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# Memory for items and associations: Distinct representations and processes in associative recognition

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ABSTRACT

In two experiments, participants studied word pairs and later discriminated old (intact) word pairs from foils, including recombined word pairs and pairs including one or two previously unstudied words. Rather than making old/new memory judgments, they chose one of five responses: (1) Old–Old (original), (2) Old–Old (rearranged), (3) Old–New, (4) New–Old, (5) New–New. To tease apart the effects of item familiarity from those of associative strength, we varied both how many times a specific word-pair was repeated (1 or 5) and how many different word pairs were associated with a given word (1 or 5). Participants could discriminate associative information from item information such that they recognized which word of a foil was new, or whether both were new, as well as discriminating recombined studied words from original pairings. The error and latency data support the view that item and associative information are stored as distinct memory representations and make separate contributions at retrieval.



## Introduction

Memory theorists distinguish between two qualitatively different sources of information underlying the process of recognition (Hockley, 1992; Humphreys, Bain, & Pike, 1989; Kelley & Wixted, 2001; Murdock, 1997; Reder et al., 2000; Yonelinas, 1997). Memory for associative information, such as the co-occurrence of two words, can be distinguished from memory for the individual items (for reviews, see Clark & Gronlund, 1996; Raaijmakers & Shiffrin, 1992; Yonelinas, 2002). However, memory theorists differ with respect to just how item information and associative information are represented in memory and how each contributes to decision-making in the recognition of word pairs. One controversy is whether associative information is stored separately from item information or is stored in common with item information (Gillund & Shiffrin, 1984; Hintzman, 1988; Hockley, 1991, 1992; Murdock, 1993). A second core issue is how item and associative information are accessed and utilized in subsequent decision-making during recognition. The research reported in this article addresses these two issues.

### *The representation of item and associative information in associative recognition*

Global models of associative recognition, such as REM (Shiffrin & Steyvers, 1997), TODAM (Murdock, 1997), MINERVA II (Hintzman, 1984, 1988), and Matrix (Humphreys et al., 1989), assume that item and associative information are inseparable and are stored as part of a common memory system, whereas local models such as SAC (Reder et al., 2000) assume that associative information is represented separately from item information. In associative recognition, the REM, TODAM and Matrix models use similar mathematical operations to represent associative information as a conjoined representation of two sets of item features—either a concatenation (REM), convolution (TODAM), or tensor product (Matrix) of two item vectors. Local models, in contrast, store item and associative information in separate memory locations. For in-

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stance, the SAC model (Reder et al., 2000) representation of a studied word-pair is explicitly defined by two semantic nodes, one for each word in the pair, with each word node linked to the same episodic node encoding their association—the co-occurrence of both words in a particular study context (see models 4 and 5, Buchler & Reder, 2007, pp. 111–112; Reder, Paynter, Diana, Ngiam, & Dickison, 2007).

In the research reported in this article, we test these assumptions underlying local and global models. If associative information is a product of item information, as assumed by global models, it follows that the strengthening of item information necessitates the strengthening of associative information. However, if item and associative information are stored separately, as assumed by local models, it should be possible through appropriate manipulation of item and pair repetitions to strengthen item information without strengthening associative information.

In our study of word-pair recognition, we use two experimental manipulations—repetition (differential strength of the word pairing) and fan or multiple word-pair associates (differential associative interference)—to further differentiate item and associative sources of information. In two experiments, we manipulated how many times a specific word-pair was repeated and how many different word pairs were associated with a given word to tease apart the effects of item strength from associative strength. If associative information is stored as a conjoined memory representation of item information as assumed by global models, then the memory representation for pairs with multiple overlapping associates should be equivalent in strength to word pairs in which the same word-pair is repeatedly presented. Examples are given in Table 1 (see Fan 5–5 and Rep 5×). In both cases the underlying item strength is identical, and by extension, global matching models predict that the associative strength should be identical as well. In contrast, local models of memory predict that it should be possible to additionally strengthen associative information separately from item information. In this case, repeated word pairs should be better recognized than overlapping word pairs. Although these would seem to be straightforward predictions, we were unable to find any evidence of a test between these competing views. We explicitly confirmed these predictions with a Monte-Carlo simulation of both a global matching model of memory, REM, and a local memory model, SAC. A description of the REM and SAC model mechanics and the results of our Monte-Carlo simulations are provided in the General discussion.

*The use of item and associative information in recognition decision-making*

A second, related issue is whether item and associative sources of information make discrete contributions at retrieval or conversely, whether item and associative information contribute to an aggregate measure of memory strength. This question addresses a critical distinction between two classes of memory decision models—global matching and dual-process. Global matching models (Hintzman, 1988; Humphreys et al., 1989; Murdock, 1997) assume that the retrieval process aggregates item and associative information into a single composite measure of memory strength. Whether a stimulus is called "old" or "new" depends on whether the composite memory score falls either above or below a decision criterion. For instance, Hockley (1991, 1992) conceptualized word-pair recognition as a signal detection process based on a single memory strength statistic, the sum of item information and associative information that must exceed a decision threshold.

In contrast, the dual-process model of Yonelinas (1997, 2002) argues that recognition is not based on memory strength aggregated across sources, but is instead based on the outputs of two separable memory processes, *familiarity* and *recollection* (Mandler, 1980; Reder et al., 2000). The process of *recollection* involves retrieving specific contextual associations (i.e. episodic traces) and the *familiarity* process is based on the general strength of items in memory. *Recollection* is treated as a threshold process that can be distinguished by highly confident recognition and vivid mnemonic detail (for reviews, see Diana, Reder, Arndt, & Park, 2006; Yonelinas, 2002). Whether a stimulus is recognized as "old" or "new" depends on whether either memory process is successful.

Among dual-process models, however, there is no universal agreement on how item and associative sources contribute to an associative recognition judgment. That is, dual-process models all assume an attempt to recollect the association, but offer a number of different characterizations of the familiarity process. Conceptually, a word-pair recognition task has three potentially discrete sources of information—each word in the pair ($word_1$, $word_2$) and the association. All three sources ($word_1$, $word_2$, association) contribute to familiarity in the Kelley and Wixted (2001; Wixted, 2007) model, both item sources contribute to familiarity in the Yonelinas (1997; Yonelinas & Parks 2007) model, and each item can contribute separately in the SAC model (Buchler & Reder, 2007; Reder et al., 2000).

Theoretical treatments of associative recognition generally lump together the two words in the pair as contributing to 'item' information. However, there is evidence that participants are able to accurately make frequency judgments for words and word pairs and thus distinguish the frequency of occurrence of specific item information (each word) and associative information (pairing). Hockley and Cristi (1996) orthogonally varied the study presentation frequency of word pairs and the frequency of the individual items of the pairs across different study pairings. In separate tests, participants were asked to judge the frequency of the word pairs, a word's frequency as an individual item, its frequency as a member of word pairs, and the overall frequency of the word. Each of the four judgments was made with considerable accuracy, indicating that participants can distinguish between item and associative information when the task demands such discrimination.

If participants are able to specifically distinguish the item strength of tested word pairs in the context of an associative recognition judgment, this suggests that multiple sources of information can be queried discretely in memory, including the left and right word. Given the opportunity, participants may be able to distinguish among all sources of information in memory ($word_1$,

**Table 1**
An illustration of word-pair stimulus composition for the study and test phases in relation to the level of fan during study and the stimulus or foil type at test

| Study: condition | Number of stimuli | Study word-pair | Test condition | Level of Fan | # of stimuli | Tested word-pair |
|---|---|---|---|---|---|---|
| Rep 5× | 50 | KEY-BEACH<br>KEY-BEACH<br>KEY-BEACH<br>KEY-BEACH<br>KEY-BEACH | Intact | 1–1 | 10 | KEY-BEACH |
| Fan 1–1 | 30 | CHEMICAL-SMILE | Intact | 1–1 | 10 | CHEMICAL-SMILE |
| | | ENERGY-HOUSING<br>ARTIST-BEAUTY | Rearranged | 1–1 | 10 | ENERGY-BEAUTY |
| | | MOON-FRAME | Item | 1-new | 10 | MOON-SHOT |
| | | | Item | new-1 | 10 | FACULTY-FRAME |
| Fan 1–5 | 20 | SHELTER-PHASE<br>WOOD-PHASE<br>CREDIT-PHASE<br>CIRCLE-PHASE<br>BOTTLE-PHASE | Intact | 1–5 | 10 | SHELTER-PHASE |
| | | JURY-COMMERCE<br>CUTTING-COMMERCE<br>FOREST-COMMERCE<br>TRADITION-COMMERCE<br>RELATIONSHIP-COMMERCE<br>MINE-MESSAGE<br>PERMIT-MESSAGE<br>REALITY-MESSAGE<br>HAT-MESSAGE<br>REFERENCE-MESSAGE | Rearranged | 1–5 | 10 | JURY-MESSAGE |
| Fan 5–1 | 20 | (see Fan 1–5) | Intact | 5–1 | 10 | (see Fan 1–5) |
| | | | Rearranged | 5–1 | 10 | |
| Fan 5–5 | 30 | SOLUTION-SKY<br>TEACHER-SKY<br>VILLAGE-SKY<br>SHOULDER-SKY<br>ENEMY-SKY<br>SOLUTION-MODEL<br>TEACHER-MODEL<br>VILLAGE-MODEL<br>SHOULDER-MODEL<br>ENEMY-MODEL | Intact | 5–5 | 10 | SOLUTION-SKY |
| | | RESOLUTION-BACKGROUND<br>TITLE-BACKGROUND<br>DEVICE-BACKGROUND<br>REGION-BACKGROUND<br>CELL-BACKGROUND | Rearranged | 5–5 | 10 | SOLUTION-BACKGROUND |
| | | | Item | 5-new | 10 | SOLUTION-PARK |
| | | | Item | new-5 | 10 | GAS-BACKGROUND |
| | | | Novel | new-new | 10 | TRIP-CHAIR |
| Total pairs studied: 150 | | | Total pairs tested: 160 | | | |

word$_2$, association). This possibility would support dual-process models such as SAC (Buchler & Reder, 2007; Reder et al., 2000) which assume a local representation and a decision process that differentiates not only the associative information, but also both item sources.

Our approach is twofold as we increase both the specificity of the recognition decision and the number of stimulus-types that the subject has to differentiate. Before describing our experimental paradigm, we introduce our second manipulation, how using multiple foil-types can dissociate the contribution of item and associative information.

