern (1964), Postman, Stark, and Fraser (1968), and Slamecka (1969). We assume that on each trial the strength of association between current context and target trace will be increased by an amount f (where f is scaled assuming prior contextual associations have Strength 1). This means that after n consecutive trials the relative strength of the contextual associates to the target will be

$$C(n) = \frac{nf}{1 + nf}. \qquad (8)$$

To reflect the change in context induced by a change in list we will assume that after an intervening series of trials on another list the process of contextual association must start over again. We will estimate separate f parameters for recall and recognition. The parameter f should be larger for recognition to reflect the greater constancy in associative context provided by the intersection of the two words.

We will assume that the activation converging on the trace from each source is the relative strength times a constant amount of

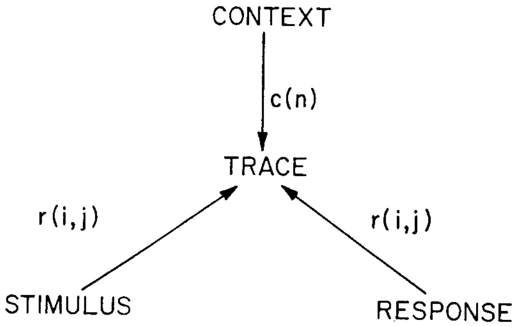

Figure 3. A schematization of the memory situation. (Activation can converge on the trace from the response, if presented, and from the stimulus and context.)

activation A. The total activation converging is just a sum of the independent sources. We use $A(i, j, n)$ to denote the activation converging on a trace with stimulus (and in recognition, response) strength $r(i, j)$ and contextual strength $C(n)$. In recall, we have

$$A(i, j, n) = [r(i, j) + C(n)]A, \quad (9)$$

and in recognition we have

$$A(i, j, n) = [2r(i, j) + C(n)]A. \quad (10)$$

The same parameter A was used for both recognition and recall. The mean time for a trace to become available is an inverse function of level of activation. This means that if a trace has total level of activation A it will take $1/A$ units of time to become available. Thus, our activation scale will reflect the time scale (in this case, seconds).

Next, we have to address the issue of the probability of forming a link. We simply assume that there is a probability of forming a link on each trial that is independent of any interference manipulation. Let $P(i)$ denote the probability that a link is formed on trial i:

$$P(i) = P^* \qquad i = 1 \quad (11)$$

$$P(i) = (1 - P^*)P^+(1 - P^+)^{i-2} \qquad i \geq 2. \quad (12)$$

This formulation allows a higher probability for link formation on the first trial than later trials (i.e., $P^* > P^+$—see the general form of the all-or-none model of Restle & Greeno, 1970). The need for this is clear in the raw data in Tables 1 and 2. A smaller portion of the to-be-learned items is acquired in subsequent trials than in the first trial, probably reflecting item and subject selection artifacts. The easy items are learned on the first trial, leaving a predominance of hard items for later trials. Also, we need to estimate separate parameters for List 1 and List 2 to reflect the more rapid learning (learning to learn) on List 2. The need for separate parameters is apparent in the better performance on List 2 than on List 1 in both Tables 1 and 2. Thus, altogether four parameters are assumed above: P_1^* and P_1^+ for List 1 and P_2^* and P_2^+ for List 2. The same parameters were used for both recognition and recall.

Another factor to consider in our representation of the processing is the speedup that was occurring in the subjects' performance of the basic encoding and response process. This is the "intercept" time in standard formulations. Assuming the well-documented power law for this speedup (e.g., Crossman, 1959; Newell & Rosenbloom, 1981) our formula for the intercept on trial t is

$$I(t) = Bt^{-b}, \quad (13)$$

where B is the initial intercept and the exponent b controls the rate of speedup. We estimate separate parameters for recognition and recall, since there is no reason to expect the encoding and response factors to be the same for the two experiments.

The intercept affects our predictions for two reasons. First, it is part of the reaction time predictions. Evidence for a decreasing reaction time can be found in the faster times for the control subjects on List 2. Second, the intercept parameter figures in how much time the subject has to retrieve the response before the cutoff time. Let $T(t)$ be the cutoff time for trial t. Given that the subject has 5 sec to recall the answer in Experiment 1, the formula for the activation cutoff is

$$T(t) = 5 - I(t) \quad (14)$$

or the total time minus the intercept time. In the case of recognition judgments we assume that the subject would stop and make a guess after G units of time. We make this assumption because unlike the recall task, almost all errors in the recognition task are errors of commission and presumably incorrect guesses. Therefore, for the recognition task the formula for activation cutoff is

$$T(t) = G - I(t), \quad (15)$$

where G is a parameter to be estimated. Presumably there is some variation in this G parameter across subjects and trials, so the above is a clear approximation.

