Journal of Experimental Psychology:
Learning, Memory, and Cognition
1989, Vol. 15, No. 5, 846-858


0278-7393/89/$00.75

# Time Course of Item and Associative Information: Implications for Global Memory Models

Scott D. Gronlund and Roger Ratcliff
Northwestern University

The time course of availability of associative and item information was examined by using a response signal procedure. Associative information discriminates between a studied pair of words and a pair with words from two different studied pairs. Item information is sufficient to discriminate between a studied pair and a pair not studied. In two experiments, discriminations that require associative information are delayed relative to those based on item information. Two additional experiments discount alternative explanations in terms of the time to encode the test items or task strategies. Examination of the global memory models of Gillund and Shiffrin (1984), Hintzman (1988), and Murdock (1982) shows that the models treat item and associative information inseparably. Modifications to these models which can produce separate contributions for item and associative information do not predict any difference in their availability. Two possible mechanisms for the delayed availability of associative information are considered: the involvement of recall in recognition and the time required to form a compound cue.

Many mechanisms have been proposed to underlie the cognitive processes of recall and recognition. One mechanism of current interest is a global matching mechanism for recognition proposed by Gillund and Shiffrin (1984), Hintzman (1984, 1986, 1988), and Murdock (1982, 1987). These recognition models have focused on asymptotic measures of performance such as untimed and unpaced recall and recognition. In contrast, the experiments in this article examine the time course of recognition of pairs of words and single words to determine if item information and associative information become available at different times in processing. Item information is knowledge of whether words were studied previously (did something occur or not?); associative information is knowledge of whether two words were studied as a pair together (are two things related?). There is considerable evidence for an empirical separation of these two types of information in memory (e.g., Humphreys, 1976; Humphreys & Bain, 1983; Murdock, 1974) but no evidence of their differential time course. Time course results will provide insights into, and important constraints on, the global memory models.

The empirical procedure used to examine the time course of processing is the response signal procedure (Dosher, 1976; Reed, 1973, 1976). In this procedure, a subject must make a recognition decision at one of several experimenter-determined times (or lags) after the onset of the test stimulus. The signal appears when the lag time has elapsed, and the subject must respond within 200–300 ms of this signal. With this procedure it is possible to map out the growth of accuracy as a function of processing time. Accuracy usually accumulates in a positive monotonic manner, and the form of the function can be described by the following three characteristics: (a) the point at which the response signal function first rises above chance (the time intercept), (b) the maximum achievable accuracy (the asymptote), and (c) the rate at which information accumulates from chance to asymptotic levels (the rate).

The experiments presented in this article used a study–test recognition memory procedure to examine the time course of information accumulation in recognition memory. Subjects studied a list of pairs of words and in the subsequent test phase were asked to make decisions about whether the test words were studied previously. The subject's decision rule was manipulated to alter the relevance of the association between the words. In the *separate* decision rule, subjects responded positively if *both* items of a test pair had been studied, irrespective of whether the test pair exactly matched a study pair or was made up of words from two different study pairs. If one or both of the words in the test pair had not been studied previously, subjects were to make a negative response. Because the association between the words in the test pair was irrelevant, item information alone was sufficient to discriminate positive from negative test pairs (though the association could have an effect).

For the *together* decision rule, subjects were to respond positively only if the words in the test pair had been studied *together*. Thus, *intact* pairs that exactly matched a study pair were to be discriminated from *rearranged* pairs made of words from two different study pairs, and associative information provided the basis for this judgment. Associative judgments have been used as diagnostic measures for evaluating global models by Clark and Shiffrin (1987), Humphreys (1976), and Humphreys, Pike, Bain, and Tehan (1989).

There are at least three ways that item and associative information can accumulate in memory. First, item and associative information may arise from a common mecha-

This research was supported by National Science Foundation (NSF) Grant BNS 8510361 to Roger Ratcliff and NSF Grant BNS 8516350 to Gail McKoon. In addition, Scott Gronlund was supported by a National Research Service Award Grant 5-T32-MH15786 to Northwestern University. We thank Gail McKoon, Barbara Dosher, Doug Hintzman, Bill Hockley, Mike Humphreys, and Ben Murdock for their comments on this article.

Correspondence concerning this article should be addressed to Roger Ratcliff, Department of Psychology, Northwestern University, Evanston, Illinois 60208.

nism and therefore have a similar time course. Information would accumulate in a positive monotonic manner with a common rate of accumulation and a common intercept for all discriminations. It will be shown that this is what extensions of the global memory models assume.

Second, if functionally distinct mechanisms give rise to item and associative information, one mechanism could be delayed relative to the other, or the two mechanisms could have the same onset but operate at different rates. If the two mechanisms have different onsets and associative information begins to accumulate after item information, two possible response signal functions can result, depending on the particular discrimination that is being made. The information accumulation could be a nonmonotonic function of processing time for those discriminations for which the initially available item information conflicts with delayed associative information (one type of information gives positive evidence, the other negative). Otherwise, for those discriminations that require only associative information, the intercept of this response signal function will be delayed relative to the intercept for discriminations that can be based on item information alone. Support for this position comes from various experiments (Dosher, 1984b; Ratcliff & McKoon, 1982, 1989) and is summarized below.

The third way item and associative information can accumulate is that they could become available at the same point in processing but accumulate at different rates; information will be a positive monotonic function of processing time, and the intercept of the response signal functions will not differ, but the rates will. Using the together decision rule, Dosher (1988) found evidence of this in an experiment that pitted associative against item information. We next review the empirical and theoretical support for the three ways item and associative information may accumulate.

## Global Memory Models

The models of Gillund and Shiffrin (1984), Hintzman (1984), and Murdock (1982) base a recognition decision on the interaction of a test probe with all items in memory. The result of this interaction is a measure of global matching or strength: The more similar the test probe to one or many traces in memory, the greater the match strength. Item and associative information are treated inseparably in the memory representations of these models.

The SAM model of recognition of Gillund and Shiffrin (1984) provides one illustration of this class of global models. In this model, memory is represented as a matrix of strengths of connections between possible retrieval cues and stored items or "images." To make a recognition decision, global match strength or familiarity is given by the product of the strengths of connection of the context cue and the retrieval probe to an image, summed over all the images in memory. This familiarity value is compared to an internal response criterion. If the value is greater than the criterion, a positive response is made; otherwise, a negative response is made. When a pair of words is tested, familiarity is calculated by taking the product of the strengths of connection of each member of the pair to a given image and the strength of connection of the context cue to that same image, and summing these products over all the images. There is no reason to expect differential availability of item versus associative information because their joint contributions are an inseparable part of the product of the strengths of connection to an image.

Gillund and Shiffrin (1984) briefly discussed an extension of their memory model into the time course (response time) domain. They suggested that the familiarity value might be used to drive a random walk decision process. But because the random walk was based on the asymptotic familiarity value, only the probability of termination at a boundary or rate of approach to a boundary could vary as a function of test type. No additional information would become available to change the direction of the walk in progress (i.e., no nonmonotonic accumulations of information). In its current configuration, the SAM model could not produce differential availability of item and associative information.

MINERVA 2 (Hintzman, 1984) differs from the Gillund and Shiffrin (1984) model in its representations of items. Each item is represented by a vector of features (each feature taking the value +1, 0, or −1). A recognition decision is based on the following: Each feature of a retrieval probe (also a vector) is multiplied with the corresponding feature of each trace in memory. These products are summed over all the features and normalized by the number of features that are nonzero in both the probe and memory trace. The normalized sum is then cubed, increasing the signal-to-noise ratio of a target trace relative to a nontarget trace. This results in an activation value for each trace in response to the retrieval probe. Recognition is based on the sum of these activation values over all traces in memory (echo intensity), the equivalent of familiarity in SAM. For a recognition decision, the echo intensity is compared to an internal response criterion.

To deal with a pair rather than a single item, Hintzman (1986) assumed that each half of a vector represents one of the members of the pair. Echo intensity is computed the same way as for single items. No mechanism currently exists in MINERVA 2 that could predict differential availability of different types of information because, as in the SAM model, the contributions of item and associative information are inseparable parts of the activation of each trace in response to the probe. Hintzman (1988) described a random walk decision model to link with the MINERVA 2 memory model. He assumed that information is not retrieved instantaneously but accumulates over time, with different features becoming available at different times. But because the model does not treat item and associative information separately, it does not predict item features to be available prior to or at a different rate from associative features.

