

Associations compete directly in memory

Jeremy B. Caplan, Mayank Rehani and Jennifer C. Andrews

Psychology Department, University of Alberta, Edmonton, AB, Canada

Author Note

Corresponding author: Jeremy B. Caplan, Psychology Department and Centre for Neuroscience, Biological Sciences Building, P217, University of Alberta, Edmonton, AB, T6G 2E9, Canada. [jcaplan@ualberta.ca](mailto:jcaplan@ualberta.ca). +1.780.492.5265. +1.780.492.1768 (fax).

We thank Isabel Lek for help testing participants, and Michael Kahana for valuable feedback on the manuscript. Supported in part by the Natural Sciences and Engineering Research Council of Canada and the Alberta Ingenuity Fund.

## Abstract

Associations are confusable when they share an item. For example, double-function pairs (with the form AB, BC), and are harder to remember than control pairs. Although ambiguous pairs are more difficult on average, it is not clear if memories for associations compete directly with one another (Associative Competition hypothesis), as assumed by models that incorporate associative symmetry (bidirectional associations). Alternatively, associative interference results might be explained away by: 1) Item Suppression hypothesis: competition only between memory for the two target items (A and C are both targets of B); 2) Candidate Competition hypothesis: the cue, (B) retrieves two potential targets, A and C, which compete to be output. These alternative hypotheses could explain previous results in the related, AB/AC learning procedure. Our procedure included a large amount of interference that had to be resolved within a single study set. Participants studied sets of control (single-function) and double-function pairs and were asked to produce one or two associates, respectively, to cue items. Recall of AB and BC were negatively correlated, and could not be explained away by item suppression or competition between simultaneously retrieved candidate items. Thus, competition can occur at the level of representation of associations, regardless of which item is the cue, consistent with associative symmetry.

Associations compete directly in memory

## Introduction

Associations between items can overlap with one another. For example, one might need to learn the word-pair PARENT–MONKEY and another pair, MONKEY–CARPET (Figure 1). Because the two pairs include a common item (MONKEY), to be able to retrieve both associations of MONKEY, this ambiguity must be dealt with. The presence of this kind of associative ambiguity is known to produce associative interference; namely, memory for ambiguous pairs is often worse than memory for unambiguous pairs, both for the kind of pair given in the example, with the relationship AB, BC, known as “double-function” pairs (Primoff, 1938), and for pairs with the relationship AB, AC (Barnes & Underwood, 1959). What is unknown is whether this kind of decrement in memory can be because associative ambiguity causes associations to compete directly with one another (regardless of how each association is tested), a characteristic that is predicted by models that incorporate associative symmetry, as we elaborate below. To understand this, consider what happens when a participant studies a set of double-function and control (“single-function”) pairs (Figure 1), and is tested with MONKEY as a probe and is asked to retrieve both its associates (Figure 3). Suppose we observe that the correlation between recall of PARENT and recall of CARPET, which we refer to as  $Q_{Same-Probe}$ , is negative (a novel result that we shall report in both experiments here), indicating that participants tend to recall PARENT at the expense of CARPET, or vice versa. Three hypotheses could have led one to predict this negative correlation (Table 1), as we elaborate next, before proceeding to lay out how additional tests can disentangle these hypotheses:

**1) Item Suppression hypothesis.** It is possible that, while studying ambiguous pairs such as PARENT–MONKEY and MONKEY–CARPET, in trying to cope with this ambiguity, the participant strengthens the memory of one of the items associated to the shared item (e.g., PARENT) and weakens the other (CARPET), in a way that makes it PARENT generally more available in memory than CARPET (cf. Horowitz, Brown, &

Weissbluth, 1964; Horowitz, Norman, & Day, 1966; Horowitz & Manelis, 1972), regardless of how the item is retrieved. This would make PARENT more likely than CARPET to be produced as a response in the later cued-recall test, but in this view, not because of any difference in memory for the associations, only in the participant's ability to generate the PARENT versus CARPET as a response. Although one could argue whether or not such a mechanism is plausible, it is logically possible, for example, by altering sampling or recovery in the Search of Associative Memory (SAM) terminology (Raaijmakers & Shiffrin, 1981) or redintegration, referring to "clean-up" of retrieved information and comparison to known item (e.g., Hulme et al., 1997; Lewandowsky & Farrell, 2000; Murdock, 1982). Importantly, this hypothesis could explain  $Q_{Same-Probe} < 0$ .