We are now in a position to formulate the probability of retrieving a link before the cutoff time. This will depend on the amount of activation of the link (described by Equations 9 and 10). Assuming this activation level is the rate parameter of an exponential time distribution describing the density of times for link retrieval, we get the following formula for $Pr(i, j, n, t)$, which is the probability of retrieving a link that has been studied i trials since formation, whose competitor has been studied j trials ($j = 0$ if no competitor), with n trials of consecutive study on the list, and where there have been t trials in all (each pass through the list since the beginning of the experiment is counted as a trial):

$$Pr(i, j, n, t) = 1 - e^{-T(t)A(i,j,n)}. \quad (16)$$

With Equations 11, 12, and 16 in hand we are in a position to formulate the probability $PC(I, J, n, t)$ of correctly recalling an item where this is the Ith trial of presentation for the list, the interfering list has been studied for J trials, this is the nth consecutive on the list, and there have been t total trials. See Equations 17 and 18 below. These equations simply weight the probability of retrieving a link in every possible configuration of strengths for the link and its competitor by the probability of each of these configurations.

The preceding equations only apply for the recall experiment. In the recognition experiment we have to consider the processing of foils and the impact of guessing. We assume that the subject could reject a foil by retrieving a trace from stimulus, response, or even context that failed to match the target. The time to do this would be the fastest of the three parallel retrievals, which, assuming exponential distributions for each, will have an exponential distribution identical to the distribution for retrieval of targets. Thus, we will assume Equations 16, 17, and 18 also describe the rejection of foils. It is for this reason we have chosen to fit the average of target and foil. (The theory attributes the difference in mean time between target and foil to an intercept effect.) This analysis of foil rejection is similar to the analysis offered by Anderson (1976) and King and Anderson (1976) who also assumed that times to reject foils should vary with conditions identically as time to recognize targets. Table 2 provides evidence consistent with this assumption.

Recall that there is a cutoff time G such that if the pair has not been rejected in the recognition task or recognized, the subject will venture a guess. Since we are averaging over targets and foils, the probability of a successful guess will be .5. This means that we have to modify our predicted probabilities of recall for the recognition condition:

$$PC^*(I, J, n, t) = PC(I, J, n, t) + .5(1 - PC(I, J, n, t)), \quad (19)$$

where $PC(I, J, n, t)$ is calculated according to Equations 17 and 18.

To calculate mean reaction time we need an expression for $\mathrm{ERT}(i, j, n, t)$, which is the expected reaction time for an item that has been studied i trials since formation, with its competitor studied j trials, n trials of consecutive study, and t total trials. This can be derived from the assumption of exponential distribution of times. However, the formulation is somewhat complicated in that long retrieval times are edited out by the cutoff time, and so mean reaction time will be less than predicted from the full exponential distribution. The correct formulation is

$$\mathrm{ERT}(i, j, n, t) = I(t) + 1/A(i, j, n) - \frac{T(t)e^{-T(t)A(i,j,n)}}{1 - e^{-T(t)A(i,j,n)}}. \quad (20)$$

We are now in a position to calculate $\mathrm{ET}(I, J, n, t)$, the expected reaction time for an item where this is Ith trial on that list, Jth trial on the interfering list, the nth consecutive trial on that list, and trial t. Analogous to Equations 17 and 18 we have

$$PC(I, J, n, t) = \sum_{i=1}^{I-1} \sum_{j=1}^{J} P(i)P(j)Pr(I - i, J - j, n, t), \text{ if interference;} \quad (17)$$

$$PC(I, 0, n, t) = \sum_{i=1}^{I-1} P(i)Pr(I - i, 0, n, t), \text{ if no interference.} \quad (18)$$

$$\mathrm{ET}(I, J, n, t) = \frac{\sum_{i=1}^{I-1} \sum_{j=0}^{J} P(i)P(j)Pr(I-i, J-j, n, t)\mathrm{ERT}(I-i, J-j, n, t)}{PC(I, J, n, t)} \quad \text{if interference;} \tag{21}$$

$$\mathrm{ET}(I, 0, n, t) = \frac{\sum_{i=1}^{I-1} P(i)P(I-i, 0, n, t)\mathrm{ERT}(J-j, 0, n, t)}{PC(I, 0, n, t)} \quad \text{if no interference.} \tag{22}$$