TODAM (Murdock, 1982) also assumes a vector representation for memory traces although, in contrast to MINERVA 2, TODAM assumes a single, common (distributed) representation to which each trace is added during storage. Each element in the memory vector is the sum of the appropriate elements from each of the individual vectors. A recognition decision is based on the dot product of the retrieval probe (a vector) with the memory vector. The more similar is the retrieval probe to one or more traces making up the memory vector, the greater is the dot product. The resulting dot product (equivalent to familiarity in the SAM model and echo intensity in MINERVA

2) is fed into a two-criteria decision system (Hockley & Murdock, 1987; see Gronlund & Ratcliff, in press).

To store a pair of items, the vectors that represent each of the individual items are added to the memory vector, plus the vector that represents the convolution of the two items. To recognize a pair of words, the test items are convolved, and the convolution is compared (the dot product is taken) with the memory vector (Murdock, 1982). The resulting value of the dot product is fed into the decision system. In TODAM, just as in the Gillund and Shiffrin and Hintzman models, when a pair is tested, item and associative information are inseparable. This is so because the dot product is based only on the match of the convolution to the memory vector, not the individual item vectors. This would not be true if the individual item vectors were also matched against memory in a separate comparison, though the SAM and MINERVA 2 models could be similarly modified to allow item and associative information to produce separate contributions. We will return to the models' treatments of item and associative information below.

The Hockley and Murdock (1987) decision model (when linked to TODAM) would suffer from the same problem as the SAM model with regard to time-course data; asymptotic accuracy drives the decision process. Over time, retrieval noise varies randomly, but the result of the memory comparison process (the dot product) stays constant. No new information becomes available that could change the result of the memory comparison process to produce differential availability of item and associative information.

## Nonmonotonic Accumulation of Information

The combination of item and associative information would accumulate in a nonmonotonic manner if the two kinds of information conflict and become available at different points in time. Three examples of nonmonotonic information accumulation are now reviewed. Ratcliff and McKoon (1982) had subjects answer questions such as "Is a bird a robin?" using response signal testing procedure. They found that early in processing (when subjects were forced to respond at short lags), there was an increasing tendency to respond "yes" in error. They suggested that the initial information was information about overall similarity and the tendency was to respond "yes" because *bird* and *robin* are related concepts. Later in processing, subjects tended to respond negatively correctly, and Ratcliff and McKoon argued that new information became available that countered the early positive information by allowing assessment of the nature of the relation between the concepts.

In a second example, Ratcliff and McKoon (1989) had subjects study sentences of the form "John hit Bill." Subjects were asked to respond positively to a test sentence with the same meaning as one that was studied. Ratcliff and McKoon (1989) found that prior to 700 ms of processing time, subjects were unable to discriminate "John hit Bill" from "Bill hit John" when "John hit Bill" had been studied. After 700 ms of processing, subjects began to correctly reject "Bill hit John" as mismatching in meaning. (Study sentences were both active and passive, so position of a word in the sentence was not a cue for the response.) Sentences made up of words never studied were discriminated from studied sentences much earlier in processing.

In a third experiment demonstrating nonmonotonic response signal functions, Dosher (1984b) had subjects study pairs of words, some of which were preexperimentally related. Subjects were to respond positively only to test pairs that had been studied together (irrespective of whether they were preexperimentally related). Early in processing, subjects responded positively to preexperimentally related pairs even if they had *not* been studied together. Dosher (1984b) argued that subjects initially responded positively to these pairs on the basis of initial recognition of association independent of source. After about 700 ms, subjects began to correctly reject these pairs.

## Differential Rate of Accumulation

A third way that item and associative information can accumulate is that the two sources of information can be available at the same time but accumulate at different rates. Dosher (1988) used the together rule in an experiment with word pair stimuli and found that discriminations that require associative information had a much slower rate of accumulation of evidence than did discriminations that did not require associative information. However, Dosher (1988) used lags at 100, 300, 600 ms, and so forth and may have missed any delayed availability of associative information. At the 600-ms lag, the discrimination based on associative information may have less evidence than discriminations based on item information, not because the rate of accumulation is slower but because associative information just began to accumulate. Once associative information begins to accumulate, it could do so at the same rate as item information or at a faster or slower rate. Experiments similar to Dosher's (1988) are conducted with additional short lags to answer this question.

In this article, the focus will be on the implications of time-course data for global memory models (Gillund & Shiffrin, 1984; Hintzman, 1984; Murdock, 1982). These models have successfully dealt with asymptotic recognition accuracy performance but have not concerned themselves with the time course of recognition. Although probably consistent with the results of Dosher (1984b), and Ratcliff and McKoon (1982, 1989) at asymptote, the models do not predict nonmonotonic accumulations of information before reaching asymptote as the result of differential availability of two types of information. However, it is important to note that none of the global memory models concern themselves with the time course of processing in any great detail. The experiments in this article are not meant to test some "prediction" of these models. Rather, the hope is to demonstrate that current instantiations of a global matching mechanism have limitations as a general purpose mechanism for recognition because they deal only with asymptotic performance and because they generally treat item and associative information inseparably. Thus, data presented will serve as a basis for revising or extending the models.

In the experiments presented below, if the availability of associative information is delayed relative to item information, the initially available item information will not discriminate between a test pair that exactly matches a study pair (intact) and a test pair that consists of words from two different study pairs (rearranged). This is so because the component words in the two test pairs had been studied. However, the associative information available later will allow discrimination of these test pairs. Nonmonotonic accumulations of information would occur in the together rule for a rearranged test pair. Over the early part of processing, item information produces incorrect positive information for the rearranged test. When associative information becomes available, it overrides the incorrect positive item information, and the probability of making a positive response decreases. Likewise, response signal functions for discriminations that can be based on item information will have an earlier time intercept than those that require associative information.

## Experiments 1 and 2

In the first two experiments, different decision rules were used to manipulate the relevance of the association between a pair of words. The two decision rules can be illustrated as follows: In Experiment 1, subjects were instructed to respond according to a "separate" decision rule. They were to respond positively if each word in the test pair was previously studied. When only a single word was tested, subjects responded positively if that word had been studied. The following notation will be used: Denote a studied pair of words as AB and a studied single word as C. At test, denote an intact pair as AB (exactly matches a study pair), a studied single word as C, and a rearranged pair as AB′ (A and B′ were each studied but not in the same pair). The test of an unstudied word will be denoted X; AX represents the test of a studied word with an unstudied word; and XY represents the test of two unstudied words. A positive response was made to AB, AB′, and C.

In Experiment 2 subjects used a together decision rule. The two words of the test pair must have been studied together for a positive response to be made. Because the components were each studied, discrimination could not be based on item information. Discriminating AB from AB′ required assessment of the association between the words. (It could be that item A is encoded differently in the context of B′ than in the context of its pairmate B (Tulving & Thomson, 1973). However, such an explanation predicts a difference in the response signal function at asymptote, but not any intercept difference.)

### *General Method*

The method for Experiments 1 and 2 will be described jointly, with any differences specified below.

*Subjects.* Four student volunteers participated in both experiments. They received $5 per 1-hr session. Two subjects participated in Experiment 2 before Experiment 1; they completed six sessions of Experiment 1, and the other 2 subjects completed eight sessions. All subjects completed eight sessions of Experiment 2.

*Procedure.* The experiments were performed by using a microcomputer that controlled stimulus presentation, timing, and response collection. In Experiment 1 (the separate decision rule), there were 28 blocks of trials per session. Each block consisted of a study phase with the presentation of 10 pairs and four singles. In the test phase there were 28 tests per block: 6 were of type XY, 2 were AX, and 2 were BX (combined for purposes of analysis), 6 were X (respond negatively to all these tests), 4 were AB, 4 were AB′, and 4 were C (respond positively to all these tests). Two rearranged test pairs were constructed by swapping B elements between two study pairs; the two respective rearranged test pairs were at least five trials apart in the test phase. (One subject reported noticing that *sometimes* the rearranged tests were constructed like this, though not until after his 13th session overall.) Words were not repeated in the test phase nor at any time during a session.

