28 Repeated Negatives in Item Recognition: Nonmonotonic Lag Functions

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ABSTRACT

The interaction of two different types of information used in item recognition is examined in three experiments using a study–test procedure. On each trial, the subject studies 16 words presented singly. The test list consists of single words to which the subject has to respond *old* or *new* by pressing either of two buttons. Both old and new words in the test list may be tested once or twice. The data of main interest are reaction time and accuracy for the second test of new words as a function of lag between the first and second tests. At lag 0, reaction time is short and accuracy high; at lags 2, 3, and 4, reaction time is long and accuracy, low; at longer lags, reaction time decreases and accuracy improves. This non-monotonicity is inconsistent with unelaborated versions of several models of memory retrieval and forces the addition of a process that allows a response to a test word to be based on the subject's memory of the previous response to the word. A three-boundary random walk model is proposed to explain the data, and the relation of this model to other current models in the item recognition literature is considered.

INTRODUCTION

An item in memory may have stored with it information about past occurrences of the item. In this chapter, we investigate the interaction of two different kinds of such information. One kind of information may indicate that the item was recently encountered. We call this *recency information;* it has been modeled by concepts such as strength (Wickelgren & Norman,

1966), short-term memory (Atkinson & Shiffrin 1968), and list markers (Anderson & Bower, 1972). A second kind of information that may be stored with the internal representation of an item is information that allows the subject to remember what response has been made to an earlier test of the item. This can be called *response information* (Theios, *et al.,* 1973).

The interaction between response information and recency information in memory retrieval has been neglected in recent research. Several models make no explicit provision for the use of response information (Atkinson & Juola, 1973; Wickelgren & Norman, 1966). In these models, processing an item changes only its recency (strength or familiarity); no information is stored in memory as to the response made to the item. This chapter demonstrates the inadequacy of such models by showing that response information interacts in a significant way with recency information to determine speed and accuracy of recognition.

Three experiments are presented in this chapter. In each, a study–test procedure was used. Subjects were presented with a 16-word study list followed by a test list of either 32 or 52 words, presented one at a time. For each test word, subjects were required to respond *old* if the test word had appeared in the study list and *new* if it had not. Some of both the old and the new words in the test list were repeated; the data of main theoretical interest are the accuracy and latency of the responses to these repeated words as a function of the lag between repetitions.

The hypothesis tested by these experiments is that a response to the first presentation of a test word in the test list leaves two kinds of information available in memory: response information and recency information. If the response was correct, then the response information in memory will serve to make the response to a second presentation of the same test item faster and more likely to be accurate. Recency information, on the other hand, may aid recognition on the second presentation of a repeated old word but hinder performance on the second presentation of a repeated new word. A further hypothesis is that the decay characteristics of response information and recency information are not the same; thus, whether response or recency information dominates when a word is presented for a second test may depend on the lag between the first and second tests. When recency information dominates, correct responses to the second tests of repeated old words should be faster and more accurate than correct responses to the second tests of repeated new words.

EXPERIMENT 1

Experiment 1 was performed to investigate reaction time and accuracy for the second presentation in the test list of old and new words as a function of the lag between the first and second presentations.

Method

Subjects. Four University of Toronto undergraduates served as subjects and were paid for their participation. All subjects completed 1 practice and 12 experimental sessions.

Apparatus. List generation, display, and response recording were controlled by a PDP-12A laboratory computer. The subjects responded on a six-key response panel connected to the computer via six sense lines. For each response, the key pressed and the latency of the response (measured from the onset of the test word to the key press) were recorded. The measurements of latency were accurate to 5 msec.

Procedure. Each session was made up of 40 study–test trials. Each trial consisted of the presentation of 16 study words followed by 32 test words. The test list was composed of 10 study words (selected randomly) of which 6 were presented twice and 10 new words of which 6 were presented twice. Thus the test list was composed of half old and half new words.

The study words were presented in an unrestricted random order. Test words were presented in a random order with the following restriction: Of the 12 test words to be repeated, two old words and two new words were randomly selected. For each of these words, a lag (the number of intervening words between each presentation of a repeated word) between 0 and 7 was randomly selected. Then one old and one new word were positioned in the first half of the test list and one old and one new word were positioned in the second half of each test list; then their repetitions were positioned to satisfy the lag determined by the random draw. This procedure guaranteed extra numbers of short lags (0–7) in both halves of the test lists. Finally, the remaining test words (both repeated and nonrepeated) were randomly placed in the empty positions of the test list. Lags longer than 7 were obtained by this random placement.

For each session, words were selected randomly without replacement from the Toronto Word Pool, a collection of 1080 common two-syllable English words not more than eight letters long with homophones, contractions, archaic words, and proper nouns deleted. The study words were shown individually for 750 msec per item with a 250-msec blank interval between words. The presentation of the test words was self-paced with the next word appearing 500 msec after a response. A row of question marks presented for 1.5 sec separated the study and test lists. The subject initiated each study trial.

The subject's task was to respond *old* if a word had been a member of the study list and *new* if the word had not been in the study list regardless of whether or not the word had been repeated in the test list. The subjects responded on the six-key response panel where the keys indicated, from left to

right, *sure new, probably new, maybe new, maybe old, probably old,* and *sure old.*

The subjects were instructed to respond both as accurately and as quickly as possible, but the emphasis was placed on accuracy. After each session, subjects were given feedback on the accuracy of their performance. Each session took less than one hour to complete and no subject did more than one session per day.