The following equations only apply for recall. In the case of recognition we have to include the guessing times. In this case the equation becomes

$$\mathrm{ET}(I, J, n, t) = \frac{PC(I, J, n, t)\mathrm{ET}(I, J, n, t) + .5(1 - PC(I, J, n, t))G}{PC^*(I, J, n, t)}. \tag{23}$$

A chi-square statistic was calculated from the predictions derived by Equations 17–19 and 21–23. Letting $\hat{\mathrm{RT}}_i$ be the predicted reaction time for condition i, $\overline{\mathrm{RT}}_i$ the mean reaction time, $\hat{PR}_i$ the predicted probability of recall, and $\overline{PR}_i$ the observed probability of recall, we have

$$\chi^2 = \sum_i [(\mathrm{RT}_i - \overline{\mathrm{RT}}_i)^2/S_{\overline{\mathrm{RT}}}^2 + (PC_i - \overline{PC}_i)^2/S_{\overline{PC}}^2], \tag{24}$$

where $S_{\overline{\mathrm{RT}}}^2$ is the standard error of the reaction time (estimated from ANOVA) and $S_{\overline{PC}}^2$ is the standard error of the percent recall (again estimated from the ANOVA). The values used were $S_{\overline{\mathrm{RT}}} = 58$ msec for Experiment 1 and 27 msec for Experiment 2 and $S_{\overline{PC}} = 2.6\%$ for Experiment 1 and 2.0% for Experiment 2. The STEPIT program (Chandler, 1965) was used to fit the data. χ^2 (139) = 134.5. The value of the best fitting parameters is given in Table 3, and the fits are illustrated in Figures 4 and 5.

The parameters are generally in accord

Table 3
Values of Best Fitting Parameters

Symbol	Parameter	Value
	Common parameters	
A	Amount of activation	1.08
K	Strength of prior associates	.71
P_1^*	Probability of link formation on Trial 1 for List 1	.59
P_1^+	Probability of link formation on later trials for List 1	.31
P_2^*	Probability of link formation on Trial 1 for List 1	.83
P_2^+	Probability of link formation on later trials for List 2	.37
	Recall experiment parameters	
B	Intercept time on Trial 1	1.07
b	Exponent governing speedup	.25
f	Amount of contextual association attached to trace	.05
	Recognition experiment parameters	
B	Intercept time on Trial 1	.63
b	Exponent governing speedup	.00
f	Amount of contextual association attached to trace	1.26
G	Time at which a subject guesses	1.81