**2) Candidate Competition hypothesis.** As a cue, a double-function item, like MONKEY, can retrieve two candidate items; in this example: PARENT, via the PARENT-MONKEY association, and CARPET, via the MONKEY-CARPET association. Most models assume that, when more than one item is a candidate for retrieval, those items compete to be retrieved (e.g., Luce, 1959). This means that production of one item as a response may be at the expense of the other (McGeoch, 1936). Thus, competition between two candidate responses to a single cue could explain  $Q_{Same-Probe} < 0$ . Note that this hypothesis takes effect only at test, with no assumptions about what happened during study.

**3) Associative Competition hypothesis.** Finally, the two associations being tested in the example, PARENT-MONKEY and MONKEY-CARPET, may compete, either during study or during test or both. During study, for example, if PARENT-MONKEY is learned with a high strength, associative competition might lead to MONKEY-CARPET being learned with a low strength. This leads to the prediction that later, given MONKEY as a cue, recall of PARENT and recall of CARPET will be inversely related—in other words, negatively correlated. Because  $Q_{Same-Probe}$  is a correlation between tests of memory for these two associations, this hypothesis would also lead one to predict  $Q_{Same-Probe} < 0$ .

In the two experiments reported here, we find support for this hypothesis that cannot be explained away by hypotheses 1 and 2. But, even if double-function pairs are treated just the same as single-function pairs during study, models that assume associative symmetry still predict competition at test, which we explain next.

***Associative symmetry weakens both the Item Suppression and Candidate Competition hypotheses.*** “Associative symmetry” (Asch & Ebenholtz, 1962) refers to the empirical finding that cued recall in the forward (given A, recall B) direction is equal in accuracy to cued recall in the backward (given B, recall A) direction (Kahana, 2002), including in double-function lists (Horowitz et al., 1966; Rehani & Caplan, 2011). Moreover, if one tests each pair twice, sometimes forward and sometimes backward, the correlation between forward and backward cued recall is extremely high, suggesting that forward and backward probes test largely the same underlying learning: memory for the pair, independent of which item is designated as cue or target. This high forward–backward correlation has been replicated numerous times in word pairs (Caplan, 2005; Caplan, Glaholt, & McIntosh, 2006; Kahana, 2002; Madan, Glaholt, & Caplan, 2010; Rizzuto & Kahana, 2000, 2001) as well as in our own double-function pair data with directional probes (Rehani & Caplan, 2011). If, in our novel double-function list procedure, forward and backward probes produce nearly perfectly correlated recall, then a negative correlation between memory of two pairs is not (or only minimally) dependent on the identity of the target item. Thus, support for associative symmetry would suggest that a negative value of  $Q_{Same-Probe}$  is unlikely to be completely accounted for by a direct competitive relationship between memory for target items (Item Suppression hypothesis), nor competition between response candidates at retrieval (Candidate Competition hypothesis).

Moreover, models, such as Theory of Distributed Associative Memory (TODAM), that use convolution as the basis of association-memory (Borsellino & Poggio, 1972; Metcalfe Eich, 1982; Murdock, 1982; Plate, 1995), without any modification, would predict a negative correlation between AB and BC, because the convolution operation embodies

associative symmetry— no distinction is made between AB and BA. To see why, assume the model learns a list of three pairs:

$$\mathbf{w} = \gamma_1 \mathbf{a} * \mathbf{b} + \gamma_2 \mathbf{b} * \mathbf{c} + \gamma_3 \mathbf{c} * \mathbf{d} \quad (1)$$

where vectors are set in boldface,  $*$  denotes the convolution operation and  $\gamma$  values denote random encoding strengths (Gaussian-distributed). Probing with B:

$$\mathbf{b} \# \mathbf{w} = (\gamma_1 \mathbf{a} + \gamma_2 \mathbf{c}) \quad (2)$$

where  $\#$  denotes the correlation operation, the approximate inverse of convolution. Thus, both associates are retrieved, but then redintegration must be carried out to deblur to one, and then the other item. If redintegration can be achieved perfectly, there may still be no competition. However, if, as usually assumed (as in the Candidate Competition hypothesis, above), redintegration is competitive, based on relative strength, then the greater the  $\gamma_1/\gamma_2$  ratio, the more likely A is to be recalled at the expense of C. The consequence of this inverse relationship is that  $\mathcal{Q}_{Same-Probe}$ , the correlation between recall of A and recall of C, given B, will be negative.