Results

Figure 28.1 shows accuracy and latency as a function of test position for high-confidence (sure) responses to once-presented (1P) old and new words. These results are similar to results usually obtained in the study–test paradigm (Murdock, 1974; Murdock & Anderson, 1975; Ratcliff & Murdock, 1976),
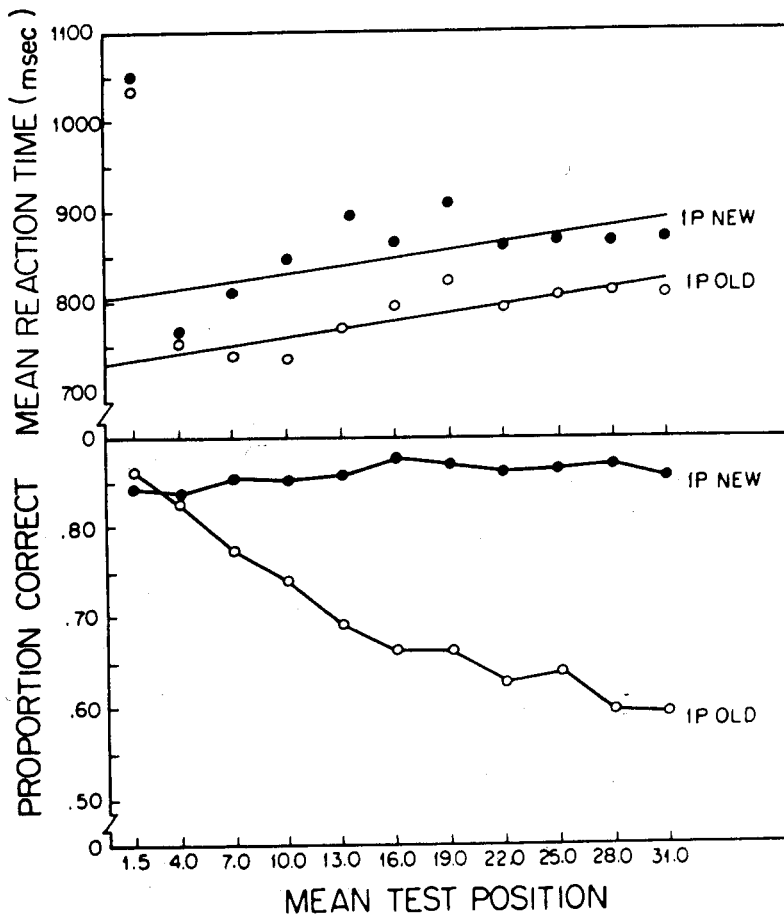

FIG. 28.1.   Mean reaction time and proportion of correct high-confidence responses of 1P items as a function of mean test position for Experiment 1. (Best-fitting linear functions derived from means excluding first and second test positions. For 1P new, RT = 805.13 + 2.79X; for 1P old, RT = 731.52 + 2.95X.)

which suggests that processing has not been radically altered by the addition to the test list of repeated words. (Note that the slow response latencies at the first and second test positions are the result of some inertia on the part of the subject in switching from the study to the test phase, see Murdock & Anderson, 1975.)

Figure 28. 2 shows the results of interest; accuracy and latency for high-confidence responses to the second presentation (2P) of twice-presented old and new words (for which the response on the first presentation was correct) as a function of lag from the first presentation. For 2P new words, the lag function is nonmonotonic in both accuracy and latency. At 0 lag, accuracy is high and latency is fast; at intermediate lags 2, 3, and 4, accuracy is relatively low and latency, slow; and as lag becomes very long, 8 to 32, accuracy becomes somewhat higher and latency, somewhat faster. The implications of these data are discussed after presentation of Experiment 2.
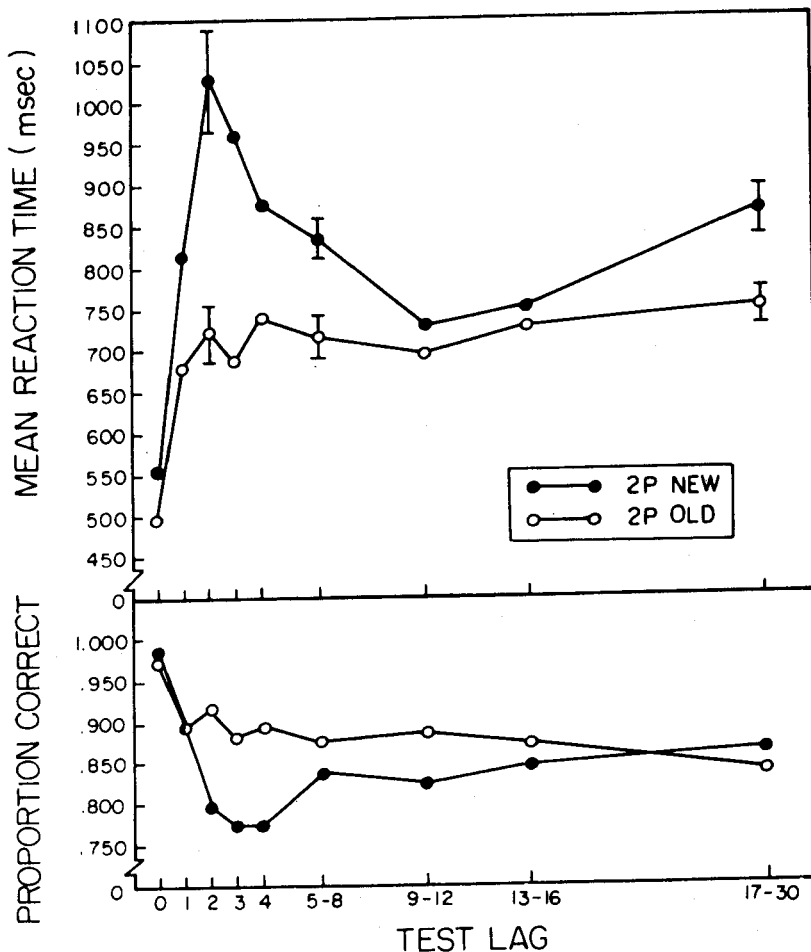

FIG. 28.2.   Mean reaction time and proportion of correct high-confidence responses to 2P items conditionalized on correct first presentation responses as a function of test lag for Experiment 1. Longer test lags are blocked as indicated. The bars indicate representative standard errors for the reaction-time means. The standard errors of the proportions are all less than .02.