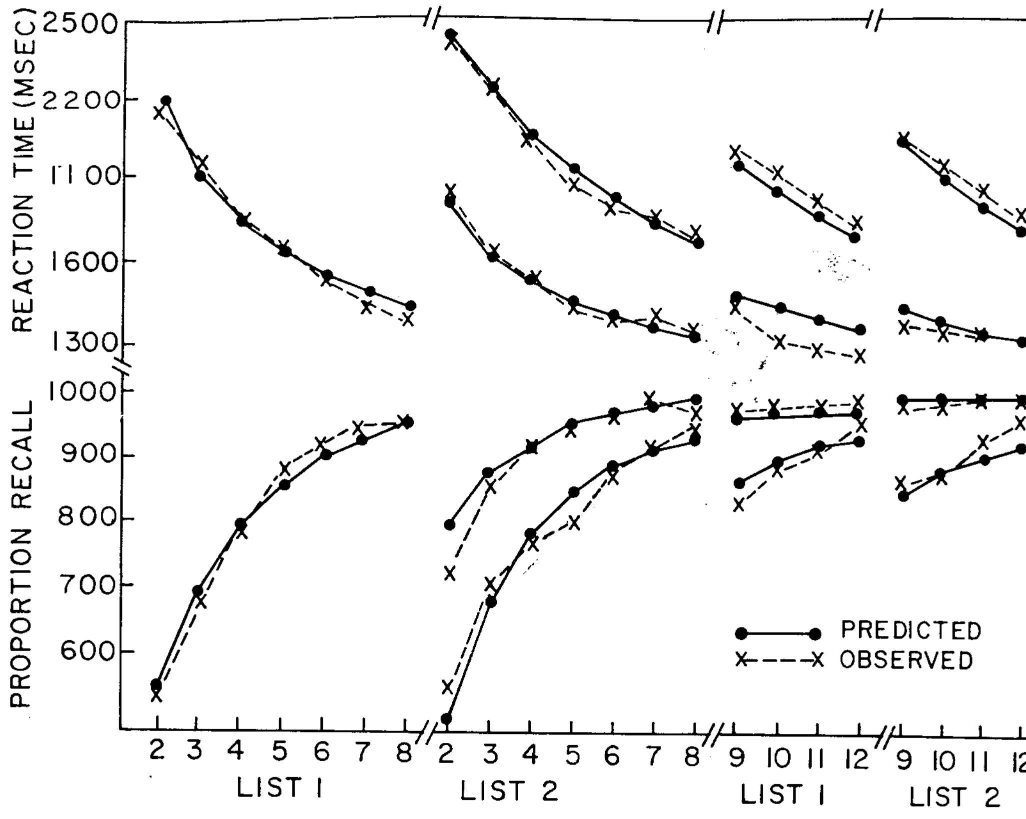

Figure 4. Plot of the predictions of the ACT theory against the data for Experiment 1. (The control condition is given by the reaction time curves that are lower and the percent recall curves that are higher.)

with expectation. The value of K is low, but similar estimates have been obtained in other experiments (e.g., Lewis & Anderson, 1976), suggesting that subjects can largely block out effects of interfering pre-experimental associations. The parameters estimated separately for the two experiments are reasonably behaved, with the intercept higher in the recall experiment and the contextual associations higher in the recognition experiment. The estimate of the exponent of the power law for the recognition experiment is almost zero (actually .001). This probably reflects some peculiarity of the data, and I doubt that a zero estimate could be replicated. However, it is not surprising that there is less speedup in the recognition than in the recall experiments.

The chi-square measure is really quite good, and this is certainly impressive given that all parameters had to be shared between control and interference conditions, and of the most essential parameters were sha between the recall and recognition expe ments. The fits in Figures 4 and 5 are visua quite good, though some apparent discr ancies appear. For instance, the the slightly but systematically underpredicts action time in the interference retests in recall experiment. However, it has to be alized that different subjects contribute these retest data points than those in other retests and they, as a group, may ha slowed more than other groups. The varia terms going into the chi-square calculati reflect individual subject variances.

Numerous assumptions going into model were approximations to some ext (for instance, that there was probability link formation on Trial 1 and a differe probability on all later trials). These sumptions could have been elaborated i