Such models also predict a negative correlation between AB and BC when they are tested with different cues, as occurs in our procedure. An example is: memory for PARENT–MONKEY when PARENT was given as the probe and MONKEY was the relevant target, and memory for MONKEY–CARPET as measured when MONKEY was given as the probe and CARPET was the relevant target (Figure 3). We call the correlation between such pairs of tests  $\mathcal{Q}_{Distinct-Probe}$ . In TODAM,

$$\mathbf{b} \# \mathbf{w} = (\gamma_1 \mathbf{a} + \gamma_2 \mathbf{c}) \quad (3)$$

$$\mathbf{c} \# \mathbf{w} = (\gamma_2 \mathbf{b} + \gamma_3 \mathbf{d}) \quad (4)$$

Thus, recall of A given B will depend on the ratio  $\gamma_1/\gamma_2$  and recall of B given C will depend on the ratio  $\gamma_2/\gamma_3$ . A high value of  $\gamma_2$  decreases recall probability of A given B but increases recall probability of B given C, hence producing a negative correlation between the two cued recall probes. Because of the additional contribution of the independent variables,  $\gamma_1$  and  $\gamma_3$ , the correlation,  $\mathcal{Q}_{Distinct-Probe}$ , should be closer to zero than  $\mathcal{Q}_{Same-Probe}$ . The same prediction would follow from any model that assumes associative symmetry, the indistinguishability of forward and backward associations (i.e., AB and BA are treated the same). This includes SAM (Gillund & Shiffrin, 1984; Raaijmakers & Shiffrin, 1981), since SAM's item-item association strengths are assumed to be symmetric.

We test for the presence of associative symmetry as follows. Each pair is tested twice. We compute two correlations (Figure 2):  $\mathcal{Q}_{Same}$  is the correlation between tests of a pair in the same direction on both tests (e.g., in Figure 2, BASKET→PEPPER on both tests).  $\mathcal{Q}_{Different}$  is the correlation computed using cases for which a given pair was tested first forward and then backward, or first backward and then forward (e.g., RUBBER→CANDLE on test 1 and RUBBER←CANDLE on test 2). For single-function pairs, direction of test is unambiguous, because each item appears only in one position, the left-hand or right-hand position, and test-direction was manipulated in the design (forward/backward on Test 1 and forward/backward on Test 2 were counterbalanced). For double-function pairs, each cue tests one forward association and one backward association. To compute  $\mathcal{Q}_{Same}$  and  $\mathcal{Q}_{Different}$  for double-function pairs, we computed accuracy for both the corresponding forward and backward associates (ignoring response position) and included all pairings of test 1/test 2 accuracies their corresponding correlation (i.e., forward/forward and backward/backward for  $\mathcal{Q}_{Same}$ ; forward/backward and backward/forward for  $\mathcal{Q}_{Different}$ ). Associative symmetry would be supported if  $\mathcal{Q}_{Different}$  were quite high and close to  $\mathcal{Q}_{Same}$ , which can be viewed as the simple test/re-test correlation.