There were very few lower-confidence responses (less than 7% of the responses were not high confidence) and the proportion of lower-confidence responses as a function of lag was approximately constant, except at lag 0 where there were very few such responses. Thus the use of the confidence-judgment procedure gave little additional information.

EXPERIMENT 2

Experiment 2 was designed to replicate Experiment 1. The only differences were that selection of lags for repeated words was more strictly controlled so that accuracy and latency at a particular lag could be obtained (instead of an average over several lag values as in Experiment 1) and that a yes/no response procedure was used instead of a confidence-judgment procedure so that error responses and correct 2P responses conditionalized on incorrect first presentation responses could be inspected without needing to take into account the various confidence categories.

Method

Subjects.   Four University of Toronto undergraduates served as subjects and were paid for their participation. All subjects completed 13 sessions.

Apparatus.   The subjects were tested on the PDP-12A computer. As in Experiment 1, list generation, display, and response recording were under computer control. All word lists were again constructed from the Toronto Word Pool.

Procedure.   Each session was made up of 32 study–test trials. Each study list consisted of 16 words and was followed by a test list of 52 words. The test list was composed of the 16 study words of which 10 were repeated and 16 new words of which 10 were repeated. Thus half the test words were old and half were new.

The study words were presented in an unrestricted random order. In the test list, the lags of the repeated words were carefully controlled. There were 10 possible lags: 0, 1, 2, 3, 4, 8, 12, 16, 24, and 32. Each lag was used for one repeated old word and one repeated new word in each test list. The test lists were constructed by the following procedure: First, 10 old words and 10 new words were randomly selected. For each of these words, a lag was randomly selected without replacement from the set of possible lags. This was done independently for old and new words. Then each of these words was fitted into the test list in a random position and each repetition was fitted into the list according to the lag selected. If the second word (the repetition) was to be

positioned past the end of the test list, a new random position was chosen and the cycle repeated. This procedure was continued until all 20 words and their repetitions were fitted into the test list. Then the remainder of the old and new words were randomly selected and positioned in the remaining unfilled positions of the test list.

The study list words were presented individually for 750 msec per word with a 250-msec blank interval between words. The presentation of test words was self-paced with the next word appearing 250 msec after a response. Subjects were required to respond *yes* if the test word was in the study list and *no* otherwise.

In all other respects, Experiment 2 was identical to Experiment 1.

Results

Figure 28.3 shows accuracy and latency as a function of test position for 1P words. These results replicate those shown in Fig. 28.1. Figure 28.4 shows the lag functions for 2P old and new words; these are similar to those shown in
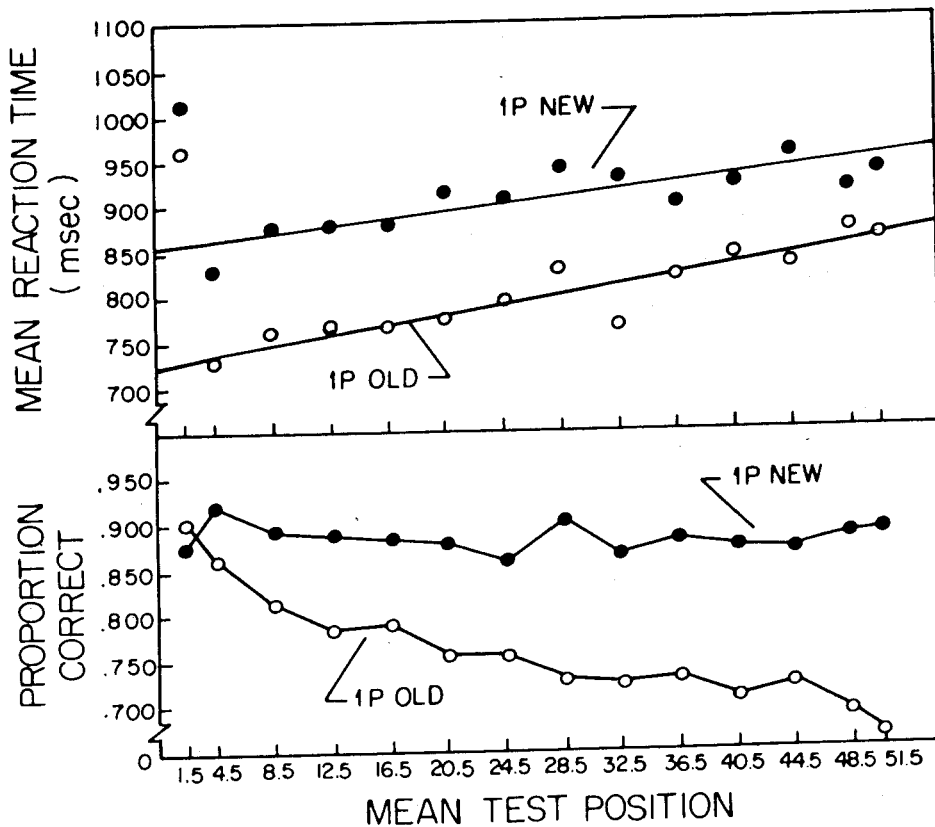