Each block of trials proceeded as follows: First, "Press space bar to begin study phase" appeared on the CRT screen. The initiation of any particular block of trials was therefore self-paced. The pairs and singles were randomly mixed in the study phase and presented sequentially. Each pair was on the screen for 4 s and each single for 2 s. After completion of the study phase, "Place fingers on / and *Z* keys and press space bar to begin test phase" appeared (/ for positive, *Z* for negative). Initiation of this phase was also controlled by the subject. A pair or single test item was presented, followed at some variable lag with a row of 10 asterisks directly under the test item. Subjects were instructed to respond *within* 300 ms of the presentation of this signal. The screen went blank as soon as the subject responded, and his or her response time was presented for 500 ms (no accuracy feedback was given). This was followed by 250 ms of blank screen before the next test commenced. Every seven blocks of trials, the following summary information was provided: average response time at the shortest lag and accuracy at the longest lag.

The assignment of response signal lag to condition was random, with the constraint that each of the 28 tests that made up a block were tested at each of the seven lags every seven blocks of trials. The seven response signal lags were 100, 200, 300, 450, 600, 1,200, and 2,500 ms. There were 1,288 words required by the experiment, with 1,150 of these coming from the Toronto word pool (Murdock & Walker, 1969) and 138 others generated randomly. All words were two syllables and from four to eight letters long. For each session for each subject, a different random assignment of words was made to the various conditions of the experiment.

In Experiment 2 (the together decision rule), the composition of the study and test lists changed slightly. Two pairs and two singles were added to the study list (giving 12 pairs and 6 singles total). The 28 tests per block were composed as follows: 4 were of type XY, 4 were AB′, 4 were X (respond negatively to all these), 2 were A, 2 were B (single word from a pair), 6 were AB, and 6 were C (respond positively to all of these). The required 1,176 words were randomly selected from the pool of 1,288 words used in Experiment 1. This selection was different for each subject for each session. Other aspects of the procedure were the same as for Experiment 1.

### *Results and Discussion*

Each subject's first day was treated as practice and excluded from the data analyses. All analyses were based on only those responses that occurred no later than 350 ms after the response signal. Any responses beyond this time window were considered to reflect additional processing of the stimulus prior to a decision. (At the shortest lag, this cutoff excluded from 0% to 15% of the responses, though usually below 10%.) In what follows, the response signal function ($d'$ accuracy as a function of lag) and the probability of making a positive response as a function of lag provide the primary data for each experiment. Fits of theoretical functions to the response signal data are performed to provide estimates of the intercept, rate, and asymptote of the empirical functions. The intercepts are approximately equal for the discriminations of Experiment 1 because only the item information from each component of the pair is necessary to make these discriminations. In Experiment 1, the discrimination of AB from AB′ requires associative information. The intercept for this function is about 220 ms later than any of the others.

Figure 1 shows the response signal functions for Experiment 1 for the following comparisons: AB versus XY, AB versus AB′, C versus X, AB′ versus XY, and AX versus XY. These data were averaged over all 4 subjects (because there were no noteworthy differences among subjects) for all six or eight sessions. Note that the $d'$ tendency to respond positively is plotted as a function of lag plus response time, the total processing time. The vertical bars indicate 97.5% confidence intervals. These are calculated from a $d'$ value obtained from the hit rate minus one standard deviation and the false alarm rate plus one standard deviation, and the hit rate plus one standard deviation and the false alarm rate minus one standard deviation. Standard deviation was calculated from $\sqrt{(p(1-p)/N)}$, where $p$ is the hit rate and $N$ is the total number of responses.

Figure 2 shows the probability of making a positive response as a function of total processing time for each condition in Experiment 1 (a replotting of the data from Figure 1). The vertical bars indicate one standard error of the mean. Because only item information is necessary for these discriminations, there is no evidence of nonmonotonicities in these functions. Note the criterion shift for single versus pair tests at the shortest lag, which indicates that subjects were more likely to respond positively to a single item than a pair.

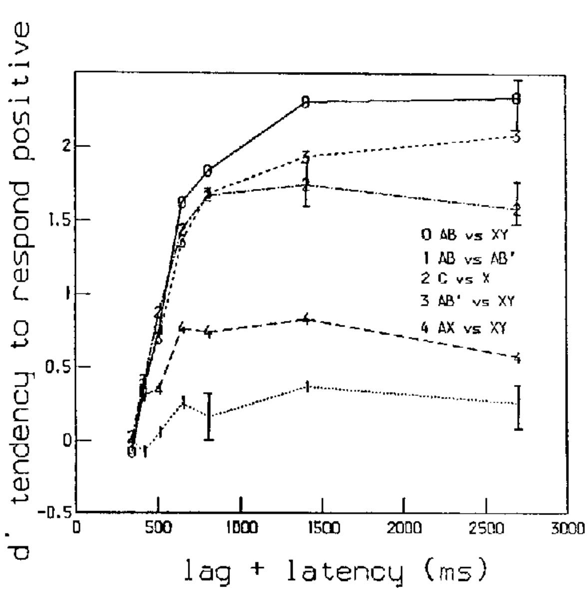


*Figure 1.* Response signal functions for Experiment 1 averaged over all 4 subjects and all sessions. (The $d'$ tendency to respond positively is given as a function of the total processing time [lag + latency]. Function 0 is AB vs. XY; Function 1 is AB vs. AB′; Function 2 is C vs. X; Function 3 is AB′ vs. XY; Function 4 is AX vs. XY. Vertical bars are 97.5% confidence intervals calculated as described in the text.)

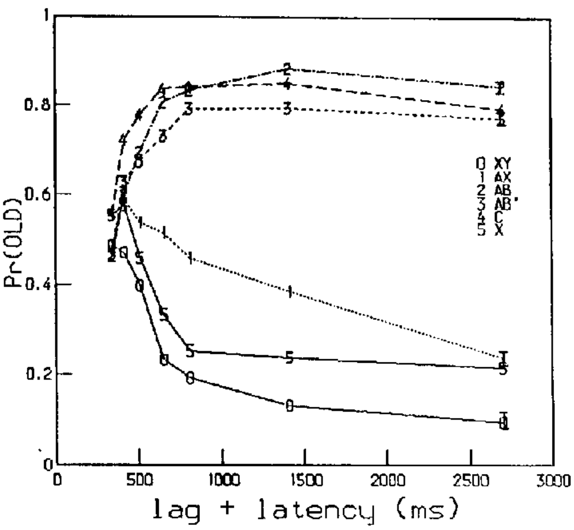


*Figure 2.* The probability of a positive response for each condition of Experiment 1 (averaged over all 4 subjects and all sessions) as a function of the total processing time (lag + latency). (Function 0 is XY; Function 1 is AX; Function 2 is AB; Function 3 is AB′; Function 4 is C; Function 5 is X. Vertical bars indicate one standard error of the mean.)

At the very shortest lag, discriminability was at chance for all comparisons. In Figure 1, all except Function 1 (AB vs. AB′) begin to rise above chance at about the same point in time. This indicates that the information necessary to make these discriminations begins to accumulate at the same point in processing. The association between the words does have a small effect on the comparison of AB versus AB′. They diverge at about 600 ms in Figure 2, with the advantage to the AB test. This is shown in Figure 1 by the delayed intercept of the AB/AB′ response signal function. Associative information is available after the item information that is responsible for the other discriminations. This is consistent with suggestions by Humphreys (1978). The delayed availability of associative information is demonstrated more clearly in Experiment 2, where a different response is required of AB and AB′.