**Previous findings consistent with associative competition**

In the large literature on AB/AC learning, to test the relationship of AB and AC, the gold standard was the so-called “modified modified free recall” (MMFR) procedure introduced by Barnes and Underwood (1959). In the MMFR test, the participant is given an A item as a probe and asked to produce both associates (B and C), in any order they choose (hence “free”). In MMFR, recall of B and recall of C given A as the cue were found to be statistically independent, a result that was replicated numerous times (e.g., Delprato, 1972; Martin, 1971a, 1971b; Wichawut & Martin, 1971). It was then argued (Hintzman, 1972) that independence was in fact evidence of interference, offset by a positive correlation due to subject variability, a claim that was later supported (Burton, Lek, & Caplan, submitted; Kahana, 2012; Riefer & Batchelder, 1988). Furthermore, Burton et al. (submitted) showed that facilitation between recall of B and C (a truly positive correlation) can also be obtained, particularly with pairs of nouns (see also Bruce & Weaver, 1973; Tulving & Watkins, 1974). Thus, the evidence for an inverse relationship between memory for AB and AC is unclear, and seems at least to vary in sign across participants. However, even if one considers participants with a negative correlation between recall of B and C, in the AB/AC procedure, this could be explained by the Item Suppression hypothesis: it could be the case that the availability of B as a response and the availability of C as a response are inversely related, as a means for the participant to resolve associative ambiguity. The Candidate Competition hypothesis could also explain this negative correlation as due to competition between the two targets, B and C, of the probe item, A (McGeoch, 1933), as implemented in, for example, a model by Chappell and Humphreys (1994), although this was an implementation detail, not a theoretical argument (see also the discussion in Mensink & Raaijmakers, 1988). To our knowledge, it has not been shown that associative competition can be explained away by the Item Suppression and Candidate Competition hypotheses in AB/AC learning.

In a clever variant of AB/AC learning with visual stimuli, Ceraso, Timmerman, and

Velk (1982) posed a similar question as we ask here. They found that recall of A, given B as a cue was nearly as poor as recall of B, given A as the cue. They built upon previous work with the related, AB/CB learning paradigm (Postman, 1971). In AB/CB learning, the targets (B) are ambiguous, but the cues (A and C) are unambiguous. Ceraso et al. (1982) constructed stimuli with three features (standing in for items). Their critical tests were of the memory for the third feature (the feature that was neither cue, nor ambiguous-target feature). Memory for these compound stimuli suffered if they had features in common with other stimuli. However, while mean-accuracy indicates reduced memory, mean-accuracy does not tell us whether this is due to association-specific competition, one association competing with another association due to the fact that they share an item. The findings of Ceraso et al. (1982) therefore leave open the possibility that stimuli that shared features with other stimuli were disadvantaged as a set, not due to specific competition mediated by their shared items. To test for association-specific interference, it is necessary to measure the correlation between recall of one pair and recall of a potentially competing pair.

In previous work (Rehani & Caplan, 2009), we tested for associative competition in the data sets reported by Rehani and Caplan (2011), in which participants studied sets containing both double-function and single-function (control) pairs and were tested with cued recall. In those experiments, cued recall was directional: participants were asked specifically for either the left-hand (given B, recall A) or right-hand (given B, recall C) associate of the cue item; any other response was scored as incorrect. The correlation between recall of overlapping associations (e.g., AB and BC) was negative, and significantly more negative than a control for independence (based on single-function pairs). However, it was possible that these negative correlations were purely because participants could not retrieve within-pair order information, since only one response (in the requested direction) was allowed per cue in those experiments. For this reason, we borrowed from the MMFR procedure (Barnes & Underwood, 1959): participants were given single-item probes and asked to attempt to recall both associates of double-function pairs.

### Distinguishing the three hypotheses

The mechanisms implicated by the three hypotheses are not mutually exclusive, and could very well all be present, contributing jointly to a negative correlation between A and C, given B as the probe:  $\mathcal{Q}_{Same-Probe} < 0$  (Figure 3). We first present the novel finding of  $\mathcal{Q}_{Same-Probe} < 0$ . Then we test whether Item Suppression and Candidate Competition can be ruled out as *complete* accounts of  $\mathcal{Q}_{Same-Probe} < 0$ , which would provide novel support for the presence of direct competition between association-memories. The central tests are summarized in Table 1.