FIG. 28.3. Mean reaction time and proportion correct of 1P items as a function of mean test position for Experiment 2. (Best fitting linear functions derived from means excluding first and second test positions. For 1P new, RT = 856.55 + 1.81X; for 1P old, RT = 721.34 + 2.76X.)
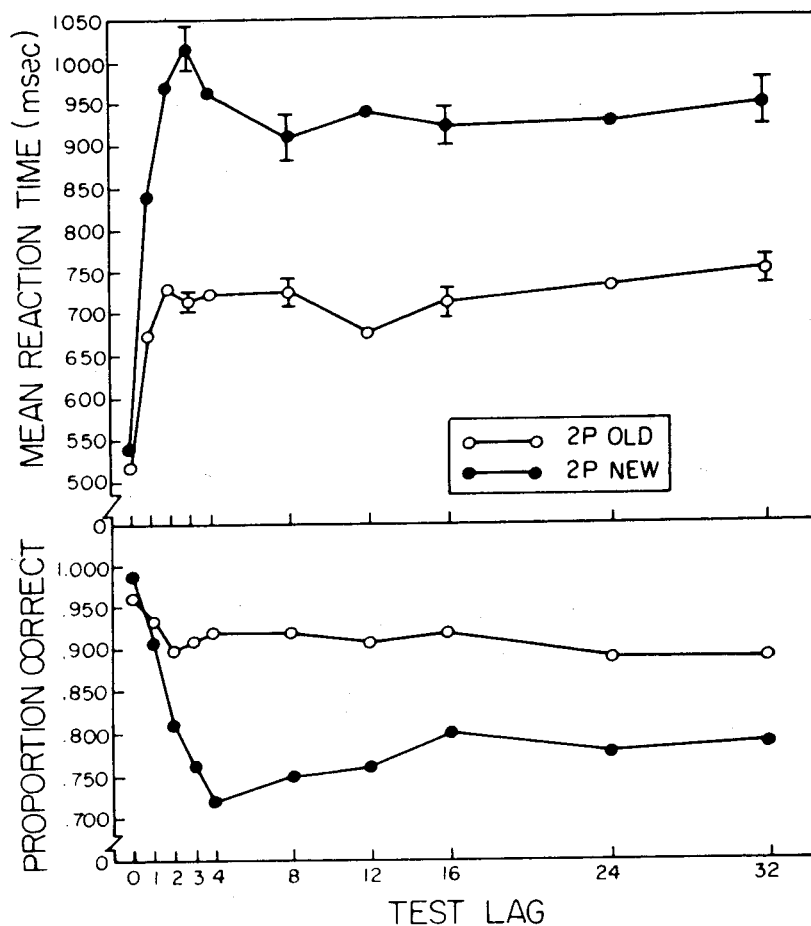
FIG. 28.4. Mean reaction time and proportion correct of 2P items conditionalized on correct first presentation responses as a function of test lag for Experiment 2. The bars indicate representative standard errors for the reaction time means. The standard errors of the proportions are all less than .02.

Fig. 28.2. The function for 2P new words is again nonmonotonic. Figure 28.5 shows accuracy for 2P responses conditionalized on an incorrect response to the first presentation. Accuracy increases from a relatively low value at lag 0 to a moderate value at longer lags, but the function does not appear nonmonotonic. (Note that with the relatively small number of responses contributing to the measured accuracy, there is not enough sensitivity to detect nonmonotonicity if it were there.)

Discussion

The results from Experiments 1 and 2 show that both accuracy and latency as a function of lag are nonmonotonic for 2P new words. This nonmonotonicity suggests the operation of two opposing factors, one dominating over short lags, 0, 1, and 2, using information about the response to the first presentation, and the other dominating over intermediate and longer lags using
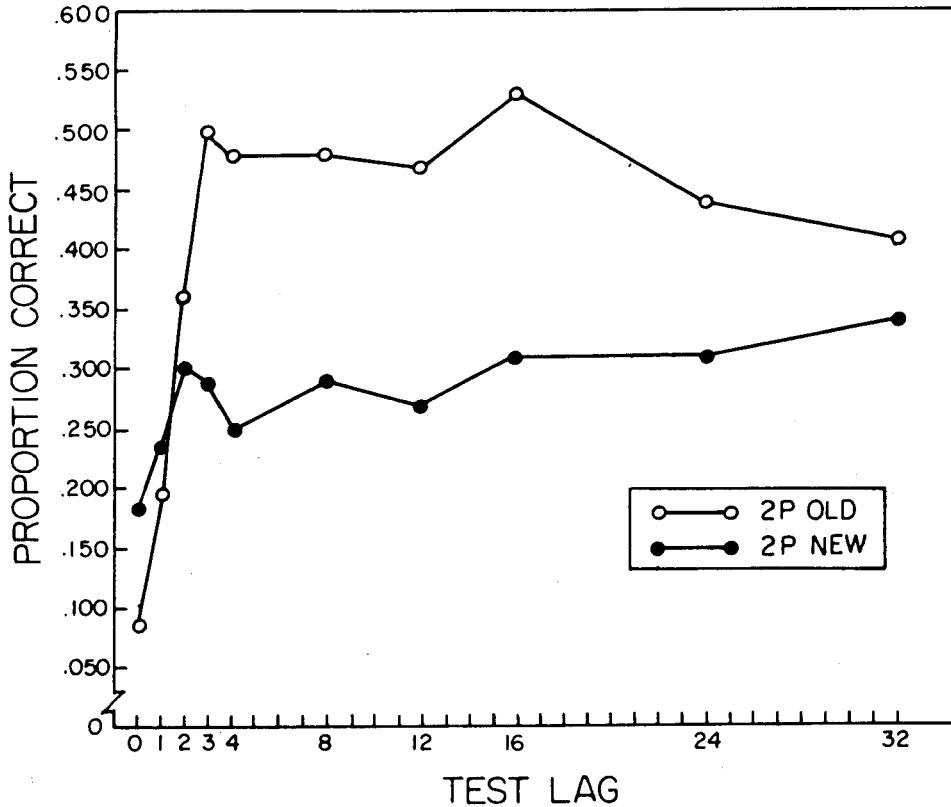
FIG. 28.5. Proportion correct of 2P items conditionalized on incorrect first presentation responses as a function of test lag for Experiment 2. The standard errors of the proportions are all less than .04.

recency information. At very short lags, response information is available; this information leads to fast and accurate responses (given that the response to the first presentation was correct). At intermediate lags, response information has been forgotten and recency information competes, leading to slower and less accurate responses for 2P new items (for 2P old items both response information and recency work together). At longer lags, recency information has been lost and latency and accuracy both improve a little. Thus, we can explain the nonmonotonic lag function in terms of fast decaying response information and more slowly decaying recency information.