There are two simple expressions commonly used to describe the growth of accuracy in the response signal procedure. The first is an exponential growth to a limit (Corbett, 1975; Dosher, 1976):

$$d'(t) = d'_a(1.0 - \exp(-v(t - t_{er}))), \tag{1}$$

where $d'$ at time $t$ is a function of $d'_a$, the asymptotic level of accuracy, $v$ the rate of approach to that asymptote, and $t_{er}$ the time intercept (the point at which accuracy first rises above chance). The second expression is derived from the diffusion model of Ratcliff (1978):

$$d'(t) = d'_a/\sqrt{(1 + v/(t - t_{er}))}, \tag{2}$$

where $v$ represents the rate of approach to asymptote and is the ratio of the variance in the drift rate of the diffusion process to the variance in the retrieval probe-memory relat-

Table 1
*Parameters of Exponential and Diffusion Equations Fitted to Response Signal Functions for Experiments 1–4*

| Discrimination | Exponential (Equation 1) $t_{er}$ | Exponential (Equation 1) $1/v$ | Exponential (Equation 1) $d'_a$ | Diffusion (Equation 2) $t_{er}$ | Diffusion (Equation 2) $v$ | Diffusion (Equation 2) $d'_a$ |
|---|---|---|---|---|---|---|
| Experiment 1 | | | | | | |
| AB vs. XY | 380.8 | 268.5 | 2.35 | 407.5 | 593.4 | 2.75 |
| AB vs. AB′ | 554.4 | 31.5 | 0.36 | 560.0 | 40.8 | 0.28 |
| C vs. X | 378.1 | 156.6 | 1.69 | 406.0 | 196.0 | 1.82 |
| AB′ vs. XY | 361.5 | 286.2 | 2.05 | 400.3 | 611.2 | 2.42 |
| AX vs. XY | 351.4 | 145.8 | 0.74 | 393.9 | 131.8 | 0.77 |
| Experiment 2[a] | | | | | | |
| AB vs. XY | 332.3 | 288.9 | 2.25 | 411.8 | 406.3 | 2.52 |
| AB vs. AB′ | 569.5 | 178.9 | 1.24 | 625.3 | 199.1 | 1.33 |
| C vs. X | 340.1 | 160.8 | 1.72 | 402.0 | 149.6 | 1.83 |
| A,B vs. X | 330.8 | 198.8 | 1.65 | 400.0 | 204.0 | 1.77 |
| Experiment 3 | | | | | | |
| AB vs. AB′ | 570.9 | 383.2 | 1.96 | 635.8 | 823.4 | 2.36 |
| Experiment 4 | | | | | | |
| AB vs. XY | 241.9 | 331.5 | 2.91 | 308.4 | 591.2 | 3.35 |
| AB vs. AB′ | 544.5 | 166.4 | 1.50 | 614.3 | 175.9 | 1.62 |

[a] Equations 2 and 3 (Ratcliff, 1980) were fitted to AB′ versus XY in Experiment 2 because of the nonmonotonicity. The accumulation of evidence changes when associative information becomes available: $t_{er} = 349.4$; $v = 507.6$; $d'_{a1} = 1.63$; $t_1 = 660.7$; $d'_{a2} = .98$.

edness distribution. Both functions are used to summarize response signal functions in these types of experiments (e.g., Corbett & Wickelgren, 1978; Dosher, 1976, 1984a, 1984b; Ratcliff, 1981; Reed, 1973, 1976; Wickelgren & Corbett, 1977).

The parameter values for the fits of Equation 1 and Equation 2 to the functions in Figure 1 are given in Table 1. For Equation 1, $1/v$ is tabled so as to facilitate comparison with $v$ of Equation 2. For both equations, then, small values indicate more rapid approach to asymptote.

These equations were fitted to each response signal function individually, letting all three parameters vary. The intercepts for all functions except AB versus AB′ are approximately equal. At this point in processing, item information becomes available, and these discriminations can begin to be made. The AB versus AB′ intercept is estimated to be later (about 560 ms). This is the point at which associative information begins to become available.

The rate of accumulation of information for single items (C vs. X) is more rapid than pair information (AB vs. XY). Dosher (1988) found a similar result for the together decision rule. Note that this difference is not due to having to read one versus two words. A difference of that sort would show up in the intercept. However, the rates for the AX versus XY discrimination are comparable to the C versus X discrimination, so it cannot be that pair information always accumulates more slowly than single information. Dosher (1988) did not include any tests like AX. The rise to asymptote for AB versus AB′ is very rapid but is unreliable because of the very low asymptote. More will be said about the rates after Experiment 2.

*Probabilistic model.* The data from Experiment 1 suggest that two types of information with different time courses are available in memory. Decisions over the early part of processing are based on the contributions of the individual components (i.e., item information); beyond this point, additional information becomes available (associative information), and decisions need no longer be based solely on the match of the individual components. Ratcliff and McKoon (1988) developed a simple multiplicative probability model that instantiated this explanation. The model assumes that decisions over the early part of processing are based on the matching strengths of the individual components of the test stimulus. The model provided a good approximation to the "John hit Bill" data up to about 600–700 ms into processing; beyond this point, relational (associative) information became available, and the model did not apply. The same model was applied to Experiment 1. In this case, the model should hold over the entire time course of processing because item information is sufficient for these discriminations (the effect of the association was found to be very small because it was not relevant).

The model assumes that if a positive response is made to test pair AB′ (a hit), it means that both A and B′ produced a positive decision. (AB′ is used rather than AB because AB′ does not possess the associative information AB does.) If a positive response is incorrectly made to XY (a false alarm), it means that a positive decision was made to both X and Y. The model assumes that only the separate strength of each component of a pair is used to make a decision; therefore, the false alarm rate for AX should be predictable from a combination of the hit rate of AB′ and the false alarm rate of XY in the following way: Let $p+ \times p+$ be the hit rate for AB′ and let $p- \times p-$ be the false alarm rate for XY, where $p+$ is the probability of a correct positive decision to one component of an AB′ pair and $p-$ is the probability of an incorrect positive decision to one component of an XY pair. Because AX is one half of an AB′ pair and one half of an XY pair, the false alarm rate for AX should be equal to $p+ \times p-$. Table 2 gives the observed and predicted false alarm rate for AX. This multiplicative probability model provides a reasonable approximation to these data and supports the argument that only item information is used for the separate decision rule over the entire time course.

Table 2
*Multiplicative Probability Model Predictions (Pred.) for AX From AB′ and XY Data for the Separate Decision Rule*

| Condition | Response signal lag (in ms) 100 | 200 | 300 | 450 | 600 | 1,200 | 2,500 |
|---|---|---|---|---|---|---|---|
| AB′ data | .468 | .628 | .675 | .732 | .792 | .795 | .772 |
| XY data | .487 | .471 | .398 | .233 | .192 | .131 | .094 |
| AX data | .485[a] | .591 | .537 | .515 | .460 | .385 | .239 |
| AX pred. | .477 | .544 | .518 | .413 | .390 | .323 | .269 |

[a] Standard error approximately .02.

The predictions in Table 2 generally underestimate the data. This is due in part to the fact that the model assumes no variability in the matching strengths of the components of a test pair. If the more reasonable assumption is made that the strengths of the components of the pair vary across items and trials, the probabilistic model will more closely approximate the data. This can be illustrated with an example. For the 1,200-ms lag, if no variability is assumed in the matching strengths, the predicted value of AX is assumed to be one half of the probability of making a positive response to AB′ multiplied by one half of the probability of making a positive response to XY ($p+ = \sqrt{.795} = .89$ and $p- = \sqrt{.131} = .36$; predicted $p+ \times p- = .323$; observed equals .385). However, if the strengths of the components of a test pair are assumed to differ, the predicted value of AX will be greater. For example, suppose that the probabilities of making a positive response for the components of XY were .65 and .20 rather than .36 and .36. Then the predicted value of AX would equal $(.89 \times .65 + .89 \times .2)/2 = .38$, which is much closer to the observed value. Thus, the deviations of the model should not be taken as evidence to reject it; rather, if anything, the underestimations lend support to the model because the assumption of variability serves to bring theory and data into closer accord.

## Experiment 2

The together rule in Experiment 2 requires that associative information be used to make the discrimination between AB and AB′. Figure 3 shows the response signal functions for Experiment 2 averaged over subjects and sessions. The $d'$ tendency to make a positive response is plotted as a function of total processing time, with 97.5% confidence intervals indicated by the vertical bars. Most interesting is AB versus AB′. Unlike the functions for the other Experiment 2 discriminations (as well as for the discriminations in Experiment 1 except AB vs. AB′), discriminating an intact studied pair (two words that had been studied together) from a rearranged pair (the components were studied but not together) remains at chance until about 570 ms into processing. This same pattern was evident in the data of each individual subject.

Associative information had an effect in both experiments, but it was a very small in Experiment 1 (where it was not necessary to make discriminations). Compare the AB versus AB′ functions in Figures 1 and 3; the asymptote was about 0.3 in Experiment 1 and about 1.25 in Experiment 2. Part of the difference between experiments is due to the increased attention focused on associative information by the together rule. However, encoding differences could also play a role because it is not necessary to limit rehearsal to only the current study pair for the separate decision rule; this is required by the together rule. In an experiment by Humphreys (1976) (with unpaced testing), subjects were not told which decision rule to use until after study. Humphreys (1976) still found a greater difference between intact and rearranged tests in the together decision rule, thereby ruling out encoding differences as an explanation of this difference.