To address Hintzman’s (1972) concern that subject-variability can produce positive correlations which could offset a negative correlation, leading to an illusory independence results (see also Riefer & Batchelder, 1988), we rule out such effects in two ways, as we have done in recent related studies (Burton et al., submitted; Caplan, 2005; Caplan et al., 2006; Madan et al., 2010; Rehani & Caplan, 2011): First, we compute correlations for individual participants before applying statistical tests across participants. This removes all positive correlation due to individual differences. Still, some positive correlation could remain due to variability in memory performance across the multiple study sets in our procedure. We therefore compare  $\mathcal{Q}_{Same-Probe}$  to  $\mathcal{Q}_{Control(within-test)}$  (Figure 2), which is an empirical estimate of the correlation between what should be independent memory retrievals: cued recall of arbitrarily combined pairs of single-function pairs.  $\mathcal{Q}_{Control(within-test)}$  is computed with a bootstrap, examining, for example, the relationship between recalling PIGEON given RIBBON as the probe and recalling CUSTOM given MEADOW as the probe.

***Ruling out the Item Suppression hypothesis.*** The Item Suppression hypothesis would predict that the inverse relationship between the response-probabilities of two items that share a common associate should persist regardless of how the two items are retrieved—even when they are produced in response to different probes and via different associations. In our experimental design, we can find cases for which a pair of targets, B and D, to a given cue, C, are retrieved with different cues (at different times within a single

cued-recall test set); formally: A as a probe for B (retrieved via association A–B) and E as a probe for D (retrieved via association D–E). We correlate recall of B given A as the cue with recall of D given E as the cue, which we refer to as the “Yoked” correlation (Figure 3).

For a concrete example, consider the pairs NEEDLE–PARENT and PARENT–MONKEY.

Their relationship is tested with  $Q_{Same-Probe}$  by examining recall performance when the common item, PARENT is the probe, and the relevant targets are NEEDLE and MONKEY.

Both targets are also tested via completely different associations; for example, accuracy for BEGGAR→NEEDLE and accuracy for CARPET→MONKEY in the example (Figure 3).

$Q_{Yoked}$  measures the correlation between such pairs of tests of items with a common associate, but without using the common associate as the probe. If  $Q_{Yoked} < 0$ , that would suggest that item suppression effects are *present* in our data. To test the Item Suppression hypothesis, that item suppression may explain the entire “Same-Probe” correlation, these two correlations should be equally negative. Thus, if  $Q_{Yoked} > Q_{Same-Probe}$ , Item Suppression would be ruled out as a complete alternative account to Associative Competition.<sup>1</sup>

***Ruling out the Candidate Competition hypothesis and the Item Suppression hypothesis together.*** As already explained, we can test the relationship between AB and BC using such pairs of tests that came from different cues (e.g., memory for PARENT–MONKEY when PARENT was given as the probe and MONKEY was the

---

<sup>1</sup>Note that one could equally conceive of a facilitatory relationship between memory for the two associates of a given item. For example, during study, if PARENT–MONKEY is encoded with high strength, and later, MONKEY–CARPET is presented to the participant, the participant’s ease in retrieving the prior pair associate of MONKEY (PARENT) could have a positive consequence for encoding of the new associate item (CARPET). The critical point, though, is that this would predict a positive correlation between memory for PARENT and memory for CARPET whether tested with a common probe (MONKEY; “Same-Probe” condition in Figure 3) or when tested with different probe items (“Yoked” correlation in Figure 3); thus, this kind of “item facilitation” effect would only weaken any observation of a negative correlation due to associative competition and therefore could not explain away any empirical support for the Associative Competition hypothesis.

relevant target compared to memory for MONKEY–CARPET as measured when MONKEY was given as the probe and CARPET was the relevant target). This relationship, quantified by  $Q_{Distinct-Probe}$ , should be non-significant according to the Candidate Competition hypothesis, because although there may be competition between candidate items in response to both cues, there is no ambiguity problem between the two target items we are comparing. Also note that the Item Suppression hypothesis would also not predict a negative “Distinct-Probe” correlation, since the target items being compared (e.g., MONKEY and CARPET) were never both possible targets of a single cue item; to the contrary, they were studied within the same pair (MONKEY–CARPET). The Associative Competition hypothesis still predicts  $Q_{Distinct-Probe} < 0$  (as well as  $Q_{Distinct-Probe} < Q_{Control(within-test)}$ ). Thus, if  $Q_{Distinct-Probe} > Q_{Same-Probe}$ , that would suggest the presence of competition between candidate items. However, if the  $Q_{Distinct-Probe} < Q_{Control(within-test)}$ , this would rule out the Item Suppression and Candidate Competition hypotheses as a complete alternative account to Associative Competition (Figure 3).