*Using multiple foil-types in word-pair recognition*

Word-pair recognition tasks have been used to distinguish the contributions of item and associative sources of information in a recognition judgment. In a typical associative recognition task, participants are required to distinguish previously studied "old" word pairs (KEY-BEACH, CHEMICAL-SMILE) from "new" foil pairs composed of recombined study pairs not paired together during study (KEY-SMILE). Correct identification of previously studied word pairs requires the retrieval of associative information—that two words were presented together during study. Only associative information can be used to distinguish between targets and foils because the foil pairs all involve previously studied words that are combined into new pairings. That is, item information is not diagnostic since all words are equally familiar.

In order to also examine the contribution of item information, Castel and Craik (2003), (see Humphreys, 1976, 1978) presented three different types of word-pair foils in a paired-associate recognition test. Word pairs studied in an initial learning phase are denoted by A–B and C–D, where A, B, C, and D are studied words. In the test phase, participants responded "old" or "new" to four types of word pairs: (a) *intact* pairs (A–B, C–D), (b) *rearranged* pairs (A–D, C–B, with word position in the pair preserved), (c) *item* pairs (A–X, X–D), and (d) *novel* pairs (Y–Z), where X, Y, and Z are new words. The pattern of hits and false alarms helped separate the contributions of item and associative information to word-pair recognition. The discrimination of *intact* from *rearranged* word pairs requires the retrieval of associative information, whereas item information can be used to discriminate between the various types of *item*, and *novel* word-pair foils. Castel and Craik (2003) found that false alarm rates increased with the number of study words reinstated at test, from *novel* pairs (zero), to *item* pairs (one), to *rearranged* pairs (two). They attributed this pattern to differences in accumulated memory strength of the items in the foil word pairs.[1] As discussed below, our research examines the assumption proposed by a number of composite strength accounts (Donaldson, 1996; Dunn, 2004; Hirshman & Master, 1997) that multiple recognition decisions can be assigned by using more than one decision threshold (i.e. low versus high confidence).

### Five-choice paired-associate recognition (5-PAR) task

We provide a fine grain-size for examining the basis of recognition decision-making. Our experimental procedure emphasizes the decision-making aspects of recognition, which we operationally define as the process of assigning test stimuli to response categories. Participants studied word pairs and later discriminated original word pairs from various types of foils including recombined word pairs and foils composed of one or no previously studied words. Instead of old/new memory judgments, they chose one of five responses: (1) Old–Old (original), (2) Old–Old (rearranged), (3) Old–New, (4) New–Old, (5) New–New. This five-choice paired-associate recognition (5-PAR) experimental procedure allowed us to tease apart the contributions of item and associative information to a word-pair recognition decision, and to examine whether participants are able to explicitly dissociate the specific item strengths of the left and right words in the pair, as well as the ability of participants to detect novel stimuli.

Global matching models account for multiple recognition responses, whether the additional specificity of a "remember/know" response (Gardiner & Java, 1991) or confidence level, by specifying response thresholds at gradations of memory strength. For instance, some researchers maintain that the increased specificity of "remember/know" responses indicates low and high levels of confidence in a unitary memory strength statistic and that these responses do not differentiate between the dual-processes of recollection and familiarity (Donaldson, 1996; Dunn, 2004; Hirshman & Master, 1997). It is conceivable that a similar procedure will be used by participants in assigning our 5-PAR responses to the word-pair stimuli. If so, a strong prediction of models assuming composite memory strength is that participants will be unable to differentiate between *item* word pairs with the studied word (A) in the left (A–X) or right position (Y–A) since the overall memory strength is identical. On the other hand, participants may be able to recognize specific item information ($word_1$, $word_2$) and discriminate the separate source contributions of the right and left word in the pair by responding Old–New or New–Old in our 5-PAR task. The 5-PAR decisions will be assessed in response to two experimental manipulations—repetition and multiple word-pair associates (fan)—used to orthogonally vary the item strength of words and the associative strength of studied word pairs.

### The role of associative information in associative recognition

A number of recent findings suggest that prior exposure to associative information can have negative consequences for recognition memory. Ability to retrieve the associative component of the memory trace can be manipulated by presenting pairs that share words with other pairs, such that each word in the pair is also presented in the same left or right position with other words from other pairs (e.g. SOLUTION-SKY, TEACHER-MODEL, SOLUTION-MODEL, TEACHER-SKY). In this example both the left and right words of a pair were studied in exactly two pairs, which we denote as Fan 2–2 after Anderson and Bower (1973) who demonstrated that both error rates and response latencies increase with fan (e.g. Anderson, 1974; Anderson & Lebiere, 1998; Anderson & Reder, 1999; Reder & Anderson, 1980; Reder & Ross, 1981; Sohn, Anderson, Reder, & Goode, 2004), a result ascribed to associative interference. This effect has been modeled by assuming that activation is shared among associated memories and second, that this spreading activation is increasingly diffuse for higher levels of fan. Activation is distributed in proportion to the total number of associations so that with increased fan each association receives a smaller amount of activation, leading to increases in both response latencies and the number of false alarm errors.

Verde (2004) used interference to examine associative recognition and manipulated the fan of the word pairs up to Fan 4–4. Like others (Diana et al., 2006; Reder et al., 2000), Verde found results consistent with associative interference models, such as a diminished ability to discriminate *intact* from *rearranged* pairs. Using remember-know judgments to supplement an 'old' recognition judgment, Verde (2004) found that the proportion of *remember* responses decreased whereas *know* responses increased with fan. *Remember* responses have historically been attributed to associative recollection and *know* responses to item familiarity (see Diana et al., 2006; Hockley & Consoli, 1999). Using that logic, these results suggest that the availability of associative information decreased as a result of the associative interference generated by the fan manipulation.

### The time-course of recognition responses

Recognition models should be able to explain patterns of response times as well as patterns of accuracy. Timing

[1] A slightly different explanation is proposed by multi-trace theorists (see Hintzman, 1988) such that the probability of recognizing at least one of the words increases as more old words are stored as traces in memory.

considerations have generally favored dual-process interpretations because the retrieval of item and associative information has different temporal characteristics. For instance, differential forgetting rates have been found for item (rapid decay) and associative (relatively stable) information (Hockley, 1991). This finding challenges the notion that item and associative information are stored and retrieved as part of the same memory system representation (but see Murdock, 1997). Furthermore, a number of researchers have found that the accuracy of recognizing *rearranged* word pairs varies with response deadlines; as the time allotted for a recognition response is increased, the probability of incorrectly endorsing *rearranged* word-pair foils initially increases and then decreases (Dosher, 1984; Gronlund & Ratcliff, 1989; Hintzman & Curran, 1994; McElree, Dolan, & Jacoby, 1999). That the false acceptance function is initially inflected upward indicates that associative information takes longer to recruit than item information (but see Dewhurst, Holmes, Brandt, & Dean, 2006). In defense of composite strength accounts, it is possible that timing differences reflect differing degrees of completeness of a memory trace, whose gradual accumulation has been curtailed by deadline procedures. That is, the composite strength account may be correct, but for some reason, associative traces take longer to accrue.

We examine decision latencies for the various 5-PAR responses under self-paced conditions when accuracy is stressed. Dual-process models assume that when accuracy is stressed, participants first attempt recollection, which can yield a highly-detailed memory trace and a corresponding high confidence response. If recollection fails, participants can respond based on the familiarity of the word-pair (see Kelley & Wixted, 2003; Yonelinas, 2002). In our 5-PAR task, dual-process models predict dissociation in the timing of the recognition responses based on the type of information retrieved. On the other hand, we hypothesized that if the accumulation of the composite signal is gradual, then we would expect the timing of the various recognition responses to be continuously arrayed as a function of combined item and associative strength. The recognition response should speed up with the strength of the underlying memory trace, being fastest for *intact* studied word pairs, faster for *rearranged* word pairs, and slowest for *item* word pairs. Our analysis of decision latencies should be informative about how information is queried in memory, either *en masse* or as part of a serial retrieval process, or a bit of both.

## Experiment 1

### *Method*

#### *Participants*

Thirty-four participants (14 males), recruited from the Carnegie Mellon University undergraduate community, participated in exchange for $5.

#### *Materials and design*

Table 1 illustrates the different experimental conditions in this within subject design. We varied the fan or number of different pairings associated with a word (either 1 or 5) and orthogonally varied the fan of the left and right words of a pair. During the study phase, this meant that participants were presented with Fan 1–1, Fan 1–5, Fan 5–1, and Fan 5–5 word pairs. Some 1–1 pairs were repeated 5 times (Rep 5×) such that the exact same pair was studied 5×. All other word pairs were studied only once. No pairs involving a Fan 5 word were repeated 5 times. The study phase had a total of 150 word-pair study events and the exact numbers for each type of study pair are given in Table 1.

The recognition test included 160 word pairs that were either reinstated study pairs (*intact*) or were one of three different types of foils: *rearranged, item,* or *novel.* Foil-type was crossed with the repetition and fan manipulation factors with the constraint that rearranged pairs involved reassignment within the same level of fan condition. That is, a Fan 1–5 pair would be rearranged with another Fan 1–5 word-pair. Word position within a pair was always preserved in *rearranged* and *item* foils. New, previously unstudied, words were used in constructing the *item* and *novel* foil stimuli. The recognition test probes were constructed so that all of the previously presented study words were used, either in intact word pairs or in foil stimuli.

Word pairs consisted of two words, each four to 12 characters in length ($M = 6.1$) 18-point font separated by a dash, presented in the center of the computer screen. The assignment of words to conditions (including unstudied) was randomly determined for each participant from a pool of 320 common nouns with word-frequencies (Kucera & Francis, 1967) between 55 and 95 occurrences per million ($M = 71.3$, $SD = 11.8$) generated from the MRC psycholinguistic database (Wilson, 1988). The order of presentation of word pairs and test pairs was also randomly determined for each participant. The dependent measures were proportion of responses and response latencies to each of the 5 response categories: (1) Old–Old (original), (2) Old–Old (rearranged), (3) Old–New, (4) New–Old, and (5) New–New. We focus here on the accuracy data, deferring discussion of the latency data until we have described the results of Experiment 2.