This two-factor explanation for the nonmonotonic lag function gains support from the data for correct responses to 2P items conditionalized on an incorrect first presentation response. We assume that at short lags the subject is using response information. Then, if the subject made an incorrect first presentation response, he should be more likely to make an incorrect 2P response. At longer lags, the subject should have lost the response information and accuracy should improve. This is just what is shown in Fig. 28.5.

If we accept the hypothesis that there are two factors giving rise to the nonmonotonic function, then the simplest kind of model is one that asssumes a probability mixture of two processes. Suppose that there is one fast process

based on response information that produces fast reaction times (e.g., 500 msec; see Fig. 28.2) at short lags and a second, slower process based on recency information that competes at intermediate lags producing slower reaction times. As the recency information is forgotten, reaction times speed up again slightly. Thus the nonmonotonic lag function is composed of a high proportion of fast processes at short lags and a high proportion of slow processes at intermediate and long lags.

There is an easy way to test the assumption of a probability mixture of two processes if the two individual processes are stationary and the only change in reaction time as a function of lag is a change in the relative proportion of the two distributions. This assumption predicts that reaction distributions for responses at each lag will be bimodal. In fact, it can be seen by inspection that the reaction-time distributions are unimodal. Table 28.1 shows parameter averages across subjects for the convolution of normal and exponential distributions fitted to observed reaction-time distributions for Experiment 2. This convolution model (Ratcliff, 1978; Ratcliff, 1979; Ratcliff & Murdock, 1976) has been used as an empirical summary of the reaction-time distributions found in memory retrieval paradigms. In the model, there are three parameters: μ and σ are the mean and standard deviation, respectively, of the normal distribution, and τ is the mean of the exponential distribution. Changes in the parameter μ reflect changes in the leading edge or mode of the distribution; changes in τ represent spread in the tail of the distribution. In the previous case (two stationary processes), bimodality at lags 1 and 2 would show up as no change in μ between lags 0, 1, and 2. In Table 28.1, this pattern is not observed; both μ and τ increase (τ faster than μ) and σ increases a little

TABLE 28.1

Parameter Values (averaged across subjects) for Fits of
the Distribution that Is the Convolution of Normal and
Exponential Distributions to the Observed Reaction-
Time Distributions for 2P (twice-presented) New Items
in Experiment 2

Test Lag	μ	σ	τ
0	406	34	135
1	484	60	340
2	517	70	429
3	530	73	433
4	538	78	403
8	506	59	363
12	487	51	410
16	518	57	374
24	491	53	385
32	496	62	390

Note: μ, σ, and τ are measured in milliseconds.

as a function of lag (cf. Ratcliff & Murdock, 1976). (Note that chi-square values for goodness of fit of the convolution model range from 4.7 with 10 degrees of freedom for the best fit to 34.4 with 9 degrees of freedom for the worst fit. These fits are somewhat better than those displayed in Ratcliff, 1979, Fig. 3.) Thus, the hypothesis that the nonmonotonic lag function for 2P new items is the result of a probability mixture of two processes, each process stationary as a function of lag, and changes in reaction time resulting from a change in the proportion of the two processes, can be dismissed.

Let us now describe an alternative two-factor view using the retrieval model proposed by Ratcliff (1978). In that model, a test item makes contact with the representation of each study item in memory. We shall further assume that the test item also makes contact with the representations of test items presented earlier in the list (an assumption left implicit in Ratcliff, 1978, p. 65; see Crowder, 1976, chap. 9). In Ratcliff's model, evidence as to whether the test item matches one of the items contacted in memory is accumulated by a random walk process. If a match occurs, processing immediately terminates with a *yes* response. If none of the comparisons terminates with a match, then, when the last nonmatch terminates, a *no* response is initiated. This model is not able to account for the very fast *no* responses for 2P items at lag 0. This is because the model assumes processing to be exhaustive for nonmatch comparisons; one fast finishing nonmatch comparison cannot speed up the other slower nonmatch comparisons that all must terminate before a *no* response can be made.

To overcome this problem, we propose a generalization of Ratcliff's model that is consistent with the data presented in this chapter (and other data providing similar problems that are discussed later). The *no* responses to 2P new items at zero lag appear to have a strong nondefault character; information about the previous response seems to be used in making the decision. This suggests a comparison process in which there are two nondefault matches (yes and no) and a default nonmatch: a three-boundary random walk (see Audley & Pike, 1965; Laming, 1968). (Note that a similar argument could be made for the existence of two types of *yes* responses, one based on response information and one based on recency information. The resulting four-boundary random walk would not produce any important changes in the qualitative discussion of the three-boundary random walk that follows.)

The three-boundary random walk can be conceptualized as three counters accumulating information: one counter for information leading to a positive response (recency and positive response information), a second counter for negative response information, and a third default counter. A decision is made when the information accumulated in one counter first exceeds the information in the maximum of the other two by some criterial amount. This is a relative stopping criterion and should not be confused with an absolute stopping criterion (Audley & Pike, 1965). The usual two-boundary random

walk model with an absolute criterion (starting point, C, and boundaries, A and $-A$) is formally equivalent to a counter model with two counters, one starting with an advantage of C counts, that accumulate information until one counter exceeds the other by the criterial amount $(2A)$ (Audley & Pike, 1965; Pike, 1973).