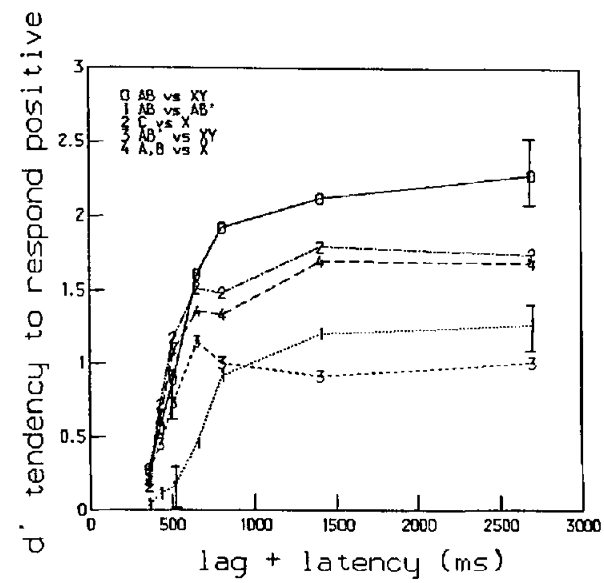


*Figure 3.* Response signal functions for Experiment 2 (all sessions averaged over all subjects). (The $d'$ tendency to respond positively is given as a function of the total processing time [lag + latency]. Function 0 is AB vs. XY; Function 1 is AB vs. AB′; Function 2 is C vs. X; Function 3 is AB′ vs. XY; Function 4 is A, B vs. X. Vertical bars are 97.5% confidence intervals.)

Figure 4 gives the probability of responding positively for each condition as a function of total processing time. One standard error of the mean is given by the vertical bars. As in Experiment 1, at the shortest lag, subjects were more likely to respond positively to a single item than a pair of items, even if the single item was from a studied pair. The AB and AB′ functions rise together (equally likely to be responded to positively based on item information) until about 600 ms, at which time associative information becomes available, and these two functions begin to diverge. The accumulation of information for the rearranged test is a nonmonotonic function of processing time.

The function representing two negative test pairs (AB′ vs. XY) scaled against one another is nonmonotonic. Equation 2 can be modified to account for nonmonotonic accuracy functions (as could Equation 1) by assuming that the drift rate of the diffusion process changes at some point in processing (when new information becomes available). Equation

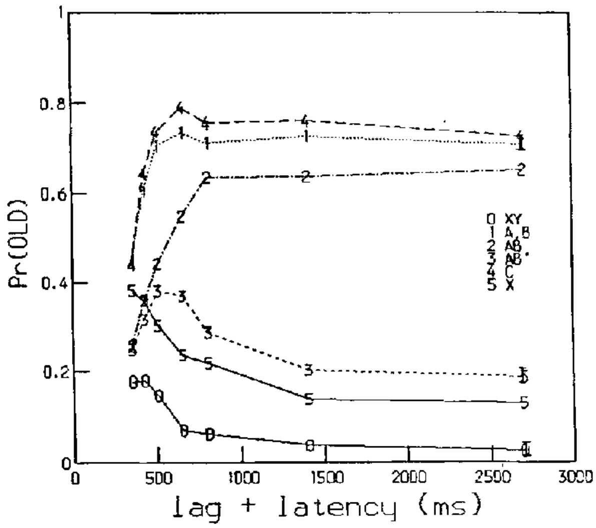


*Figure 4.* The probability of a positive response for each condition of Experiment 2 (averaged over all 4 subjects and all sessions) as a function of the total processing time (lag + latency). (Function 0 is XY; Function 1 is A, B; Function 2 is AB; Function 3 is AB′; Function 4 is C; Function 5 is X. Vertical bars indicate one standard error of the mean.)

2 holds for $t \leq t_1$, and Equation 3 holds for $t > t_1$ (see Ratcliff, 1980).

$$[d'(t) = d'_{a2} + (d'_{a1} - d'_{a2})(t_1 - t_{er})/(t - t_{er})] \Big/ \sqrt{(1 + v/(t - t_{er}))}\,, \qquad (3)$$

where $t_1$ is the point in processing at which the rate of accumulation of evidence changes, $d'_{a1}$ is the asymptote for $t \leq t_1$, and $d'_{a2}$ is the asymptote for $t > t_1$. Early in processing, the AB versus XY and the AB′ versus XY functions rise together. This is so because there is an increasing tendency to respond positively to AB as well as to AB′ based on item information. When associative information becomes available (estimated by Equation 3 to be 660 ms) these two functions (AB vs. XY and AB′ vs. XY) begin to diverge because the tendency to make a positive response to AB′ decreases.

## *Rate of Accumulation of Information*

Table 1 gives the parameter estimates for the fit of Equations 1, 2, and 3 to the response signal functions in Figure 3. The intercept for the AB versus AB′ function which requires associative information is about 220 ms greater than the intercepts of the other functions which require only item information. As in Experiment 1, the rates for the C versus X discrimination are twice as rapid as the AB versus XY discrimination. The rate for A or B versus X was similar to that for C versus X. The rate difference between pairs and singles is therefore not due to differential encoding for single items (see Dosher, 1988, for a similar result). In Experiment 1, AX versus XY had a rapid rate; in Experiment 2 so did AB versus AB′. The rate difference among tests does not seem to be a function of single versus pair tests either.

## *Trade-Off of Rate and Intercept*

Ratcliff and Iverson (1985) showed that the rate and intercept can trade off in Equations 1 and 2. A later intercept can be compensated for by a faster rate; an earlier intercept can be compensated for by a slower rate. For the AB/AB′ discrimination, an approximately equal fit (in terms of sum of squared deviations) was found for a function with an earlier intercept (90 ms earlier) and twice as slow a rate as given in Table 1. Which one better approximates the data? The fact that associative information is delayed relative to item information is not affected by the choice, though the exact estimate of when associative information becomes available is. What is affected by the choice of fits is conclusions about the rate. Does associative information accumulate as rapidly as single item information (as if it was a single piece of information), or does it accumulate more slowly as Dosher (1988) suggested?

Figure 5 compares the AB versus AB′ data with the two fits of Equation 1. The fits are equivalent over the first two lags and the last two lags. The difference between the fits arises because the early intercept fit treats Lag 3 as above chance (associative information has begun to accumulate), whereas the late intercept fit treats Lag 3 as representing chance responding. The early intercept fit is much closer to the Lag 3 point than is the late intercept fit. However, the late intercept fit is closer to the Lag 4 and 5 data, which the early intercept fit overestimate and underestimate, respectively. The key is the Lag 3 point; if it is spurious and really should be at chance, the late intercept fit with the rapid rate is to be preferred. We think it is spurious for two reasons: (a) If we allow some variability in the onset of availability of associative information, the observed rise from chance would not be expected to be abrupt but gradual (as the data show). Associative information is usually not available until after 570 ms,

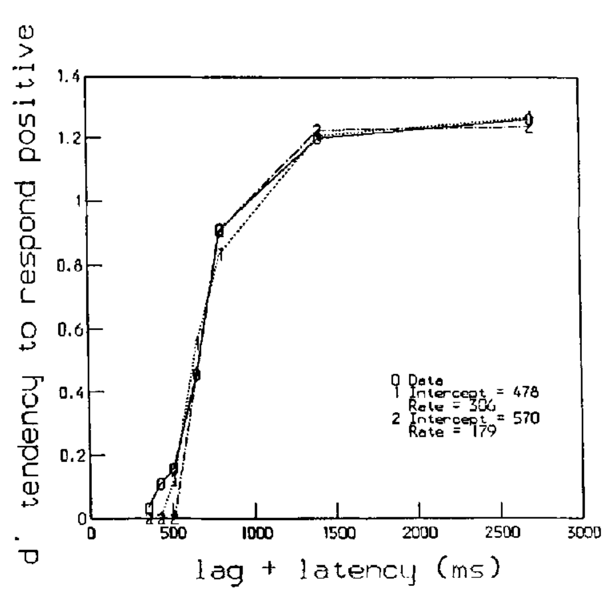


*Figure 5.* Response signal function for AB versus AB′ discrimination in Experiment 2. (Also given are fits of Equation 1 with early intercept and late intercept.)

but on occasion (e.g., if the two test words are both one syllable, high frequency, and four letters long) associative information is available somewhat sooner. (b) The sharp break in the function from Lag 3 to Lag 4 supports the idea that additional information (associative) is available at Lag 4 that was not available at Lag 3. For these reasons and in the absence of further information, we think that the late intercept fit with the rapid rate better represents the data.