#### *Procedure*

Participants were informed prior to study that some word pairs would be repeated and that some words would be repeatedly presented, but each time with a different associate. During the study phase, word pairs were presented one at a time for 4 s, followed by a 1.5 s delay before the next pair was presented. After study and just prior to the recognition test, participants were told about the five possible response choices and also informed about the different types of foil stimuli. The test phase consisted of 160 test pairs (see Table 1), presented one at a time. The pair remained on the screen until the participant selected one of the five alternatives that were listed in the following order—Old–Old (original), Old–Old (rearranged), Old–New, New–Old, New–New—at the bottom of the screen by pressing one of the five designated keys. The screen cleared after the response and remained blank for .5 s followed by

**Table 2**
Mean proportion of responses to each of the four word-pair types in the word-pair recognition test as a function of the number of associates (fan) for word1 and word2 and whether the pair was repeated in Experiment 1

| Word-pair | Response | | | | |
|---|---|---|---|---|---|
| | Old–Old (Original) | Old–Old (Rearranged) | Old–New | New–Old | New–New |
| *Intact pair* | | | | | |
| Fan 1–1 | **.45** (.09) | .09 (.04) | .09 (.04) | .09 (.03) | .28 (.06) |
| Fan 1–5 | **.44** (.09) | .18 (.05) | .04 (.02) | .25 (.07) | .09 (.06) |
| Fan 5–1 | **.44** (.07) | .17 (.05) | .29 (.07) | .04 (.02) | .06 (.04) |
| Fan 5–5 | **.55** (.09) | .34 (.08) | .03 (.02) | .06 (.03) | .01 (.02) |
| Rep 5× | **.84** (.06) | .06 (.02) | .03 (.02) | .03 (.02) | .02 (.02) |
| *Rearranged pair* | | | | | |
| Fan 1–1 | .06 (.03) | **.24** (.06) | .19 (.04) | .16 (.04) | .34 (.06) |
| Fan 1–5 | .13 (.05) | **.41** (.08) | .03 (.03) | .34 (.07) | .07 (.05) |
| Fan 5–1 | .14 (.05) | **.34** (.07) | .41 (.07) | .04 (.02) | .06 (.03) |
| Fan 5–5 | .32 (.08) | **.54** (.08) | .06 (.03) | .04 (.02) | .04 (.03) |
| *Item pair* | | | | | |
| Fan1-New | .04 (.02) | .12 (.05) | **.29** (.07) | .06 (.03) | .48 (.08) |
| New-Fan1 | .04 (.04) | .09 (.04) | .09 (.04) | **.31** (.07) | .45 (.08) |
| Fan5-New | .04 (.03) | .19 (.06) | **.65** (.09) | .04 (.03) | .09 (.04) |
| New-Fan5 | .08 (.04) | .16 (.05) | .04 (.03) | **.58** (.10) | .13 (.07) |
| *Novel pair* | | | | | |
| New–New | .04 (.02) | .07 (.03) | .10 (.03) | .09 (.03) | **.70** (.09) |

Correct responses are shown in bold. Variability is listed in parentheses as 95% confidence intervals.

a fixation stimulus of two dashed lines for 1 s before the next test trial began.

### Results and discussion

Table 2 lists the proportion of responses to each of the five possible choices for the four different types of test probes: *intact*, *rearranged*, *item*, and *novel* word pairs. Each row represents the mean proportion of responses for each of the five possible responses for one of the fan or repetition conditions for a given type of test probe. Of the five choices of response, each type of test probe had its own correct response that is indicated in Table 2 in bold font. Note that for *item* word pairs, the correct response was either 'Old–New' or 'New–Old' depending on whether the reinstated word was on the left or the right. Visual inspection of the correct responses (and 95% confidence intervals) in Table 2 strongly suggests that participants were able to correctly identify each type of test probe. A level of $p < .05$ was used for all significance tests, unless otherwise noted.

Although the pattern of results in Table 2 strongly suggests that the assignments of correct and incorrect response proportions are not due to chance (see 95% confidence intervals in parentheses), we developed a way to assess the reliability of these numbers. If participants were able to distinguish among the various word-pair types, then the proportion of correct responses should differ reliably from the proportion of responses to *novel* word pairs for that particular response category. That is, we took the proportion of incorrect responses to *novel* word pairs as an estimate of response bias for each response category. This analysis examined the proportion of correct and incorrect responses for stimuli in which words were studied once[2]—the *intact* (Fan 1–1), *rearranged* (Fan 1–1), and *item* (Fan 1-new, new-Fan 1) word-pair types—compared to *novel* (new–new) word pairs. Multiple pairwise comparisons using the Dunnett (1955) procedure established that the proportion of correct responses for each type of word-pair was significantly different from the response bias to *novel* word pairs. All correct responses were significantly different from the response bias to *novel* word pairs.[3] For example, the proportion of hit 'Old–Old (original)' responses to *intact* (Fan 1–1) word pairs ($M = .45$) differed from the proportion of incorrect 'Old–Old (original)' responses to *novel* (new–new) word pairs ($M = .04$). Just as the correct responses were reliably different from the response proportions to novel pairs, the incorrect responses were not. This finding adds more evidence that participants were able to calibrate responses to the various stimuli. For example, the proportion of incorrect 'Old–Old (rearranged)' responses to *intact* (Fan 1–1) word pairs ($M = .09$) did not differ from those to *novel* (new–new) word pairs ($M = .07$).

In summary, the proportion of correct responses was significantly different from baseline for each type of word-pair, whereas the proportions of incorrect responses were not, clearly demonstrating the ability of participants to distinguish among all five word-pair stimulus-types on the recognition test. We now examine the roles of other factors in the study, specifically the effects of associative interference and repetition strengthening on performance,

[2] These differences are even larger when words are repeated in various pairings as a result of the fan manipulation.

[3] As a logical exception, the proportions of 'New–New' responses for *intact, rearranged,* and *item* word pairs were all significantly different ($p < .001$) from the proportion of 'New–New' responses to *novel* word pairs, for which they it constituted a correct response.

and turn to our first question: How are item and associative sources of information represented in memory?

*The representation of item and associative information in memory*

*A discrete strengthening of associative information*

A comparison of Rep 5× and Fan 5–5 word pairs indicates that associative information can be discretely strengthened in memory, as separate from a strengthening of the underlying item memory representation. Repetition was found to increase the availability of associative information, aside from the increased availability of item information. For instance, the fivefold repetition of an *intact* word-pair (Rep 5× condition) resulted in significantly higher proportions of hits [Old–Old (original) responses] than in the *intact* Fan 5–5 condition, $F(1,67) = 25.16$, $MSE = 1.41$. In both cases, each word was studied 5×, so it can be assumed that the underlying strength of the two words was equivalent. Thus, the increase in hit rate observed for *intact* Rep 5× word pairs compared to *intact* Fan 5–5 word pairs was due to increased success in retrieving the association. A key difference was that the same association has been seen 5× in the Rep 5× condition. This result supports a local memory representation (see Fig. 4B), such that item and associative information are discretely stored as separate memory representations. We now examine our second question: How are item and associative information used in recognition decision-making?

*Signal detection analysis of the contribution of associative information to recognition*

In this analysis, we compared 'Old–Old (original)' responses to *intact* and *rearranged* word pairs. Hits were defined as 'Old–Old (original)' responses to *intact* word pairs and false alarms were defined as 'Old–Old (original)' responses to *rearranged* word pairs. We examined whether associative interference impaired the ability of participants to correctly or falsely recognize word pairs. Hits and false alarms were examined as a function of increasing associative interference (i.e. the number of overlapping word pairs)—Fan 1–1, (Fan 1–5, Fan 5–1), and Fan 5–5. Fig. 1A shows a large incremental increase in the proportion of false alarms whereas the proportion of hits increased only for Fan 5–5 pairs. The proportion of hits did not significantly increase across the three levels of the fan manipulation, $F(2,134) = 2.33$, $MSE = 0.15$, but the proportion of false alarms did significantly increase with associative interference, $F(2,134) = 23.38$, $MSE = 0.63$. Unfortunately, this analysis could not be extended to the Rep 5× condition as our design did not include *rearranged* Rep 5× word pairs (but see Experiment 2). A series of contrasts indicated that false alarms increased significantly between the first two levels of the fan manipulation—Fan 1–1 and (Fan 1–5, Fan 5–1)—$F(1,100) = 4.01$, $MSE = 0.11$, but there was no increase in hits, $F(1,100) = 0.04$, $MSE = 0.002$. However, between the last two levels of the fan manipulation—(Fan 1–5, Fan 5–1) and Fan 5–5—significant increases were observed for both the hits, $F(1,100) = 4.38$, $MSE = 0.28$, and the false alarms, $F(1,100) = 30.21$, $MSE = 0.82$. This result

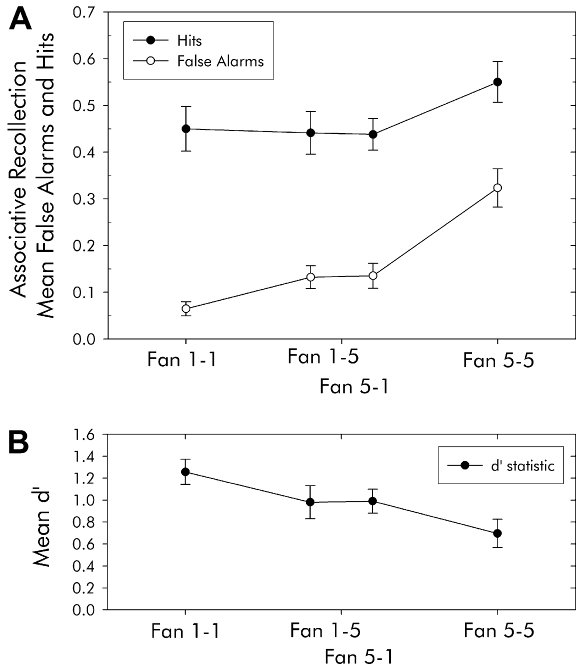


**Fig. 1.** Associative recognition results of Experiment 1. (A) Proportion of 'Old–Old (original)' hit responses to *intact* word pairs and 'Old–Old (original)' false alarm responses to *rearranged* word pairs as a function of associative interference (Fan 1–1, [Fan 1–5, Fan 5–1], Fan 5–5). (B) Mean $d'$ statistic as a function of associative interference (fan). The error bars are standard errors of the mean.

suggests that interference from the fan manipulation may impair the retrieval of associative information, since we did not observe a linear increase in hit rate with pair strength. By contrast, the false alarm rate did increase as a function of word-pair strength.