To model the pattern of results obtained in Experiments 1 and 2 with the three-boundary random walk model, it is necessary to make some assumptions about how response information and recency information vary as a function of lag. The assumptions are the same as those made earlier, namely, that response information, available at short lags, decays very quickly and that recency information decays more slowly and so is available at intermediate lags. Given these assumptions, the three-boundary random walk model can account for the nonmonotonic lag functions for 2P words quite simply. At very short lags, response information accumulates quickly in the nondefault negative counter; at intermediate lags, recency information accumulating in the positive counter dominates information accumulating in both the nondefault and default negative counters; finally, at long lags, neither the response nor the recency information dominates. This account of the 2P lag functions is consistent with the shape of the reaction-time distribution as it changes with lag; increases in mean reaction time are mainly due to spread in the distribution, with a smaller increase in reaction time of the fastest responses. This account is also consistent with the result that accuracy increases as the rate of accumulation of information increases.

The major problem with the three-boundary random walk model is that there are far too many parameters and so far too much model freedom. Thus the model cannot make quantitative predictions about data. This does not, however, reduce the usefulness of the model as a metaphor nor detract from the fact that the model can account adequately for both changes in mean reaction times and accuracy and changes in the shape of the reaction-time distribution.

EXPERIMENT 3

Characterizing the retrieval process in terms of three counters suggests that there are at least three separate responses that the subject could make: old; new, first presentation; and new, second presentation. In Experiment 3, subjects were asked to make these responses explicitly; there were three response keys: one for old responses; one for new, first presentation; and one for new, second presentation. By using these three keys, we hope to separate the default and nondefault components in 2P new responses and thus to separate response and recency information.

We could also have separated the responses to first and second presentation old words. We did not do this because we wanted to keep Experiment 3 as

analogous as possible to Experiments 1 and 2 and because we wanted to reduce the probability that the subjects would view the task as judgment of frequency.

Method

Experiment 3 is the same as Experiment 2 except that subjects responded by pressing one of three (instead of two) response buttons. The three buttons were placed at positions equidistant from a resting position and the subject responded by moving his index finger from the resting position and depressing the response key. Four subjects were each tested for eight sessions plus one practice session.

Results

The main results are shown in Fig. 28.6 and 28.7. Figure 28.6 shows accuracy and latency as a function of lag for 2P old and 2P new words conditionalized on a first presentation correct response. The interesting result is that the nonmonotonicity found for 2P new words in Experiments 1 and 2 has moved to 2P old words. Otherwise, results are the same as in Experiments 1 and 2; overall reaction time is longer and accuracy is lower for 2P new words compared with 1P new words, and reaction time is shorter and accuracy is higher for 2P old words compared with 1P old words.

There is a further nonmonotonic accuracy function shown in Fig. 28.7, where 2P new words conditionalized on an incorrect first presentation response have a very low probability of being correct at lag 0. The probability increases to a maximum at lag 3 and then decreases again as lag increases further.

The nonmonotonic hit and false alarm rates shown in Fig. 28.6 and 28.7 also lead to nonmonotonic d' functions.

Discussion

In Experiment 3, we added a third response key for responses for the second presentations of new words. Addition of a special response category for 2P new words might have changed the subject's perceived task to a combination of recognition, frequency judgment, and recency judgment. However, the pattern of results for Experiment 3 is much the same as the pattern of results for Experiments 1 and 2. The main exception is that the nonmonotonic lag function that appeared for 2P new word responses in Experiments 1 and 2 appeared for 2P old word responses in Experiment 3.