***Retrieval during study: a possible mechanism of associative competition.***

It is plausible that, when a participant encounters a repeated item during study of a given pair, they attempt to retrieve its prior associate (Ceraso et al., 1982). This should produce a pattern of *proactive interference* and *retroactive facilitation*. That is, if we assume that the retrieval attempt shifts study time away from the current double-function pair, a double-function pair studied before any of its overlapping pairs had been presented (e.g., CHERRY-BEGGAR, Figure 1) should be remembered better, on average (due to retrieval during subsequent study), than single-function pairs presented at the same serial position (from different lists). Similarly, if a double-function pair were presented after one of its overlapping pairs (as for NEEDLE–PARENT) or both of its overlapping pairs (as for MONKEY–CARPET) had been studied, this pair should be at a disadvantage, on average, compared to single-function pairs presented at the same serial position. Thus, evidence of

proactive interference along with retroactive facilitation would be consistent with retrieval during study. If the retrieved pair were strong (encoded well), it would presumably be more likely to be retrieved during study of the later overlapping pair, disadvantaging that later pair. Conversely, if the earlier pair is weak, it would be less likely to be retrieved, thus, failing to disrupt study of the current pair. This alone could lead to a negative correlation between overlapping pairs and could be a cause of associative competition as tested by  $Q_{Same-Probe} < 0$  and  $Q_{Distinct-Probe} < 0$ . However, one could just as easily invert this logic if retrieval were deliberate. A strong pair would be more easily, not less easily retrieved than a weak pair. The retrieval of a strong pair may take less time than retrieval (or failure to retrieve) a weak pair. In this way, retrieval of a strong pair could leave more time for study of the current pair, leading to a prediction of a positive correlation, which would act against the negative correlation result we are testing. If, however, retrieval during study produces a negative correlation between memory of overlapping pairs, those effects should depend on how much time the participant has to study each pair.

Experiments 1 and 2 differ in presentation rate, so a comparison between experiments will inform the retrieval-during-study account.

***Bias against producing two responses to a cue.*** We had one final concern: that participants may have a bias against producing two responses to a cue. If participants had even a slight tendency to abort retrieval after making their first recall, that would make recall of the two target items, to some degree, mutually exclusive, which would translate into a negative  $Q_{Same-Probe}$ . We address this possibility in two ways. First, we note that  $Q_{Distinct-Probe}$  does not suffer from this problem; if there is a bias against producing two responses to a single cue, that would only induce a negative correlation between recall of the two target items to that cue.  $Q_{Distinct-Probe}$  instead compares responses given to different cues, so this kind of bias does not apply to  $Q_{Distinct-Probe}$ . Second, Experiment 2 had a faster presentation rate, and consequently, lower probability of recall. If a bias against producing two responses to a cue were contributing to the negative

value of  $Q_{Same-Probe}$ , then in Experiment 2, where lower accuracy means fewer opportunities to produce both responses to a cue,  $Q_{Same-Probe}$  should be less negative. If, on the other hand,  $Q_{Same-Probe}$  is equivalent between the two experiments, that would suggest the effect of this kind of bias is negligible.

### Design of the current study

To be able to carry out all the tests detailed above, we adapted the double-function list procedure (Howard, Jing, Rao, Provyn, & Datey, 2009; Primoff, 1938; Provyn, Sliwinski, & Howard, 2007; Rehani & Caplan, 2011; Slamecka, 1976), as illustrated in Figure 1, in which participants are asked to learn a set of pairs, many of which share a common item. Shared items are members of two pairs in a study set, but always in a different location within each pair (e.g., MONKEY is in the right-hand position in PARENT–MONKEY but in the left-hand position in MONKEY–CARPET). Each pair is presented only once, and unlike most instantiations of the AB/AC procedure, the ambiguous associations are not presented in separate study sets, which should preclude list-context-based strategies participants might use to prevent associations from interfering with one another as has been suggested for AB/AC learning (Martin, 1971b; Underwood & Schulz, 1960; Wang, 1980) and directed forgetting (Sahakyan & Delaney, 2003, 2005; Sahakyan & Kelley, 2002). Participants studied sets of pairs that included both double-function and single-function pairs, and were probed for their memory for the pairs with single-item cues. Adapting the MMFR cueing procedure (Barnes & Underwood, 1959), participants were instructed that if the probe item had been paired with two items, they should try to recall both. Each pair was tested twice, enabling us to test for associative symmetry.