The false alarm rate in Fig. 1A reflects false 'original' attributions based on the memory strength of the items in the pair. However, the hit rate also includes correct 'original' attributions based on this memory strength of the items in the pair. That is, the false alarm proportion is subsumed in the hit rate, which has the additional contribution of associative information to the recognition process. Thus, the contribution of associative information can be determined by the difference in hits and false alarm rates.[4] We calculated $d'$ (Swets, 1961; Tanner & Swets, 1954), a common statistical expression of signal detection (hits) out of noise (false alarms), to determine the sensitivity of the recognition process to associative information across the fan conditions. As shown in Fig. 1B, $d'$ declined monotonically as a function of increasing associative interference—Fan 1–1, (Fan 1–5, Fan 5–1), and Fan 5–5, $F(2,133) = 4.13$, $MSE = 2.67$.

[4] Alternatively, these data can be expressed as a corrected score by subtracting out *rearranged* false associative recognition values [i.e. 'Old–Old (original)' responses] from the hit rate to *intact* word pairs (see Castel & Craik, 2003). The corrected scores declined significantly ($p < .05$) across the Fan 1–1, (Fan 5–1, Fan 1–5), and Fan 5–5 conditions of: .39 (.05), [.31 (.05), .30 (.04)], and .23 (.04), respectively (with standard errors in parentheses).

*How is item information used in associative recognition?*

Previous studies have shown that repetition increases the 'old' hit rate in 'old'/'new' judgments. The increased specificity of the recognition response in our 5-PAR procedure allows us to examine whether repetition increases the general item strength of a word-pair [Old–Old (rearranged) response] and whether participants are able to make more specific item-based recognition decisions ('Old–New' and 'New–Old' responses). Our analysis used multiple pairwise comparisons with the Tukey–Kramer correction (Kramer, 1956; Tukey, 1953) to examine the response proportions listed in Table 2 across the fan manipulations (i.e. as a function of repetition) for *intact, rearranged*, *item* and *novel* test pairs. For example, for *rearranged* word pairs, we examined the proportions of correct 'Old–Old (rearranged)' responses across the repetition (fan) manipulation (Fan 1–1, Fan 1–5, Fan 5–1, Fan 5–5): 24%, 41%, 34%, 54%.

The results of the multiple pairwise comparisons ($p < .05$) indicate that the underlying memory strength of words increased as a function of repetition, even though in the fan conditions the words were studied each time with a different associate. First, with repetition, participants made fewer incorrect 'New–New' responses and more correct responses. Second, we examined unbalanced word pairs (e.g. Fan 5-new, new-Fan 5, or Fan 1–5, Fan 5–1) where the item strength of the left and right word in the pair were differentially strengthened. Participants were able to correctly identify unbalanced word pairs and assess each word independently by responding 'Old–New' or 'New–Old' to discern the stronger of the two words in the pair. For *item* word pairs, in which the studied word had only been studied in a single pair (i.e. Fan 1-new, new-Fan 1), participants were able to discriminate the position of the new versus old item ('Old–New' or 'New–Old' hit responses, respectively). And, the identification of *item* word pairs was reliably better when the studied word was presented in five different pairings (i.e. Fan5-new, new-Fan5) ($M = .61$ versus .30), $F(2, 133) = 58.05$, $MSE = 3.30$, than Fan1-new, new-Fan1. These results indicate that associative recognition decisions can also involve an independent assessment of the specific item strength of each word in the pair. This result has implications for current memory models which are discussed further below.

Third, the pattern of errors also shows that participants were sensitive to the differential strength of the two words in an unbalanced pair. For example, when participants *missed* recognizing an *intact* pair, they were more likely to assume that the word presented only once was new and to judge the word that was seen 5× as old. As can be seen in Table 2, participants were extremely good at discriminating Fan 5–1 from Fan 1–5 in all types of targets and foils. Further, there was no evidence of bias in tendency to select the right or left member of the word-pair.

These results indicate that associative recognition memory decisions can involve an independent assessment of the specific item strength of each word in the pair. If item-based recognition decisions were based on an aggregation of item information ($\text{word}_1 + \text{word}_2$), without regard to the left or right word source of item familiarity, then we would expect the 'Old–New' and 'New–Old' response proportions to be indistinguishable. Overall, these results also support the conclusion that, in addition to decreasing the availability of associative information, a second effect of the fan manipulation was to increase both item-based [Old–Old (rearranged)] and item-specific (Old–New, New–Old) responding by increasing item strength through stimulus repetition.

## Experiment 2

The results of Experiment 1 raise a number of questions that we addressed in Experiment 2. The results of Experiment 1 suggested that item and associative sources were dissociable as our interference manipulation affected one kind of recognition (association) but not the other (item). Experiment 2 includes *rearranged* Rep 5× word pairs, which were repeatedly presented together five-times during study, but re-paired with another five repetition word as a foil pair for the recognition test. This new condition allows us to obtain a measure of false associative recognition, the proportion of 'Old–Old (original)' response to *rearranged* Rep 5× word pairs.

This condition can critically distinguish between dual-process and composite strength models, which make opposite predictions. Composite strength models assume that 'Old–Old (original)' responses are reserved for word pairs with the highest overall strength. Based on this assumption, *rearranged* Rep 5× word pairs are expected to have a false alarm rate that is similar to *rearranged* Fan 5–5 word pairs, which has equivalent overall item strength. Dual-process models assume that for *rearranged* word pairs, associative information is either not retrieved or, if successfully retrieved, is used to oppose the item strength of the foil pair. Even if this process is only intermittently successful, we would expect the associative false alarm rate to be substantially lower for Rep 5× word pairs compared to Fan 5–5 word pairs, since opponent processing for Rep 5× word pairs benefits from a fivefold strengthening of associative information. It is also possible that these two accounts can be distinguished based on response time. Decision latencies should be prolonged if participants are engaged in opponent processing (i.e. *recall-to-reject* strategy). Thus, the second goal of Experiment 2 was to examine decision latencies for making the various five recognition decisions, which may help inform our earlier findings. For instance, participants were able to dissociate the specific item strengths of the right and left words in the pair by responding 'Old–New' and 'New–Old' in an associative recognition judgment. One possibility is that in response to the task demands, each word is queried in memory after first interrogating the word-pair. In this case, we would expect average decision latencies for response categories pertaining to associative information (i.e. 'Old–Old (original)' and 'Old–Old (rearranged)') to occur before those indicating item information (i.e. 'Old–New' and 'New–Old'). A study of latencies in recognition decision-making allows us to examine this possibility, among others.

## Method

### Participants

Thirty participants (8 males) recruited from the Pitzer College community, participated in exchange for $10.

### Materials and design

The materials and procedures of Experiment 2 were identical to those of Experiment 1 with the exception of the additional foil condition described above: *rearranged* Rep 5×. This necessitated that during study, an additional ten word pairs were repeatedly presented with the same associate 5× each, lengthening the study list to 200 study events. At test, half of the Rep 5× pairs (i.e. 10 of the 20 word pairs) were re-assigned so that a word was presented with another Rep 5× word, preserving their respective left-right positions in the pair. With these additional 10 foils, there were 170 test trials. As in Experiment 1, assignment of words to condition and foil condition and the order of study and test were randomly determined for each participant.

## Results and discussion

The results of Experiment 2 are presented in Table 3 in an analogous fashion to Table 2 for Experiment 1. Table 3 contains one additional row to present the results from the new condition of *rearranged* Rep 5× word pairs.

### The response proportions of Experiment 2 replicate those of Experiment 1

Our initial analysis examined whether the results of Experiment 2 replicated those of Experiment 1. Multiple pairwise comparisons with the Tukey–Kramer correction (Kramer, 1956; Tukey, 1953) compared the corresponding proportions of five-choice responses to each word-pair type from Table 3 (Experiment 2) to those in Table 2 (Experiment 1). All of the response proportions in Experiment 2 closely matched those of Experiment 1. No value listed in Table 3 was significantly different from the corresponding value listed in Table 2. We also replicated prior results by subjecting the data of Experiment 2 to the same set of analyses as in Experiment 1. The pattern of findings were identical at a significance level of $p < .05$. To save space, these results are not reported, but can be obtained upon request to the first author. Below, we examine selected accuracy results and then move on to the latency results of Experiments 1 and 2. First, with the inclusion of *rearranged* Rep 5× word pairs, the results of Experiment 2 bear on the availability of associative information and the nature of false associative recognition. Second, we examine the time-course of associative recognition decision-making.

### Associative attribution errors increase with interference, not memory strength

Our study measured false associative recognition, whereby a participant mistakenly reports that a word-pair was previously associated during study when it was not. For example, this occurs when a participant makes an 'Old–Old (original)' response to a *rearranged* word-pair foil. Experiment 2 included *rearranged* Rep 5× word pairs. Participants correctly identified *intact* Rep 5× word pairs 84% of the time. When these words were reconstituted as part of a *rearranged* word-pair foil, participants false alarmed only 12% of the time. Rep 5× word pairs can be compared to Fan 5–5 word pairs to demonstrate the gains in recognition performance due to associative strengthening. For

**Table 3**

Mean proportion of responses to each of the four word-pair types in the word-pair recognition test as a function of the number of associates (fan) for $word_1$ and $word_2$ and whether the pair was repeated in Experiment 2

| Word-pair | Response | | | | |
|---|---|---|---|---|---|
| | Old–Old (Original) | Old–Old (Rearranged) | Old–New | New–Old | New–New |
| *Intact pair* | | | | | |
| Fan 1–1 | **.45** (.07) | .11 (.05) | .06 (.03) | .10 (.03) | *.28* (.07) |
| Fan 1–5 | **.40** (.07) | .19 (.05) | .04 (.02) | .29 (.06) | *.07* (.05) |
| Fan 5–1 | **.40** (.07) | .19 (.07) | .31 (.06) | .02 (.01) | *.08* (.05) |
| Fan 5–5 | **.53** (.08) | .37 (.07) | .04 (.03) | .05 (.02) | *.01* (.01) |
| Rep 5× | **.84** (.07) | .06 (.03) | .04 (.02) | .03 (.02) | *.03* (.02) |
| *Rearranged pair* | | | | | |
| Fan 1–1 | .06 (.03) | **.20** (.05) | .19 (.04) | .20 (.04) | *.35* (.07) |
| Fan 1–5 | .13 (.04) | **.35** (.08) | .04 (.02) | .42 (.07) | *.07* (.05) |
| Fan 5–1 | .13 (.05) | **.32** (.07) | .45 (.06) | .02 (.01) | *.07* (.03) |
| Fan 5–5 | .26 (.08) | **.61** (.08) | .05 (.03) | .06 (.03) | *.01* (.01) |
| Rep 5× | .12 (.04) | **.53** (.08) | .14 (.04) | .14 (.04) | .08 (.04) |
| *Item pair* | | | | | |
| Fan1-New | .02 (.03) | .08 (.03) | **.29** (.07) | .08 (.02) | *.53* (.08) |
| New-Fan1 | .04 (.03) | .07 (.03) | .06 (.03) | **.31** (.07) | *.52* (.08) |
| Fan5-New | .04 (.03) | .17 (.06) | **.69** (.08) | .02 (.02) | *.08* (.05) |
| New-Fan5 | .07 (.04) | .10 (.04) | .02 (.01) | **.72** (.08) | *.09* (.05) |
| *Novel pair* | | | | | |
| New–New | .01 (.01) | .05 (.02) | .10 (.03) | .10 (.02) | **.74** (.07) |

Correct responses are shown in bold. Variability is listed in parentheses as 95% confidence intervals.