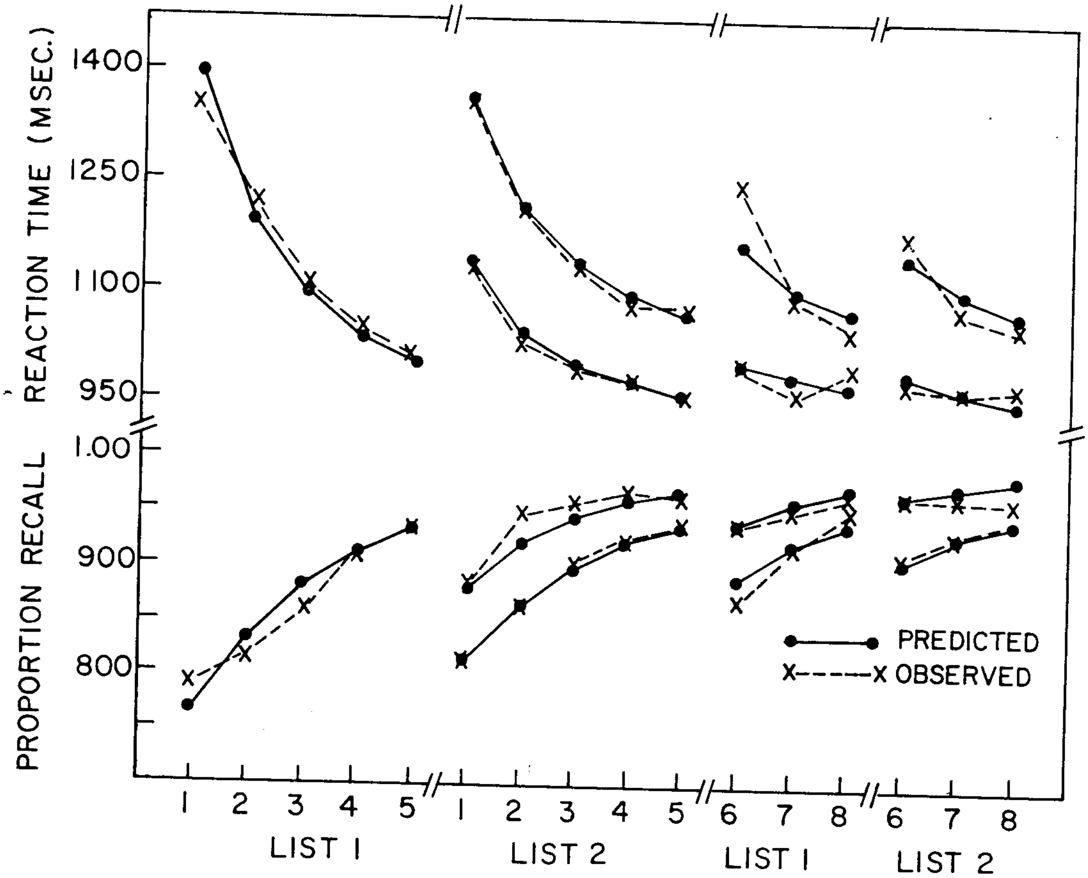

Figure 5. Plot of the predictions of the ACT theory against the data for Experiment 2. (The control condition is given by the reaction time curves that are lower and the percent recall curves that are higher.)

more complex and less approximate form. However, the current goodness of fit indicates that the data are not reliable enough to test such refined assumptions. So we can go away from this model-fitting exercise with the knowledge that a model in correspondence with the ACT theory is consistent with the data.

A critical feature of this ACT theory is that it assumes that there is no impact of interference on the probability of link formation. The overall goodness of fit is one sign that this assumption is confirmed. However, we can look for residual discrepancies that might be signs of the failure of this assumption. If this assumption were wrong, we would expect the theory to underpredict probability of recall in the learning of the second test in the control condition (because the common parameter was lower than the true parameter for control) and overpredict probability of recall in the interference case (because the common parameter was higher than the true parameter for interference). The results in Figures 3 and 4 yield no hint of such a discrepancy. The estimated probability for the control condition in the recall experiment was .921; the observed probability was .906. For the interference condition the estimate was .792 and the observed probability was .794. In the control condition of the recognition experiment, the estimated probability was .933 and the observed probability was .940. In the interference condition of this experiment, the estimated probability was .883 and the observed probability was .890. There is not much in the way of discrepancy, but it is largely the opposite of what would be predicted if there were a lower probability of encoding in the interference case.

The process by which 13 parameters are fit to 152 data points is complex, and it is possible that a combination of parameters was achieved that hid the underlying need for different encoding probabilities in the interference and control cases. Therefore, we fit a form of the model to the data that allowed separate encoding parameters for List 2 in the control and interference cases. There was only a marginal decrease in χ^2—from 134.5 to 129.9. Given that two degrees of freedom were lost it is clear that this is not a significant improvement. The estimated Trial 1 probability of link formation in the control case was .81 compared with .87 for the interference case. The probabilities for later trials were .40 in the control case and .36 in the interference case. If anything, the probability of link formation is higher in the interference condition, but basically there are no real differences. Thus, we can conclude that interference has its negative effect on recall only through the retrieval process.

Summary

The only class of theories considered that is consistent with the data is that which assumes there are separate processes governing link formation and retrieval. It was shown that for these theories the present pattern of data (interference effects in reaction time when probability of recall is equated) implies that interference has a greater impact on retrieval than on encoding. ACT was shown to be one version of such a theory consistent with the total pattern of data across both a recall and a recognition experiment. In this ACT theory, interference has no effect on encoding but does have an effect on retrieval. The fit of the theory to the data was not improved significantly by extending it to permit an interfering effect on encoding. Although hardly deciding the issue definitively, these patterns of results support the conclusion that interference has its effect on retrieval and not on encoding.

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Notice of Journal Title Change

By action of APA's Publications and Communications Board, the title of the

Journal of Experimental Psychology: Human Learning and Memory

will be changed to

Journal of Experimental Psychology: Learning, Memory, and Cognition

as of the January issue of the 1982 volume (Vol. 8, No. 1). The volume numbering will continue from the last volume published under the former title, and the journal will continue to be published bimonthly, in one volume per year.

This title change reflects the journal's expanded coverage in the area of human cognition. For further information on content and submission of manuscripts, authors should refer to the editorial in the July 1980 (Vol. 6, No. 4, pp. 439-440) issue of *JEP: Human Learning and Memory* and to the Instructions to Authors, which are published in each issue of the journal.