We present data from two experiments, identical in design but differing in presentation rate during study. Experiment 1 used a slow presentation rate (1 pair/5 s), which was slow enough to produce accuracy levels close to mid-range (50%), but also

potentially allowed participants to apply deliberate strategies to overcome associative interference. Experiment 2 used a fast presentation rate (1 pair/2.5 s), which should have made it difficult for participants to apply deliberate anti-interference strategies, and produced lower accuracy levels. To the extent that the same pattern of results is obtained in both experiments, we can infer that the findings do not depend on active application of specific strategies to handle associative interference and this would argue against a simple form of retrieval during study as a major cause of associative competition.

As summarized in Table 1, we look for evidence of associative competition by testing for the following pattern: 1)  $Q_{Same-Probe} < Q_{Control(within-test)}$  to test for the basic empirical result we seek to explain, 2)  $Q_{Different} \simeq Q_{Same} \simeq 1$ , expected based on prior studies (Rehani & Caplan, 2011), which would suggest that the negative correlation from (1) does not depend on probe direction (i.e., which item was the cue and which was the target). 3) A non-negative value of  $Q_{Yoked}$ , not significantly different than  $Q_{Control(within-test)}$ , as well as  $Q_{Yoked} > Q_{Same-Probe}$ , to provide evidence ruling out Item Suppression as a complete account of  $Q_{Same-Probe} < Q_{Control(within-test)}$ , 4)  $Q_{Distinct-Probe} < Q_{Control(within-test)}$ , to test whether the negative correlation predicted by Associative Competition persists when Item Suppression and Candidate Competition accounts are not possible. We also test two ancillary hypotheses: 1) Participants retrieved prior associations (potentially contributing to associative interference effects. 2) Participants are biased against producing two responses to a cue (potentially contributing to negative  $Q_{Same-Probe}$ ).

## Experiment 1

### Methods

**Participants.** Participants ( $N = 57$ ) were recruited from the introductory psychology research participation pool in partial fulfillment of course requirements. Of these, 2 participants were excluded due to floor ( $< 10\%$  mean accuracy across all conditions) performance. No participants were near ceiling performance ( $> 90\%$ ).

**Materials.** Stimuli were 181 two-syllable, six- to seven-letter nouns drawn from the MRC Psycholinguistic Database (Wilson, 1988). Kucera-Francis frequency was constrained 7–52/million and both imageability and concreteness were limited to 240–560/700. Words were paired at random with the restriction that single-function pairs did not share words with other pairs listed and double-function pairs comprised a ring structure (AB, BC, CD, DE, EF, FA) wherein every word was the left-hand member of one pair and the right-hand member of another pair within a study set. Each study set consisted of six single-function pairs and six double-function pairs.

**Procedure.** The experiment was designed and run using the Python experiment programming library, pyEPL (Geller, Schleifer, Sederberg, Jacobs, & Kahana, 2007). The experimental testing session began with a practice set including all experimental phases, as well as more detailed instruction screens, but was not included in the analysis, followed by eight experimental sets, each of which included a study phase, a distractor task and two successive cued recall phases, also separated by a distractor task. At the end of the session, a final free recall test was given, as well as a strategy survey, both not reported here.

*Study phase.* Pairs were presented for study in random order. Each pair was displayed in a horizontal configuration, with the two items separated by a space in the center of the screen. Each pair was displayed for 5000 ms, followed by a 500-ms blank inter-pair interval.

*Distractor phase.* One block of the distractor task consisted of five mathematical equations requiring the addition of three randomly selected digits between 2 and 8, inclusive. Once the equation was presented on the screen, participants were given 5000 ms to type their response, followed by a blank screen for 260 ms.