## *Lag–Latency Data*

A standard result in response signal experiments is that the latency to respond is a decreasing function of lag. Reed (1976) suggested that the latency can be used as a measure of the subject's relative readiness or preparedness to respond, with differences between conditions reflecting differing processing demands. A two-way analysis of variance (Condition × Lag) was performed on the lag–latency data of Experiment 1. There was a main effect of condition, $F(5, 15) = 3.90$, $p < .05$; a main effect of lag, $F(6, 18) = 3.97$, $p < .05$; and a significant interaction of these two factors, $F(30, 90) = 1.83$, $p < .05$. A two-way analysis of variance (Condition × Lag) was also performed on the lag–latency data of Experiment 2. There was a main effect of condition, $F(5, 15) = 3.60$, $p < .05$; a main effect of lag, $F(6, 18) = 19.95$, $p < .05$; and a significant interaction of these two factors, $F(30, 90) = 1.63$, $p < .05$.

The lag–latency data can be best summarized by looking at the average over subjects, sessions, and conditions. In both experiments, the lag–latency function generally decreased over the first four lags, indicating an increasing preparedness to respond through this point in processing. The latency to respond increased somewhat for the 600- and 1,200-ms lag, reflecting a decreased readiness to respond. This may be a function of sometimes having to withhold a prepared response while waiting for the response signal (see Ratcliff, 1988; Reed, 1976).

In both experiments, when Condition C is a test item, the latencies are less than in the other conditions, though according to a Tukey test the difference is significant only for 200-, 300-, 450-, and 600-ms lags. It is interesting that the same is not true when X is a test item nor when A or B from the pair is tested in Experiment 2. Perhaps the subject gets some additional "single" information for C that supplements the item information. An interesting difference between experiments was found for the AB′ test; its latency did not differ significantly from any of the other tests for the separate rule, but it is generally slower than any of the other tests for the together rule. This difference was significant for the 300- and 450-ms lags. This could be so because associative information is first available over this range (Lag 300 plus 230-ms response time corresponds to the estimated intercept), and it conflicts with the item information.

These two experiments provide evidence for separate sources of item and associative information in recognition. This is supported by similar intercepts in the fits to those Figure 1 discriminations that are based on item information (all except AB vs. AB′). It is also supported by the success of the probability model that predicts AX performance from the separate item contributions of AB′ and XY. When the association is relevant to the decision (AB vs. AB′, Experiment 2, especially), the intercept is estimated to be about 220 ms later than those discriminations that can be based on item information. The delayed availability of associative information is most clearly demonstrated in Figure 4, where subjects respond equivalently to AB and AB′ for the first 600 ms of processing and then begin to correctly reject AB′.

The next two experiments test two explanations of these data that assume that some other factor besides the differential time course of information is responsible. These are a strategic explanation in Experiment 3 and an explanation involving the time required to encode the two test items in Experiment 4.

# Experiment 3

Experiment 3 sought to determine if the delayed availability of associative information is due to a strategy the subject might adopt due to task demands, rather than being a fundamental property of memory. Do subjects employ a strategy whereby they first check to determine whether the words were studied or not (item information), and if they were, do they then attempt to determine if they were studied together (associative information)? To test the possibility of a strategic explanation, only AB versus AB′ discriminations were required in Experiment 3, making item information irrelevant. If the delay is purely strategic, it should be eliminated when subjects can focus directly on associative information.

As a secondary manipulation, Experiment 3 included a manipulation of word frequency to evaluate a potential mechanism responsible for the discrimination delay: that the delayed availability of associative information is a function of the time required for a recall process to assess the association between the words. Much research has demonstrated that low-frequency words are recognized better than high-frequency words but that high-frequency words are recalled as well as or better than low-frequency words (see Gillund & Shiffrin, 1984, for a review). If recall was responsible for the delayed discrimination, asymptotic performance for the high-frequency pairs should be superior to that of the low-frequency pairs. On the other hand, if the secondary mechanism is a recognition (strength) mechanism, asymptotic performance for the low-frequency pairs should be superior to that of the high-frequency pairs.

## *Method*

*Subjects.* Four volunteers were paid $5 per 1-hr session for their participation. One subject participated in eight sessions, another in seven, the other two participated in six and five.

*Procedure.* The procedure was identical to that of Experiments 1 and 2. Eleven high-frequency and 11 low-frequency word pairs were presented for study in a random order. There were 21 blocks of study–test trials in a session. In each block of the test phase there were five high-frequency intact (AB) tests and six high-frequency rearranged (AB′) tests. There were also five low-frequency intact and six low-frequency rearranged tests. The tests were presented in random order. The same lags were used as previously, with the assignment of response signal lag to experimental condition being random and with the constraint that each of the 22 tests was tested at each of the seven lags every seven blocks of trials. The 462 high-frequency and 462 low-frequency words required for a session were selected at random from pools of 720 high- and 720 low-frequency words taken from Kučera and Francis (1967). All words were from four to eight letters in length. The pairings of the words were different for each subject for each session, as was the particular subset of words selected. The high-frequency words all had a count of 75 per million or higher; the low-frequency words all had a count of 15 per million or lower. The average frequency count of each set was estimated by calculating the average for a randomly selected subset of 100 words. The estimated average frequency for the high-frequency set was 164.0, and for the low-frequency set it was 4.1.

### *Results and Discussion*

Figure 6 shows the response signal function for the intact versus rearranged discrimination averaged over all 4 subjects for all sessions and collapsed over frequency (which did not differ in this experiment, see below). Accuracy in terms of $d'$ is plotted as a function of total processing time (lag plus response time), with 97.5% confidence intervals indicated by the vertical bars. Table 1 has the exponential (Equation 1) and diffusion (Equation 2) fits to this function. As in Experiment 2, subjects were unable to determine whether a pair had been studied together or came from different studied pairs until about 600 ms into processing. The intercept parameter values are similar to those for the intact–rearranged discrimination in Experiments 1 and 2. Apparently, the delayed availability of associative information is not due to a choice on the part of the subject to do the "simpler" item discrimination (XY vs. AB) before the "more difficult" associative discriminations (AB vs. AB'). The discrimination delay is found even when item discriminations are irrelevant.

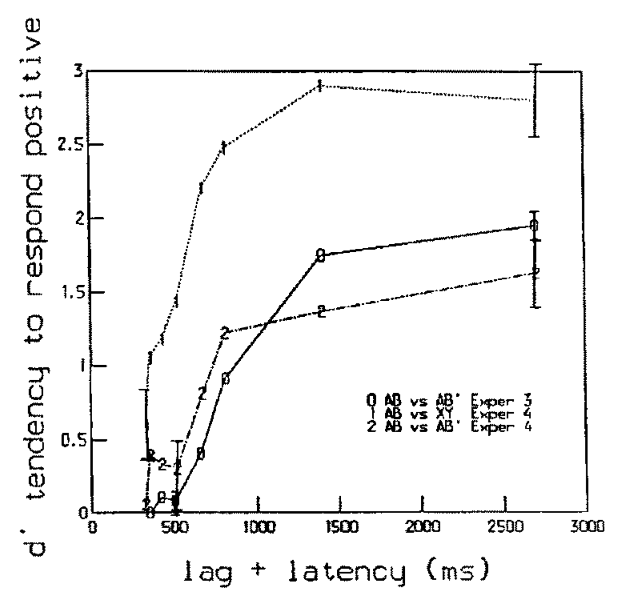


*Figure 6.* Response signal functions for Experiments 3 and 4. (The $d'$ tendency to respond positively is given as a function of the total processing time [lag + latency]. For Experiment 3, only intact vs. rearranged discriminations were required [Function 0]. For Experiment 4, Function 1 is AB vs. XY and Function 2 is AB vs. AB'.)

The rate parameter is slower here than in Experiment 2. However, this is due primarily to 1 slow subject. (Reed, 1976, also had a subject that was much slower than the other subjects.) Removal of this subject halved the rate, making it more in line with the AB versus AB' discrimination in Experiment 2. The latency of response decreased for the first three lags, rose slightly for the 450- and 600-ms lags (decreased preparedness), and then decreased for the two longest lags.