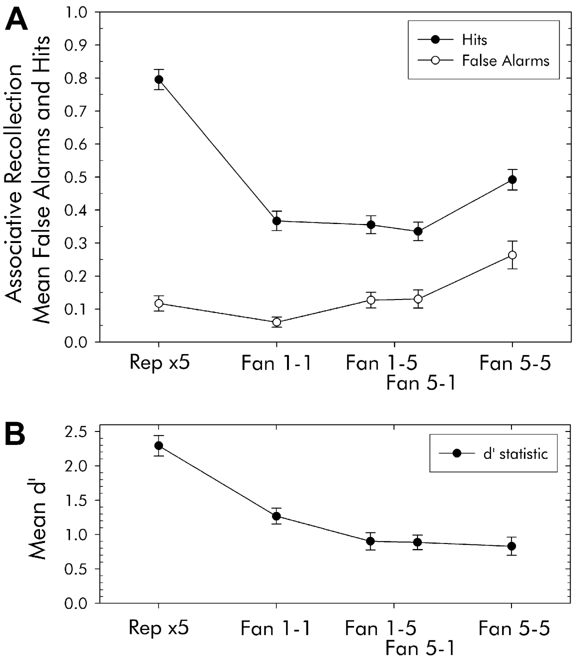


**Fig. 2.** Associative recognition results of Experiment 2. (A) Proportion of 'Old–Old (original)' hit responses to *intact* word pairs and 'Old–Old (original)' false alarm responses to *rearranged* word pairs as a function of associative interference (Rep 5×, Fan 1–1, [Fan 1–5, Fan 5–1], Fan 5–5). (B) Mean $d'$ statistic as a function of associative interference (fan). The error bars are standard errors of the mean.

instance, the hit rate to *intact* Fan 5–5 word pairs was much lower, at 53%, and the false alarm rate to *rearranged* Fan 5–5 word pairs was much higher, at 26%.

The Experiment 2 results are presented in Fig. 2B.[5] The mean $d'$ statistic for the Rep 5× word pairs was 2.29 with a standard error of 0.15. Contrasts of the $d'$ statistic demonstrated that participants were better able to discriminate the Rep 5× word pairs than either Fan 1–1 word pairs, $F(1,59) = 32.64$, $MSE = 15.72$, or Fan 5–5 word pairs, $F(1,59) = 66.47$, $MSE = 32.02$. It is evident in Fig. 2A that the hits to Rep 5× word pairs were much higher than the hits to both the Fan 1–1 word pairs, $F(1,59) = 49.65$, $MSE = 2.32$, and the Fan 5–5 word pairs, $F(1,59) = 30.84$, $MSE = 1.44$. Participants made fewer false alarms to Rep 5× word pairs than Fan 5–5 word pairs, $F(1,59) = 14.08$, $MSE = 0.32$, but made about the same number of false alarms in the Fan 1–1 and Rep 5× conditions, $F(1,59) = 2.10$, $MSE = 0.05$. Constancy in false alarms across repetition conditions has been previously reported (e.g. Kelley & Wixted, 2001; Light, Patterson, Chung, & Healy, 2004; but see Malmberg & Xu, 2006).

False associative recognition was found to increase with associative interference (see 'false alarms' in Fig. 2A) or the number of overlapping associates paired with a given word. Words studied with many different associates were more likely to be falsely judged as part of an intact word-pair, an effect that increased with the number of associates (fan). By comparison, participants demonstrated little false associative recognition when the same association was strengthened five-times by repetition (i.e. Rep 5× word pairs). This result discounts the possibility that false associative recognition is based only on item strength. If this were the case then the proportions of false associative recognition would be equivalent in the Fan 5–5 and Rep 5× conditions. A key difference between the conditions was that the recognition of Fan 5–5 word pairs was subject to associative interference but not Rep 5× word pairs.

As noted above, the Fan 1–1 and Rep 5× word-pair conditions had equivalent false alarms, whether one association was presented or the same association was presented 5×. This result supports the conclusion that false associative recognition is determined in part by the number of available associations (see also Malmberg & Xu, 2006). This suggests that for *rearranged* word pairs, participants retrieved an associate, but perhaps not the correct one. Retrieving the correct associate would allow participants to use a *recall-to-reject* strategy to correctly identify and not falsely associate a *rearranged* word-pair foil. It is likely that false associative recognition involves retrieving the wrong associate, a point we return to later.

### *An analysis of decision latency in associative recognition*

The times taken to make the five types of recognition judgments were examined in response to the recognition test probes (intact, rearranged, item, novel) across the fan manipulation test conditions. The mean median response latencies are displayed in Fig. 3 for correct responses across both Experiments 1 and 2. The patterns of latency data across Experiments 1 and 2 were identical for the conditions shared by the two studies, which justifies an aggregation of the data to reduce standard errors. Because the Rep 5× rearranged lures were present only in Experiment 2, no aggregation was possible for these items and, not surprisingly, the error bars are larger for this Experiment 2 condition.

There was a clear ordering in the time taken to make various types of recognition decisions across the test conditions: Old–Old (original) < New–New < Old–Old (rearranged) < Old–New ≈ New–Old. Participants were fastest at deciding whether the words were previously associated. Participants were also fast at assessing novelty when neither word of the pair was familiar. This novelty detection occurred more rapidly than deciding that the words were both old but not studied together. They were slowest when one word was old and one word was new. One striking finding was the speed of the novelty response. This finding is consistent with two standard accounts of choice RT (see Ratcliff, 1978)—random walk models and diffusion models—that predict fast responses for response categories that are at extreme values (i.e. 'New–New' and 'Old–Old (original)' responses) rather than at an intermediate level of evidence.[6] Furthermore, it is possible that participants could

[5] Alternatively, these data can be expressed as a corrected score by subtracting out *rearranged* false associative recognition values [i.e. 'Old–Old (original)' responses] from the hit rate to *intact* word pairs (see Castel & Craik, 2003). The corrected scores declined significantly ($p < .05$) across the Rep×5, Fan 1–1, (Fan 5–1, Fan 1–5), and Fan 5–5 conditions of: .73 (.04), .39 (.04), [.28 (.04), .28 (.03)], and .27 (.04), respectively (with standard errors in parentheses).

[6] We thank Reviewer 3 for pointing this out to us.

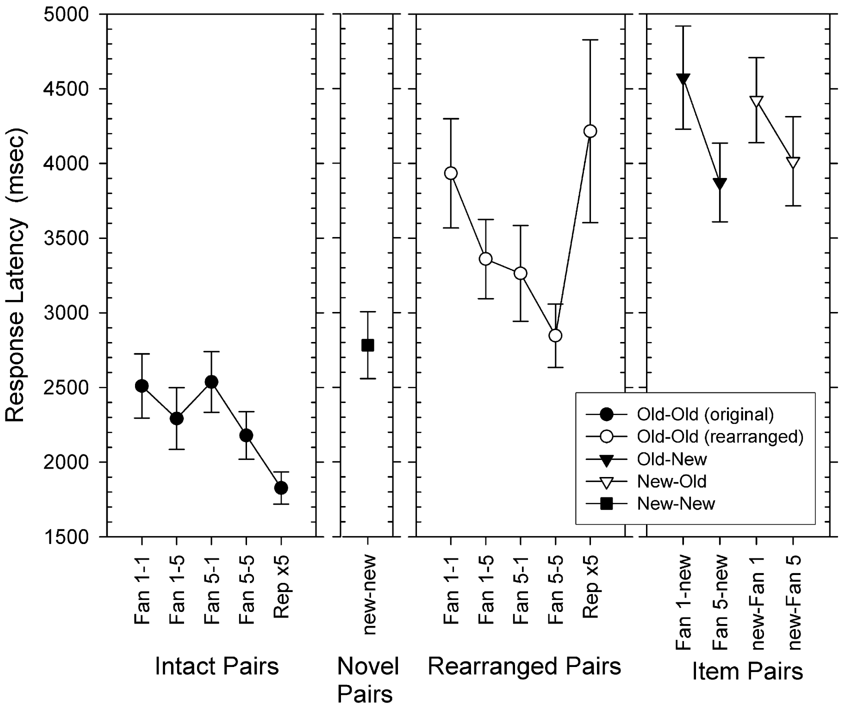


**Fig. 3.** Mean median response latency for correct responses to intact, novel, rearranged, and item tested word pairs. Variability is shown as 95% confidence intervals.

more quickly decide 'new–new' based on low item strength than 'Old–Old (rearranged)' based on high item strength: Only if the words seem familiar would a search be initiated to see whether they were associated. The overall ordering of the time taken to make the various types of recognition decisions was also maintained for all incorrect responses (not shown) across all of the test conditions.[7] See the appendix for the full tabulation of correct and incorrect RT data. As shown in Fig. 3, RTs generally sped up with the repetition manipulation.[8] For intact test pairs, there was marginal speedup in correctly identifying previously associated study pairs across the three levels of fan repetition (Fan 1–1, [Fan 1–5, Fan 5–1], Fan 5–5), $F(2,246) = 2.16$, $MSE = 1880405$. Associative strengthening significantly sped up recognition as participants were faster at correctly identifying intact Rep 5× word pairs than Fan 5–5 word pairs, of equivalent item strength, $F(1,125) = 5.16$, $MSE = 39134371$.