A clue to the reason for the switch of nonmonotonicity from 2P new words to 2P old words can be found by examining 2P new responses to old words. There is a marked nonmonotonic trend in the proportion of these errors. It is
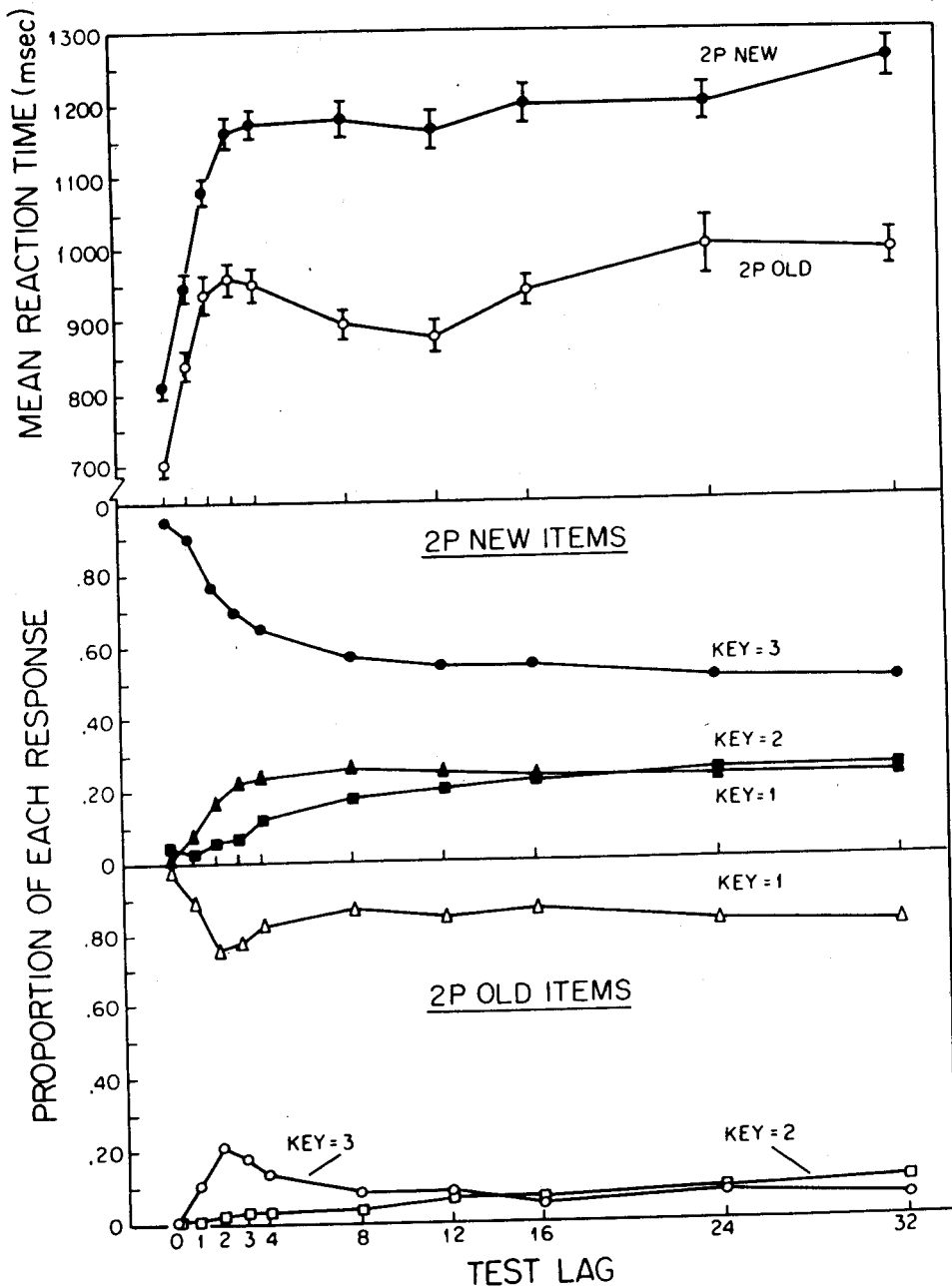
FIG. 28.6. Mean reaction time and proportion of each response for 2P items conditionalized on 1P correct responses as a function of test lag for Experiment 3. The bars indicate standard errors of the reaction-time means. The standard errors of the proportions are all less than .02. (Key = 1 indicates an old response, Key = 2 indicates a 1P new response, and Key = 3 indicates a 2P new response.)
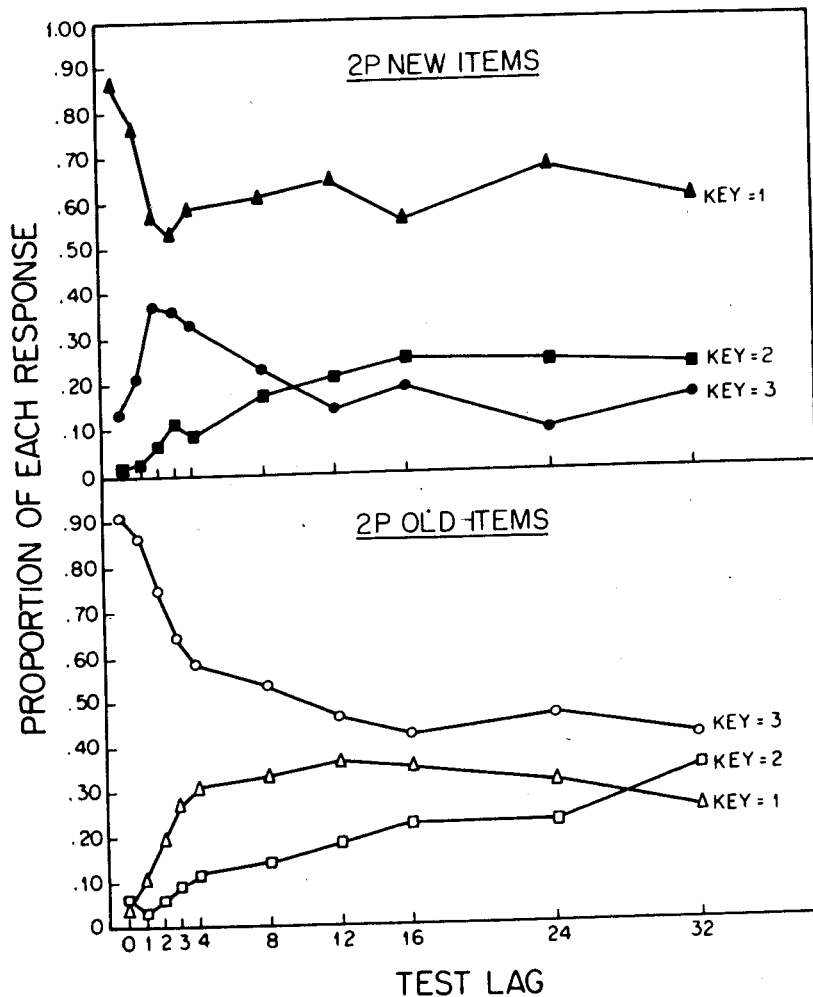
FIG. 28.7. Proportion of each response to 2P items conditionalized on first presentation incorrect responses as a function of test lag for Experiment 3. The standard errors of the proportions are all less than .05. (Key = 1 indicates an old response, Key = 2 indicates a 1P new response, and Key = 3 indicates a 2P new response.)

as though the subject has decided to respond 2P new if he is sure that the test word is a repetition but not sure whether the word is old or new. In Experiments 1 and 2, if subjects were sure they had seen a test item recently, then they may have been biased toward responding *old* because they viewed the task as detecting old words among new. When a special category for 2P new items was added in Experiment 3, the emphasis shifted to the 2P–1P new discrimination and subjects may have been biased to respond 2P new for words they had seen recently. This can be translated into the three-counter random walk model postulated earlier as follows: Suppose that, for the second test of a repeated test word, recency is very strong but response information is missing. Then, in the two-key procedure in Experiments 1 and 2, criteria are set so that evidence is accumulated toward an old response. On the other hand, in the three-key procedure in Experiment 3, criteria are set so that evidence is accumulated toward a new response.