The manipulation of word frequency resulted in little difference in performance. On average, over the first six lags the high- and low-frequency performance differed by no more than .085 in $d'$ units. Two subjects showed an advantage for high-frequency tests; 2 showed an advantage for low-frequency tests. In a similar experiment with the same materials and the addition of high- and low-frequency XY tests, 3 different subjects showed a low-frequency advantage. More research is necessary to determine exactly what effect the repetition of the words across sessions has on the word frequency effect and if the addition of XY tests is a crucial variable. (In Gillund & Shiffrin, 1984, the frequency effect found with pairs had only AB versus XY discriminations.) Nevertheless, the data do rule out a strategic explanation of the delayed availability of associative information. The likelihood of recall operating in recognition will be taken up again in the General Discussion. First, an explanation involving the time to encode the test items will be tested in Experiment 4.

## Experiment 4

To discriminate between AB and XY requires that only the first word of the pair be processed. However, to discriminate AB from AB' in the together decision rule requires that both words be used. Therefore, the delay in discriminating AB from AB' may be due to the time to encode the second word. In Experiment 4, a 200-ms pause was introduced between the presentation of the first and second word of the test pair to encourage subjects to encode both words before making a decision and to give them the time to do that (normal reading time per word is approximately 200–250 ms). The response lag is measured from the onset of the second word. If the time required to encode the second word is responsible for the delayed AB versus AB' discrimination, the sequential presentation should eliminate the delay. If reading time is not responsible, the intercept for the AB/AB' discrimination should be comparable to that observed in the other experiments.

### *Method*

*Subjects.* Two volunteers were paid $5 per 1-hr session for their participation. Each subject participated in five sessions.

*Procedure.* The procedure was the same as in the previous experiments. The only change was the addition of a 200-ms pause between presentation of the first word of the test pair and the second (the first word remained on the screen during and after the 200-ms pause).

Fourteen pairs of words were presented for study at a 4-s rate. In the test phase there were six AB tests, eight AB' tests, and six XY tests per block. These tests were in a random order. The eight response lags were 50, 100, 200, 300, 450, 600, 1,200, and 2,500 ms, with lag time measured from the onset of the second word. The assignment of response signal lag to experimental condition was random, with the constraint that each of the 20 tests was tested at each of the eight lags once every eight blocks of trials. There were 24 blocks of trials per session. The 960 words required for each session of the experiment were selected at random from the same pool of words used in Experiment 1. The pairings of the words were different for each subject for each session, as was the particular subset of words selected for a given session.

### *Results and Discussion*

Figure 6 shows the response signal functions for the AB versus XY and AB versus AB′ discriminations averaged over the 2 subjects and the five sessions. Accuracy in terms of $d'$ is given as a function of total processing time, with 97.5% confidence intervals indicated by the vertical bars. Performance at even the shortest lags is above chance for the AB versus XY discriminations. This shows that inserting the 200-ms pause between the first and second word had an effect on performance; subjects did use the 200-ms pause to encode the first word. If the first word was unstudied, subjects could begin to initiate a negative response before the second word was even presented. Table 1 shows the fits of Equations 1 and 2 to the response signal functions. Because the first word is predictive for XY, it is not surprising that the intercept for the AB/XY discrimination is 100 ms earlier than for the other experiments. In contrast, the delay had little effect on the intercept for AB versus AB′ which is about the same as in the previous experiments. (An experiment that directly compares simultaneous to 200-ms pause tests would provide more definitive evidence.) The discrimination delay is not eliminated by giving subjects time to encode the words of the test pair. As for the lag–latency data, the function decreases in a more consistent fashion than in previous experiments. Subjects were increasingly prepared to respond, given additional processing time.

The results of Experiment 4 show that the delay in discriminating intact from rearranged tests is little affected by providing additional time to encode the words. Experiment 3 ruled out an interpretation of the delay based on the proposal that the subject chooses to use item information before associative information. Although the possibility exists that one or both of these factors may play some role in the discrimination delay, it appears to be very small. Therefore, the primary reason for the delayed availability of associative information is due to a fundamental property of the memory system. Two proposals are offered for what this delay may be due to and how the global models could be modified to incorporate these proposals. The proposals are (a) the time to construct a compound cue and (b) the operation of recall in recognition. We shall discuss these proposals after a brief summary of the experiments.

## General Discussion

A series of experiments examined the time course of item and associative information in recognition. In Experiment 1, the association between the test pairs was not relevant, and information necessary to discriminate positive and negative pairs began to become available after about 350 ms of processing time. Item information based on the memory strength of each component of the test pair was sufficient for these discriminations. A multiplicative probability model that assumes independent contributions from the components of the test pair was used to predict AX performance from the estimated strengths of the components of the AB′ and XY data. The success of this model supported the hypothesis that individual item information was the basis for these decisions. The association between the words did have a small effect favoring the AB tests, though this advantage did not show up until about 600 ms into processing.

In the together decision rule of Experiment 2, subjects were instructed to discriminate intact from rearranged test pairs. This required associative information and took place about 220 ms later than those discriminations in Experiment 2 that could be based on item information alone. The delayed availability of associative information is most clearly illustrated by the AB and AB′ data in Figure 4. Early in processing, subjects were equally likely to make a positive response to either test. This is so because the initially available item information is the same. It was not until associative information began to become available at about 570 ms that the correct negative response began to be made to AB′.

The models of Gillund and Shiffrin (1984), Hintzman (1984), and Murdock (1982) assume that recognition decisions are based on a global-matching, strength-based process in which the contributions of item and associative information are inseparable. However, the time-course data require that these sources of information make separate contributions. We will consider two possible ways the global models can be modified so that item and associative information do make separate contributions. One modification is to assume two types of global-matching information which are based on cues with differing time courses. We refer to the two types of cues as *concurrent* and *compound cues.* Item information results from the match of concurrent cues to memory; associative information results from the match of a compound cue to memory. The other modification assumes that a global matching process gives item information but that recall is necessary to get associative information.

The difference between concurrent and compound cues can be illustrated as follows: For a pair test, a compound cue is a joint match of the two words to memory. A concurrent cue, on the other hand, means that each item in a pair is individually matched against memory and that the individual contributions are combined to arrive at an aggregate on which to base a decision. The use of concurrent cues would be sufficient for all discriminations except the discrimination of intact from rearranged tests in the together rule. For the together rule, over the early part of processing, AB and AB′ should be responded to equivalently because the contribution of concurrent cues is identical for intact and rearranged tests. Not until associative information (the contribution of the compound) becomes available are subjects able to make this discrimination. This describes the AB and AB′ data in Figure

4. Can these two types of cues be incorporated into the various global memory frameworks?

In the SAM model, the familiarity of the test of a pair of words is calculated by taking the product of the strength of connection to an image of each component of the pair and the context cue and summing over all the images in memory. The model would be consistent with the idea of concurrent and compound cues (separate contributions of item and associative information) if, in addition to probing memory as was just described, memory was also probed with each component of the test pair together with context. Item information would result from an aggregate of the familiarity resulting from the separate components; associative information would result from the joint probe.

MINERVA 2 assumes that when a pair is studied, the memory representation consists of one word of the pair for each half of a vector. One way in which MINERVA 2 can be modified in light of these data is by assuming that when a pair is studied, a vector is stored for each component of the pair, in addition to a joint vector. Then when a pair is tested, memory is probed with the two concurrent cues (the individual vectors), as well as by the compound cue (the joint vector). Item information results from an aggregate of the match of the former; associative information results from the match of the latter. However, Hintzman does not propose such a model; he proposes matching of the whole compound.

Murdock (1982) assumed that when a pair is tested, match strength is based on only the dot product of the convolution with memory. Alternatively, Murdock (personal communication, July, 1988) suggested that memory could be probed with each of the separate item vectors, as well as the convolution vector. Then item information results from an aggregate of the dot products of the separate item vectors with memory, associative information from the dot product of the convolution with memory. It should be stressed that the proposed modifications to all these models could cause problems with formerly adequate fits to data presented in the original articles. Nevertheless, they do show that item and associative information can be treated separately by global models. However, no mechanism exists that could produce a differential time course for the two types of cues nor any a priori reason why their time course should differ. By assuming different cues with different time courses, all we have done is describe the data rather than integrate temporal processing characteristics into the fabric of the model.