For rearranged test pairs, the pattern of results was different. There was a marked decrease in the time taken to correctly identify rearranged study pairs across the repetition (Fan 1–1, [Fan 1–5, Fan 5–1], Fan 5–5) conditions, $F(3,232) = 6.44$, $MSE = 11547132$. This was not the case, however, for the rearranged Rep 5× test pairs. Compared to the Fan 5–5 condition, which has equivalent item strength, the identification of Rep 5× word pairs was considerably slower, $F(3,232) = 6.44$, $MSE = 11547132$, and less error prone. We take this dramatic reversal as compelling evidence that participants are using opponent processing—a *recall-to-reject* strategy—to correctly classify these responses. When we consider the prolonged decision latencies to *rearranged* Rep 5× foil pairs, it is clear that participants are able to use associative information to effectively reject some foils, such as *rearranged* Rep 5× word pairs, but not others, such as Fan 5–5 pairs. This phenomenon solidifies the case for a dual-process interpretation of our data.

For the item pairs, either the left or the right word was strengthened 5× and paired with a novel word. The recognition latencies of item test pairs improved with the fivefold strengthening of the item, for the left word, $F(1,122) = 7.41$, $MSE = 15280304$, but only marginally so for the right word, $F(1,117) = 2.71$, $MSE = 4957994$. It is possible that this last latency result reflects the sequential reading of the words from left to right in a test pair.

## General discussion

In two experiments, our results demonstrate that associative-recognition makes use of three discrete sources of information—word$_1$, word$_2$, association—each of which could be distinguished at test, especially if they were selectively strengthened during the study period. Participants

[7] A series of pair-wise contrasts across the latency orderings of the correct as well as incorrect recognition decisions also established this pattern within test pairs. For example, for intact Fan 1–1 word pairs, correct 'Old–Old (original)' decisions were significantly ($p < .05$) faster than incorrect 'New–New' responses, which were significantly faster ($p < .001$) than incorrect 'item' (Old–New, New–Old) responses. The incorrect 'Old–Old (rearranged)' responses fell in between the 'New–New' and 'item' responses. This pattern was more difficult to establish within other test pair conditions since a less even distribution of responses across the five choices led to sparse response cells.

[8] This finding should be tempered by the increasing error rates, which suggests a speed/accuracy tradeoff.

were able to accurately distinguish source contributions ($word_1$, $word_2$, association) by selecting among five recognition responses: (1) Old–Old (original), (2) Old–Old (rearranged), (3) Old–New, (4) New–Old, and (5) New–New. Participants recognized studied word pairs (*intact* pairs) and three types of foils composed of two (*rearranged* pairs), one (*item* pairs), or no (*novel* pairs) previously studied words by choosing the correct five-choice recognition response to each type of word-pair. The retrieval of associative information was necessary to distinguish *intact* pairs from *rearranged* pair foils. And the discrimination of various word-pair foils required that participants separately consider the item strength of each word in the pair. Furthermore, our latency results demonstrate that there is a specific time-course for making various recognition decisions.

We were able to further dissociate item strength from associative strength by manipulating how many times a specific word or word-pair was repeated (1 or 5) and how many different word pairs were associated with a given word (1 or 5). Generally, as a result of our fivefold repetition of words and associations, participants were increasingly able to distinguish among the item and associative sources. In particular, we found that the association could be strengthened separately from the items, and this produced a corresponding increase in the retrieval of the association. Item information could also be distinguished in unbalanced word pairs, in which the right or left word was differentially strengthened. Participants were able to discern the stronger word in the pair. These results suggest that item and associative sources of information are stored as part of separate memory representations, as each can be discretely strengthened and retrieved.

In the associative interference conditions, one or both words in a word-pair were studied 5×, each time with a different associate. The results of the associative interference (fan) manipulation suggest that item and associative sources of information also make separate contributions at retrieval. This was demonstrated by an associative interference manipulation that adversely affected the retrieval of one kind of information (i.e. association) but not the other (i.e. item). Associative interference decreased the retrieval of the association, which was necessary for identifying *intact* word pairs, and also increased the tendency to make errors. In some cases, participants incorrectly responded that *rearranged* word-pair foils were previously studied when they were not. This increase in false associative recognition was not due to the underlying item strength of the two words in the pair (but see Kelley & Wixted, 2001). For instance, although item strength was identical in *rearranged* Rep 5× and Fan 5–5 word pairs, participants were much more likely to incorrectly associate word pairs in the interference Fan 5–5 condition. A second effect of associative interference was to strengthen items as a function of how often a given word was repeated. These two results replicate the work of Verde (2004) who demonstrated that associative interference generates opposing effects on remember and know (R/K) judgments: a decrease in the number of 'remember' responses but an increase in the number of 'know' responses. As R/K responses have been found to correspond to the dual-processes of recollection and familiarity (e.g. Hockley & Consoli, 1999), Verde's results suggest that associative interference decreases recollection and increases familiarity-based responding.

*Simulations of local and global matching models of associative recognition*

A major theoretical advance in our understanding of human memory has been the development and refinement of formalized models. Given both the complexity of the decision-making in our 5-PAR dataset and the fact that models can sometimes make surprising and counter-intuitive claims, the implications of these findings will not be fully realized until formal models are fit to the full 5-PAR dataset, something that is beyond the scope of our project. As a first step, however, we derived model predictions from Monte-Carlo simulations of both a global matching model of memory, REM (Steyvers & Shiffrin, 1997), and a local memory model, SAC (Reder et al., 2000). Our simulation focused on the key comparison between two conditions, the Rep 5× and Fan 5–5 pairs.

The mechanics of the REM model are described in Fig. 4A. Item information is represented as a vector of feature weights arbitrarily pulled from a geometric distribution. During encoding, a subset of these features (i.e. nonzero weights) is successfully transcribed to a memory representation of the item, but the model also allows for transcription errors (see each item feature in last position in A1). With repetition, more and more features are correctly transcribed to the item memory representation (see A2 and A3). Associative information is represented as two conjoined item vectors, and it can be seen in Fig. 4A that the REM model produces identical item and associative information for Rep 5× and Fan 5–5 word pairs. However, memory decisions in global matching models such as REM are based on an overall familiarity value (i.e. Bayesian likelihood) obtained by comparing the test item to the *entire* contents of a memory array. Thus, although the item and associative memory representations are identical for Rep 5× and Fan 5–5 word pairs, our modeling efforts suggest that the REM model predicts a higher hit rate for Fan 5–5 word pairs since the overlap with other word pairs on the list results in higher familiarity (i.e. likelihood) values. Specifically, the Monte-Carlo simulation[9] compared the Fan 5–5 and Rep 5× test probes when the list contained 24 word pairs that had been studied once. The predicted hit rate, the proportion of target pairs above threshold ($\Phi > 1$), was equivalent for Fan 5–5 word pairs (49%) and Rep 5× word pairs (48%). This simulation result suggests that the model representations of associative information is similar in both

[9] The REM model (Shiffrin & Steyvers, 1997) parameters used for this Monte Carlo simulation (5000 subjects) are $w = 20$, $c = 0.7$, $g = 0.4$, $u^* = .04$, old–new criterion = 1.0. The hit rate reflects the proportion of target item (one for each subject) likelihood values that were above the old–new criterion ($\Phi_j > 1$). Our efforts were focused on evaluating the mechanics of the model, so the exact hit rates are somewhat arbitrary, especially because the parameter values were adopted 'whole cloth' from previously published REM models that successfully simulated a variety of episodic memory phenomena (e.g. Criss & Shiffrin, 2004; Xu & Malmberg, 2007). All REM model parameters were fixed.

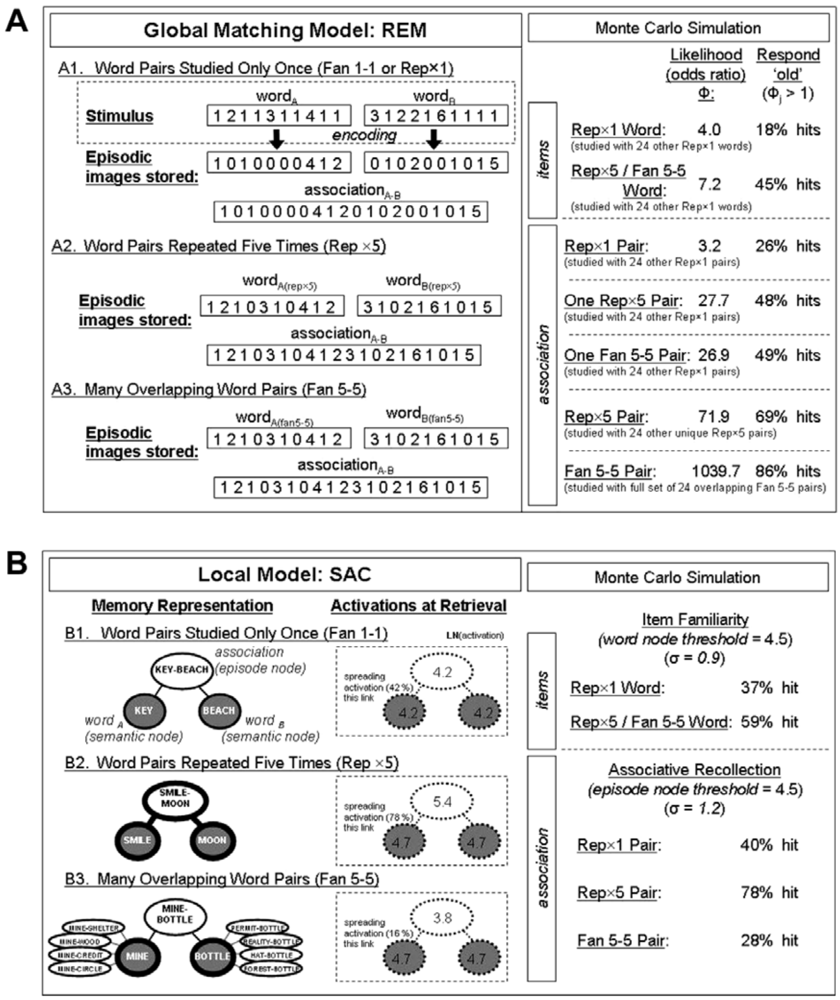


**Fig. 4.** Schematic description of a candidate global model, REM (A) and a local model SAC (B) of associative recognition. Leftmost section headers delineate the memory representations of item and associative information for three classes studied word pairs (Fan 1–1, Rep 5×, and Fan 5–5) in the REM (Sections A1, A2, A3) and SAC (Sections B1, B2, B3) models. The results of the Monte-Carlo simulation are given on the right.

conditions. Next, we simulated Rep 5× word pairs by examining performance when this target pair was also studied with 24 other unique Rep 5× word pairs. For comparison, we also simulated the recognition of Fan 5–5 word-pairs as these word pairs were studied with the full set of 24 other *overlapping* Fan 5–5 word pairs. The predicted hit rate, was much higher for Fan 5–5 word pairs (86%) than that for Rep 5× word pairs (69%). Therefore, our efforts suggest that the REM model incorrectly predicts a higher hit rate in the Fan 5–5 condition relative to the Rep 5× condition.