SUMMARY AND GENERAL DISCUSSION

We performed three experiments that investigated the effect of repeating test items in the test phase of a study–test procedure. Subjects were presented with 16 study words (one at a time) followed by a test list, presented one word at a time, and were required to respond *yes* (or *old*) if the test word was in the study list and *no* (or *new*) otherwise. Some of the old and some of the new words were repeated through the test list. The functional relationships of major interest concerned responses to the second tests of repeated words for which the response to the first test had been correct. The interesting questions were how latency and accuracy of these responses varied as a function of the lag between the two tests of a word. In the first two experiments, the lag function of 2P (twice presented) new items was nonmonotonic. At lag 0, accuracy was high and reaction time, short. At intermediate lags (2, 3, and 4), accuracy was low and reaction time was longer; at longer lags (12, 16, and 24), accuracy became a little higher and reaction time a little shorter than at intermediate lags. In the third experiment, a three-key response panel was used and subjects were required to hit one key for old responses, a second key for 1P (once presented) new responses, and a third key for 2P new responses. It was found that although the nonmonotonic lag function for 2P new items vanished, a nonmonotonic lag function for 2P old items appeared.

Implications for Models of Memory Retrieval

There are several models of memory retrieval that appear inadequate in light of the results presented in this chapter. These are models that employ the concept of strength or familiarity: for example, the Atkinson and Joula model (Atkinson & Juola, 1973; Atkinson, Herrmann, & Wescourt, 1974) and strength theory (Wickelgren & Norman, 1966). Neither of these models is capable of accounting for the fast 2P new responses at 0 lag. Both models would have to predict that reaction times for these responses would be very long and that conditional accuracy (conditional on a correct 1P response) would be very low. They would have to make these predictions because when the word is first tested, strength or familiarity should be very significantly increased and this should lead subjects to respond old when the word is presented for a second test, or at least to respond new very slowly. The thrust of this argument against strength theory is very much in line with the argument presented by Anderson and Bower (1972) who show that a strength theory is incapable of accounting for the levels of list discrimination they obtain in their experiments.

To account for the fast and accurate 2P new responses, it is necessary to postulate an additional process that allows subjects to access and use information stored about the previous response made to that item. To account

for the nonmonotonic lag function, it is also necessary to assume that response information is lost much more quickly than strength (recency information). The forgetting function for response information seems remarkably similar in decay rate to the forgetting function for associative information (see Murdock, 1974). This may indicate that the relation between the test word and the response to the test word is associative.

The random walk model for memory retrieval proposed by Ratcliff (1978) also cannot explain the fast 2P new responses at zero lag. This is not because relatedness is assumed to increase in the same way as strength in simple strength theory (Wickelgren & Norman, 1966) because Ratcliff (1978) explicitly notes that relatedness is the product of a mapping from a complex memory representation to a single dimensioned variable and it is certainly possible for response information to contribute to relatedness. Rather, the problem lies in the assumption that processing of negatives is parallel and exhaustive. This means that one fast finishing process cannot influence the overall negative reaction time because all other comparisons must terminate. Ratcliff's model can be extended to account for the nonmonotonic lag functions in the following way. The nature of the 2P new response at zero lag does not seem to have the default character of the negative responses in Ratcliff's original model; rather it seems to have a positive (self-terminating) character. To model this, we can move to a three-boundary random walk (Audley & Pike, 1965) where there is a default negative boundary, a positive boundary, and a nondefault negative boundary. This model is capable of explaining the patterns of results found in the experiments presented in this chapter.

Some Relationships Between the Multiboundary Random Walk and Other Models

The three-boundary random walk has interesting properties that relate it to other theoretical views. First, consider the model of Schneider and Shiffrin (1977) for memory scanning tasks. It has two components: controlled and automatic processing. Ratcliff's (1978) model is able to account for the controlled processing component by assuming that processing is parallel and modeling the processing by a two-boundary random walk with positive and default negative boundaries. In moving from controlled to automatic processing, subjects are assumed to learn the appropriate response (see Shiffrin & Schneider, 1977, Fig. 11) to the stimulus. This can be modeled by a three-boundary random walk with a positive, a default negative, and a nondefault negative boundary. Subjects in the controlled processing mode accumulate little evidence in the nondefault counter, and the decision is made on the basis of the positive and default negative counters; this is identical to Ratcliff's (1978) model. On the other hand, when subjects are in the automatic mode,

they accumulate little evidence in the default negative counter and the decision is made on the basis of the positive and nondefault negative counters. These two self-terminating processes would be capable of dealing with the relative lack of set size effects found by Shiffrin and Schneider (1977) because, under conditions where the memory set is very well learned, similar amounts of learning would be expected whether the memory set was 1 or 4. Note that as yet we have not considered the visual search component of the Schneider and Shiffrin model.

Second, consider a Sternberg varied set experiment in which the digit 6 whenever presented is always a negative probe (the subject may be explicitly instructed beforehand). It is not difficult to see that reaction time to the digit 6 would decrease and accuracy increase, again leading to problems with the exhaustive processing assumption used in Ratcliff's (1978) model. If we invoke the three-boundary model, then again it is easy to see that the fast responses to the digit 6 can be modeled by the nondefault negative comparison process.

Third, the three-boundary random walk model described earlier can be viewed as a restricted relative of Morton's (1969; 1970) logogen model. The logogen model is concerned with word recognition phenomena and supposes that evidence is accumulated toward a particular word as a response. The evidence boundary for response is a fixed criterion so that as soon as one of the word logogens accumulates enough evidence, a response is made. In contrast the three-boundary random walk uses a relative criterion: The evidence in one counter must exceed the evidence in the maximum of the other counters by a fixed amount before a response can be made.

From these three examples we can see that the three-boundary random walks offers the possibility for some interesting extensions and some interesting comparisons and contrasts with other models.

To conclude, we have shown in this chapter that several models of memory retrieval are inconsistent with the nonmonotonic lag functions for repeated test items that have been presented in this chapter. It is necessary to elaborate the models to include a process that allows the subject to access and use response information in making the decision about list membership.

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