An alternative mechanism that may be responsible for the delayed availability of associative information is a relatively time-consuming recall process that is required to assess the association between a pair of words. (Humphreys, 1978, equates recall with associative or relational information in circumstances such as in these experiments.) This may involve the subject's using a member of the test pair as a cue in an attempt to generate its study pairmate for comparison with the test pairmate. Recall would be required only for the intact/rearranged discrimination in the together decision rule (though it could supplement the other decisions); a global matching mechanism would be sufficient for the other discriminations. Though the global memory model theorists do not assume that a recall process operates in recognition, other theorists have assumed that one does (e.g., Atkinson & Juola, 1974; Humphreys, 1978; Mandler, 1980).

Experiment 4 offers evidence contrary to the operation of recall in recognition. If recall operates in recognition, subjects should be able to make use of the 200-ms delay after presentation of the first word to initiate a recall process to try to generate the second word or to retrieve its associative information. The result of this would be an earlier intercept for the AB versus AB′ discrimination (perhaps 200 ms earlier than in the other experiments) due to the headstart. This was not found, even though the early intercept for the AB versus XY discrimination indicated that subjects were encoding the first word during the pause. (A better test of whether recall operates in recognition would be an experiment that directly compares simultaneous to 200-ms pause tests.) Evidence against the operation of a recall mechanism in recognition was offered by Gillund and Shiffrin (1984). However, Humphreys (1978), Humphreys and Bain (1983), and Mandler (1980) presented evidence that recall does operate in recognition. Undoubtedly, subjects could use recall in a recognition task if they chose. The question is whether a particular phenomenon is a function of only a global matching process or if recall is required as part of the explanation. The data of Experiment 4 offers little support for the operation of recall in recognition.

Recall could operate in conjunction with a global matching mechanism if the matching and recall mechanisms require different cues to gain access to item and associative information. Bain and Humphreys (in press) and Humphreys et al. (1989) made a similar suggestion. Recall may require a compound cue. Because of that, the 200-ms delay in Experiment 4 would not result in a faster intercept for the AB versus AB′ discrimination because recall could not begin to operate until both words were available to form the compound cue. This recall explanation differs from the explanation described above. This recall explanation assumes that although different cues are required, the cues do not differ in time course. The delayed availability of associative information is due to the time for recall to operate (with the compound cue as the probe). Item information (based on concurrent cues) is available before associative because recall is not required. The other explanation assumes that the delayed availability of associative information is the result of the additional time to form the compound cue; a global matching mechanism operates for both types of cues once they are formed.

The global models do possess recall-like mechanisms of various sorts, and these could be incorporated into recognition if the data warranted. They can also be made to treat item and associative information separately. However, the larger problem remains that the global memory models are essentially static. An adequate explanation of these data is likely to require that retrieval dynamics be made an essential component of the models' framework. Our feeling is that time course data like these cannot be readily incorporated into the existing theoretical frameworks and are instead providing a set of phenomena with which the next generation of theories must deal.

## References


Atkinson, R. C., & Juola, J. F. (1974). Search and decision processes in recognition memory. In D. H. Krantz, R. C. Atkinson, R. D. Luce, & P. Suppes (Eds.), *Contemporary developments in mathematical psychology* (Vol. 1, pp. 242–293). San Francisco: Freeman.

Bain, J. D., & Humphreys, M. S. (in press). The relational context effect: Cues, meanings or configurations? In G. Davies & D. M. Thomson (Eds.), *Memory in context: Context in memory.* London: Wiley.

Clark, S. E., & Shiffrin, R. M. (1987). Recognition of multiple-item probes. *Memory & Cognition, 15,* 367–378.

Corbett, A. T. (1975). *Artificial categories and semantic distance in a categorization task.* Master's thesis, University of Oregon.

Corbett, A. T., & Wickelgren, W. A. (1978). Semantic memory retrieval: Analysis by speed–accuracy tradeoff functions. *Quarterly Journal of Experimental Psychology, 30,* 1–15.

Dosher, B. A. (1976). The retrieval of sentences from memory: A speed–accuracy study. *Cognitive Psychology, 8,* 291–310.

Dosher, B. A. (1984a). Degree of learning and retrieval speed: Study time and multiple exposures. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10,* 541–574.

Dosher, B. A. (1984b). Discriminating preexperimental (semantic) from learned (episodic) associations: A speed–accuracy study. *Cognitive Psychology, 16,* 519–555.

Dosher, B. A. (1988). *Retrieval dynamics of item and associative information.* Manuscript submitted for publication.

Gillund, G., & Shiffrin, R. M. (1984). A retrieval model for both recognition and recall. *Psychological Review, 91,* 1–67.

Gronlund, S. D., & Ratcliff, R. (in press). Analysis of the Hockley and Murdock decision model. *Journal of Mathematical Psychology.*

Hintzman, D. L. (1984). MINERVA 2: A simulation model of human memory. *Behavior Research Methods, Instruments, and Computers, 16,* 96–101.

Hintzman, D. L. (1986). "Schema abstraction" in a multiple-trace memory model. *Psychological Review, 93,* 411–428.

Hintzman, D. L. (1988). Judgments of frequency and recognition memory in a multiple-trace memory model. *Psychological Review, 95,* 528–551.

Hockley, W. E., & Murdock, B. B., Jr. (1987). A decision model for accuracy and response latency in recognition memory. *Psychological Review, 94,* 341–358.

Humphreys, M. S. (1976). Relational information and the context effect in recognition memory. *Memory & Cognition, 4,* 221–232.

Humphreys, M. S. (1978). Item and relational information: A case for context independent retrieval. *Journal of Verbal Learning and Verbal Behavior, 17,* 175–187.

Humphreys, M. S., & Bain, J. D. (1983). Recognition memory: A cue and information analysis. *Memory & Cognition, 11,* 583–600.

Humphreys, M. S., Pike, R., Bain, J. D., & Tehan, G. (1989). Global matching: A comparison of the SAM, MINERVA 2, Matrix, and TODAM models. *Journal of Mathematical Psychology, 33,* 36–67.

Kučera, H., & Francis, W. N. (1967). *Computational analysis of present-day American English.* Providence, RI: Brown University.

Mandler, G. (1980). Recognizing: The judgment of previous occurrence. *Psychological Review, 87,* 252–271.

Murdock, B. B., Jr. (1974). *Human memory: Theory and data.* Hillsdale, NJ: Erlbaum.

Murdock, B. B., Jr. (1982). A theory for the storage and retrieval of item and associative information. *Psychological Review, 89,* 609–626.

Murdock, B. B., Jr. (1987). Serial-order effects in a distributed-memory model. In D. S. Gorfein & R. R. Hoffman (Eds.), *Memory and Learning: The Ebbinghaus Centennial Conference* (pp. 277–310). Hillsdale, NJ: Erlbaum.

Murdock, B. B., Jr., & Walker, J. (1969). Modality effects in free recall. *Journal of Verbal Learning and Verbal Behavior, 8,* 665–676.

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review, 85,* 59–108.

Ratcliff, R. (1980). A note on modeling accumulation of information when the rate of accumulation changes over time. *Journal of Mathematical Psychology, 21,* 178–184.

Ratcliff, R. (1981). A theory of order relations in perceptual matching. *Psychological Review, 88,* 552–572.

Ratcliff, R. (1988). Continuous versus discrete information processing: Modeling accumulation of partial information. *Psychological Review, 95,* 238–255.

Ratcliff, R., & Iverson, G. (1985, August). *Methods for investigating parameter spaces of models.* Paper presented at the 18th annual meetings of the Society of Mathematical Psychology, Chicago, IL.

Ratcliff, R., & McKoon, G. (1982). Speed and accuracy in the processing of false statements about semantic information. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8,* 16–36.

Ratcliff, R., & McKoon, G. (1989). Similarity information versus relational information: Differences in the time course of retrieval. *Cognitive Psychology, 21,* 139–155.

Reed, A. V. (1973). Speed–accuracy trade-off in recognition memory. *Science, 181,* 574–576.

Reed, A. V. (1976). List length and the time course of recognition in immediate memory. *Memory & Cognition, 4,* 16–30.

Tulving, E., & Thomson, D. M. (1973). Encoding specificity and retrieval processes in episodic memory. *Psychological Review, 80,* 352–373.

Wickelgren, W. A., & Corbett, A. T. (1977). Associative interference and retrieval dynamics in yes–no recall and recognition. *Journal of Experimental Psychology: Human Learning and Memory, 3,* 189–202.


Received May 2, 1988
Revision received November 28, 1988
Accepted December 5, 1988 ■