In contrast, a Monte-Carlo simulation of the local SAC model generates the desired prediction of a lower hit rate for Fan 5–5 word pairs compared to Rep 5× word pairs. As described below, a key feature of the local SAC model is that it offers a mechanism for generating interference in the retrieval of distinct associative information. Shown in Fig. 4B the SAC model has separate representations of item (semantic nodes) and associative (episodic nodes) information. Model equations (see Reder et al., 2000) are used to calculate the representation of item and associative information, such as the residual and current node activations, number of links, and link strengths. That is, as a starting point, the semantic node activations (and number of links) for item information are based on the reported normative word frequency of occurrence of a particular word in the lexicon (e.g. Kucera & Francis, 1967). When a word-pair is presented at test, activation spreads from the relevant semantic nodes to any linked episodic nodes, and the amount of spreading activation is determined in proportion to the number and strength of the links to other episodic associates. Thus, the amount of spreading activation contributing to an episodic node is much less in the case of Fan 5–5 word pairs (16% spreading activation) than Rep 5× word pairs (78% spreading activation). Memory decisions are determined by two separate processes, whether the distribution of activation of particular semantic nodes (item familiarity) or episode nodes (associative recollection) surpasses a decision threshold. Both the variability of the distributions and the decision threshold are fitted parameters. The SAC model Monte-Carlo simulation was run by calculating the memory representations of words and word pairs randomly generated from our stimulus list. Although the item familiarities for Fan 5–5 and Rep 5× word pairs are identical, the simulation demonstrates that the resulting average activation strength of the association (*episode node*) is much less for Fan 5–5 word pairs. Therefore, the SAC model correctly predicts a lower hit rate for Fan 5–5 word pairs than Rep 5× word pairs. In sum, our Monte-Carlo simulations suggest that two candidate global and local models of memory generate opposite predictions for the hit rate for Fan 5–5 and Rep 5× word pairs. Our goal is not to prove one model correct and another wrong, but rather, to delineate the set of mechanisms necessary to account for this dataset. Toward this end, a more formal and complete analysis of various models on the full 5-PAR dataset is necessary.

To highlight the incremental nature of memory modeling, a dual-process version of the REM model has recently been proposed by Malmberg, Holden, and Shiffrin (2004). Although it is our understanding that this version of the REM model does not change the predictions described above, an additional mechanism is proposed that can account for some aspects of the 5-PAR latency data. When targets and foils are known to be very similar, a secondary recall mechanism is invoked. For instance, Xu and Malmberg (2006) proposed that if the conjoined association vector exceeds threshold ($\Phi > 1$) then specific traces are sampled using a *recall-to-reject* strategy (see discussion below). This account is compatible with the prolonged decision times for our *rearranged* word pairs. However, it is unclear whether this sampling process would also prolong decision times for *intact* word pairs, which our data show to be the fastest. Furthermore, an additional layer of decision-making may be necessary to account for the item-specificity of the recognition response ('old–new', 'new–old') to *item* foil pairs.[10]

*Two separate assessments of item strength*

An important feature of the 5-PAR paradigm is that the task demands require both associative and single-word recognition. In the context of an associative recognition task, participants were able to discern item strength and distinguish the stronger word in the pair. For instance, participants correctly matched unbalanced *item* word pairs (Fan 1-new, new-Fan 1, Fan 5-new, new-Fan 5) with 'Old–New' or 'New–Old' responses. Even *incorrect* responses to unbalanced *intact* and *rearranged* word pairs (Fan 1–5, Fan 5–1), correctly matched the 'Old–New' and 'New–Old' responses to the stronger item in the pair. Clearly, participants separately assessed each word in the pair. Our data set challenges memory models to account for both types of recognition decisions within a single system of mechanisms. This is noteworthy since the associative and single-word recognition literatures have often been treated separately.

Our findings were not anticipated by memory models that aggregate sources of item information, including a number of dual-process models of associative-recognition (Kelley & Wixted, 2001; Yonelinas, 1997; Yonelinas, 2002). All of these models describe the familiarity process as a continuous index of memory strength in which both item sources are pooled in forming a familiarity decision. The familiarity process is successful if this pooled item information surpasses a decision threshold. The item-specificity of our data would seem to be a challenge for models that aggregate item information. As an alternative to item strengthening, multiple-trace models such as MINERVA 2 (Hintzman, 1988) can, in principle, account for the item-specificity observed in our data. In response to a test probe, recognition and frequency judgments are based on the intensity of an 'echo' or a composite response to all the separate item traces stored in memory. Hintzman (1988) maintains that recognition judgments are a special case of memory for frequency. Thus, a forced-choice recognition memory test is simply a frequency-discrimination task. In our task, multiple-trace models could be modified so that if a zero count is retrieved for associative information, then participants could in a second step, assess item frequency of the left and right word in the pair and respond 'Old–Old (rearranged)', 'Old–New', 'New–Old', or 'New–New' (see Hockley & Cristi, 1996).

Although multiple-trace models could account for our item strengthening results by assuming that the likelihood of retrieving one of several traces is higher, we suspect that multiple-trace models would have difficulty reproducing the results of our associative interference manipulation. Multiple-trace models represent associative information as separate traces (Hintzman, 1988) and the availability of associative information is based on a global matching process with the test probe. It is unclear whether increasing the number of associates would interfere with this global match process. Furthermore, associative interference was not evident for Rep 5× word pairs, which would constitute five separate traces, but was evident in the Fan 1–5, Fan 5–1, and Fan 5–5 pairs. To differentiate Rep 5× pairs, our data suggest that the same associative information has to be strengthened.

The global matching model TODAM2 (Murdock, 1993; Murdock, 1997) also offers an alternative explanation for item-specificity. That is, the composite memory trace can be queried using different retrieval cues, for instance, by either an associative cue (as in associative-recognition) or an item cue (as in single-word recognition). It is possible that in response to the demand characteristics of having 'old–new' and 'new–old' as choices in the 5-PAR task, participants query memory using an item cue after querying the associative cue. This explanation is similar to what is proposed by dual-process models, and may serve as a way to bridge these views.

The results support both the representation and decision-making structure of local models such as SAC (Reder et al., 2000) that propose not only that item and associative information are repeatedly strengthened and retrieved as discrete units, but also offer an associative interference mechanism (diffusion of activation) that can account for fan effects. One limitation, however, is that previous SAC models of word recognition do not postulate spurious recollection (but see Reder & Schunn, 1996; Schunn, Reder,

[10] Another alternative would be to try to implement a REM model that permits separate representations of items and associations within the same system with both types of information flexibly contributing to item and associative recognition decisions depending on task demands.

Nhouyvanisvong, Richards, & Stroffolino, 1997 for accounts of spurious feeling-of-knowing judgments, and the analogous implementation of that idea in models described in Reder et al., 2007). Our data clearly indicate that false associative recollection occurs and increases with associative interference generated from the fan manipulation. Currently, the SAC model is being developed to provide an account of false associative recollection whereby the spread of activation in the model is enough to tangentially activate another episode node. We postulate that in the associative interference conditions, it is possible for any of the five episode nodes associated with a given word to get over threshold when lures with that word are presented (see Fig. 4B3).

*Recall-to-reject and false associative recognition*

A number of recent findings from word-pair recognition studies using repetition strengthening and associative interference manipulations are not easily reconciled with the assumption that recognition decisions are based on retrieved composite strength. Repetition can be used to further increase the hit rate and speed of recognizing studied word pairs. The strengthening of word pairs by three, four, or sixfold repetition increased the hit rates in studies of associative recognition (Gallo, Sullivan, Daffner, Schacter, & Budson, 2004; Kelley & Wixted, 2001; Light et al., 2004). A puzzling finding is that while the hit rate increases with repetition, the false alarm rate to *rearranged* word pairs remains constant for young adults. This is inconsistent with the composite strength assumption since the false alarm rate should also increase based on the strength of accumulated evidence. There is general consensus among the study authors that this phenomenon reflects opponent processing, such that associative information is used to *disconfirm* item information by a *recall-to-reject* strategy (Jones & Jacoby, 2001; Kelley & Wixted, 2001; Rotello & Heit, 2000; Rotello, Macmillan, & Van Tassel, 2004; Yonelinas, 1997, 2002). The *recall-to-reject* account proposes that *rearranged* word pairs (KEY-SMILE) are rejected because the correct association (KEY-LAMP or CHEMICAL-SMILE) is retrieved for one of the words in the *rearranged* word-pair. The false alarm rate remains constant because the increase in item strength is offset by increased success in rejecting these word pairs based on associative information. This dual-process account suggests that associative information can be used to reduce memory errors. Our results provided compelling accuracy and latency data to suggest that participants do engage in a *recall-to-reject* strategy to reject rearranged Rep 5× word pairs. However, our results also suggest that participants were not able to effectively use this strategy under our experimental conditions of increasing associative interference (fan).

Why does acceptance of *rearranged* word pairs increase with associative interference? It may be that the sheer number of possible associations that can be retrieved complicates the rejection of word-pair lures. A full disconfirmation involves an exhaustive retrieval of all associates. Objectively, increasing the fan manipulation would increase the chances of retrieving any one of five previously studied associates, which can then be used to disconfirm the lure presented as part of the *rearranged* or *item* word-pair (c.f. Gallo, 2004). Although a number of researchers (e.g. Castel & Craik, 2003; Light et al., 2004) have discussed *recall-to-reject* as retrieval of the correct instance, the problem with a *recall-to-reject* strategy in our associative interference paradigm is that the participant has to retrieve all of the associates. This difficulty was borne out by our results which demonstrated increased false recollection across the levels of fan manipulation. With five different associates during the study phase, retrieving just one of the associations does not disconfirm the lure. It is possible that participants endorsed high-fan word-pair foils based on the retrieval of one or more paired-associates matched with either or both words in the pair.

## Conclusion

Our experimental results and procedures emphasized the decision-making aspects of memory, which we defined as the assignment of test stimuli to one of five recognition response categories. How memory is queried is often constrained by the experimental procedure used in the laboratory (see Orne, 1962). For this reason, methodological advances play an important role in scientific discovery. Our new 5-PAR paradigm offered a rich pattern of results that examined how item and associative sources of information are queried in memory to support recognition decision-making that will help refine and advance current models of associative recognition. The major theoretical contribution of this paper was a clear demonstration that these results cannot be accommodated by a model of association recognition whereby item and associative information are retrieved *en masse*. Our results advance a differentiated account of associative recognition—both in terms of the underlying memory representation and the specificity and timing of the decision-processes that operate upon them. Item (word1, word2) and associative sources of information make distinct contributions at retrieval and are stored as discrete units in memory.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jml.2008.04.001.

## References


Anderson, J. R. (1974). Retrieval of propositional information from long-term memory. *Cognitive Psychology, 6*, 451–474.

Anderson, J. R., & Bower, G. H. (1973). *Human associative memory*. Oxford, England: Winston & Sons.

Anderson, J. R., & Lebiere, C. (Eds.). (1998). *The atomic components of thought*. Mahwah, NJ: Erlbaum.

Anderson, J. R., & Reder, L. M. (1999). The fan effect: New results and new theories. *Journal of Experimental Psychology: General, 128*, 186–197.

Buchler, N. E. G., & Reder, L. M. (2007). Modeling age-related memory deficits: A two-parameter solution. *Psychology and Aging, 22*, 104–121.

Castel, A. D., & Craik, F. I. M. (2003). The effects of aging and divided attention on memory for items and associative information. *Psychology and Aging, 18*, 873–885.

Clark, S. E., & Gronlund, S. D. (1996). Global matching models of recognition memory: How the models match the data. *Psychonomic Bulletin & Review, 3*, 37–60.

Criss, A. H., & Shiffrin, R. M. (2004). Pairs do not suffer interference from other types of pairs or single items in associative recognition. *Memory & Cognition, 32*, 1284–1297.

Dewhurst, S. A., Holmes, S. J., Brandt, K. R., & Dean, G. M. (2005). Measuring the speed of the conscious components of recognition memory: Remembering is faster than knowing. *Consciousness and Cognition, 15*, 147–162.

Diana, R. A., Reder, L. M., Arndt, J., & Park, H. (2006). Models of recognition: A review of arguments in favor of a dual-process account. *Psychonomic Bulletin & Review, 13*, 1–21.

Donaldson, W. (1996). The role of decision processes in remembering and knowing. *Memory & Cognition, 24*, 523–533.

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

Dunn, J. C. (2004). Remember-know: A matter of confidence. *Psychological Review, 111*, 524–542.

Dunnett, C. W. (1955). A multiple comparisons procedure for comparing several treatments with a control. *Journal of the American Statistical Association, 50*, 1096–1121.

Gallo, D. A. (2004). Using recall to reduce false recognition: Diagnostic and disqualifying monitoring. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 30*, 120–128.

Gallo, D. A., Sullivan, A. L., Daffner, K. R., Schacter, D. L., & Budson, A. E. (2004). Associative recognition in Alzheimer's disease: Evidence for impaired recall-to-reject. *Neuropsychology, 18*, 556–563.

Gardiner, J. M., & Java, R. I. (1991). Forgetting in recognition memory with and without recollective experience. *Memory & Cognition, 19*, 617–623.

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

Gronlund, S. D., & Ratcliff, R. (1989). Time course of item and associative information: Implications for global memory models. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 846–858.

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

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

Hintzman, D. L., & Curran, T. (1994). Retrieval dynamics of recognition and frequency judgments: Evidence for separate processes of familiarity and recall. *Journal of Memory and Language, 33*, 1–18.

Hirshman, E., & Master, S. (1997). Modeling the conscious correlates of recognition memory: Reflections on the remember-know paradigm. *Memory & Cognition, 25*, 345–351.

Hockley, W. E. (1991). Recognition memory for item and associative information: A comparison of forgetting rates. In W. E. Hockley & S. Lewandowsky (Eds.), *Relating theory and data: Essays on human memory in honor of Bennett B. Murdock* (pp. 227–248). Mahwah, NJ: Erlbaum.

Hockley, W. E. (1992). Item versus associative information: Further comparisons of forgetting rates. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*, 1321–1330.

Hockley, W. E., & Consoli, A. (1999). Familiarity and recollection in item and associative recognition. *Memory & Cognition, 27*, 657–664.

Hockley, W. E., & Cristi, C. (1996). Tests of the separate retrieval of item and associative information using a frequency-judgment task. *Memory & Cognition, 24*, 796–811.

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., & Pike, R. (1989). Different ways to cue a cohert memory system: A theory for episodic, semantic, and procedural tasks. *Psychological Review, 96*, 208–233.

Jones, T. C., & Jacoby, L. L. (2001). Feature and conjunction errors in recognition memory: Evidence for dual-process theory. *Journal of Memory and Language, 45*, 82–102.

Kelley, R., & Wixted, J. T. (2001). On the nature of associative information in recognition memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 27*, 701–722.

Kramer, C. Y. (1956). Extension of multiple range tests to group means with unequal numbers of replications. *Biometrics, 12*, 309–310.

Kucera, F., & Francis, W. (1967). *Computational analysis of present-day American English*. Providence, RI: Brown University Press.

Light, L. L., Patterson, M. M., Chung, C., & Healy, M. R. (2004). Effects of repetition and response deadline on associative recognition in young and older adults. *Memory & Cognition, 32*, 1182–1193.

Malmberg, K. J., Holden, J. E., & Shiffrin, R. M. (2004). Modeling the effects of repetition, similarity, and normative word frequency on old-new recognition and judgments of frequency. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*, 616–630.

Malmberg, K. J., & Xu, J. (2006). The influence of averaging and noisy decision strategies on the recognition memory ROC. *Psychonomic Bulletin & Review, 13*, 99–105.

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

McElree, B., Dolan, P. O., & Jacoby, L. L. (1999). Isolating the contributions of familiarity and source information to item recognition: A time course analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*, 563–582.

Murdock, B. B. Jr., (1993). TODAM2: A model for the storage and retrieval of item, associative, and serial-order information. *Psychological Review, 100*, 183–203.

Murdock, B. B. Jr., (1997). Context and mediators in a theory of distributed associative memory (TODAM2). *Psychological Review, 104*, 839–862.

Orne, M. T. (1962). On the social psychology of the psychological experiment: With particular reference to demand characteristics and their implications. *American Psychologist, 17*, 776–783.

Raaijmakers, J. G., & Shiffrin, R. M. (1992). Models for recall and recognition. *Annual Review of Psychology, 43*, 205–234.

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

Reder, L. M., & Anderson, J. R. (1980). A partial resolution of the paradox of interference: The role of integrating knowledge. *Cognitive Psychology, 12*, 447–472.

Reder, L. M., Nhouyvanisvong, A., Schunn, C. D., Ayers, M. S., Angstadt, P., & Hiraki, K. (2000). A mechanistic account of the mirror effect for word frequency: A computational model of remember-know judgments in a continuous recognition paradigm. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*, 294–320.

Reder, L. M., Paynter, C., Diana, R. A., Ngiam, J., & Dickison, D. (2007). Experience is a double-edged sword: A computational model of the encoding/retrieval tradeoff with familiarity. In B. Ross & A. S. Benjamin (Eds.), *The psychology of learning and motivation* (pp. 271–312). Academic Press.

Reder, L. M., & Schunn, C. D. (1996). Metacognition does not imply awareness: Strategy choice is governed by implicit learning and memory. In L. M. Reder (Ed.), *Implicit memory and metacognition* (pp. 45–77). Mahwah, N.J: Erlbaum.

Rotello, C. M., & Heit, E. (2000). Associative recognition: A case of recall-to-reject processing. *Memory & Cognition, 28*, 907–922.

Rotello, C. M., Macmillan, N. A., & Van Tassel, G. (2004). Recall-to-reject in recognition: Evidence from ROC curves. *Journal of Memory and Language, 43*, 67–88.

Schunn, C. D., Reder, L. M., Nhouyvanisvong, A., Richards, D. R., & Stroffolino, P. J. (1997). To calculate or not calculate: A source activation confusion (SAC) model of problem-familiarity's role in strategy selection. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*, 1–27.

Shiffrin, R. M., & Steyvers, M. (1997). Model for recognition memory: REM—Retrieving effectively from memory. *Psychonomic Bulletin & Review, 4*, 145–166.

Sohn, M.-H., Anderson, J. R., Reder, L. M., & Goode, A. (2004). Differential fan effect and attentional focus. *Psychonomic Bulletin & Review, 11*, 729–734.

Swets, J. A. (1961). Is there a sensory threshold? *Science, 134*, 168–177.

Tanner, W. P., & Swets, J. A. (1954). A decision-making theory of visual detection. *Psychological Review, 61*, 401–409.

Tukey, J. W. (1953). *The problem of multiple comparisons*. Princeton, NJ: Princeton University Press.

Verde, M. F. (2004). Associative interference in recognition memory: A dual-process account. *Memory & Cognition, 32*, 1273–1283.

Wilson, M. D. (1988). The MRC psycholinguistic database: Machine readable dictionary (version 2). *Behavioural Research Methods, Instruments, & Computers, 20*, 6–11.

Wixted, J. T. (2007). Dual-process theory and signal-detection theory of recognition memory. *Psychological Review, 114*, 152–176.

Xu, J., & Malmberg, K. J. (2007). Modeling the effects of verbal and nonverbal pair strength on associative recognition. *Memory & Cognition, 35*, 526–544.

Yonelinas, A. P. (1997). Recognition memory ROCs for item and associative information: The contribution of recollection and familiarity. *Memory & Cognition, 25*, 747–763.

Yonelinas, A. P. (2002). The nature of recollection and familiarity: A review of 30 years of research. *Journal of Memory and Language, 46*, 441–517.

Yonelinas, A. P., & Parks, C. M. (2007). Receiver operating characteristics (ROCs) in recognition memory: A review. *Psychological Bulletin, 133*, 800–832.