*Cued recall with successive testing.* Each cued-recall test consisted of a cue word and two response lines (blank lines) in a vertical row, centered on the screen. The cue word remained visible until the trial timed out (maximum of 10 s) or the participant typed “done” on either response line, after which a blank inter-cue interval of 250 ms was displayed. First, the upper of the two response lines was “active.” The participants’

keypresses showed up as letters in the active response field, and backspacing was permitted. To proceed, the participant pressed the ENTER key to submit the response, which remained on the screen until the second response was submitted, and then could not go back. If a response was submitted on the first response line, the second response line became active. If a response was submitted on the second response line, the trial ended and the experiment continued to the next probe. Accuracy was determined by matching the response with stimuli in the word pool. A response was considered correct if it was one of the two responses given, regardless of the other response. For cued recall, participants were instructed to type the word or words that were paired with the cue word, and that if more than one word had been paired with the cue, to attempt to recall both in any order.

In each set of cued recall probes, each single-function pair was tested once, either in the forward (left-hand item given as a cue for the right-hand item) or backward (right-hand item given as a cue for the left-hand item) direction. In the second test set, a single-function pair was either probed in the same direction (forward on both tests or backward on both tests) or in the opposite direction (forward, then backward; or backward, then forward). Each double-function *word* was used as a cue once on test set 1, and then again on test set 2.

## Results and Discussion

**Accuracy.** First we examine accuracy (Table 2) to assess whether or not the presence of associative interference reduces mean levels of performance as has been reported for double-function list learning with directional probes (Howard et al., 2009; Primoff, 1938; Provyn et al., 2007; Rehani & Caplan, 2011; Slamecka, 1976). We conducted a repeated-measures analysis of variance (ANOVA) on accuracy (a response was considered correct regardless of whether it was the first or second response given) with the design **Function**[2](single-function/double-function)  $\times$  **Direction**[2](forward/backward probe)  $\times$  **Test**[2](test 1/test 2). There was a main effect of Test, with slightly greater

accuracy on test 2 than test 1 [ $F(1, 54) = 26.3$ ,  $MSe = 0.003$ ,  $p < 0.001$ ,  $\eta_p^2 = 0.328$ , difference = 0.025]. This small amount of output encoding has been observed in successive testing procedures in the past, but has been shown to exert minimal influence on correlation measures in successive testing (Rizzuto & Kahana, 2001; Sommer, Schoell, & Büchel, 2008). There was a non-significant trend of a main effect of Function [ $F(1, 54) = 3.29$ ,  $MSe = 0.027$ ,  $p < 0.1$ ,  $\eta_p^2 = 0.057$ ] favoring single-function pairs; this non-significance contrasts with prior findings of significantly and substantially reduced memory for double-function pairs with directional probes. However, our procedure is more inclusive than prior double-function list tests, since we ask for both associates to a probe item rather than one specified response; thus, it was expected that the advantage of single-function over double-function pairs would be weakened with our procedure. There are also precedents for MMFR tests of verbal AB/AC pairs producing equivalent or even superior recall probabilities than control pairs (Burton et al., submitted; Bruce & Weaver, 1973; Tulving & Watkins, 1974). The main effect of Direction was not significant, in line with numerous prior findings of symmetry in verbal pairs (Kahana, 2002), including double-function pairs (Horowitz et al., 1966; Rehani & Caplan, 2011). No interactions reached significance.

***Test of retrieval during study.*** To seek signs of the presence of proactive and retroactive interference effects, with particular relevance for the possibility of unlearning and retrieval during study, we asked whether the accuracy of a double-function pair, compared to single-function pairs controlled for serial position, depended on whether the double-function pair was presented before its two overlapping pairs had been studied (“DF (0 prior)”; e.g., CHERRY–BEGGAR in Figure 1), after one of its two overlapping pairs had been studied (“DF (1 prior)”; e.g., CARPET–CHERRY in Figure 1) or after both of its overlapping pairs had been studied (“DF (2 prior)”; e.g., MONKEY–CARPET in Figure 1), for test 1 only. To avoid having too many missing values in the analysis, we carried out the analysis as follows. First, for each double-function pair for each participant, we computed

the difference in accuracy of the pair and the mean accuracy of all the participant's single-function pairs at the same serial position. For each participant, we then computed the average of the latter measure across pairs (thus, each pair, not each serial position, was given equal weighting; in general, middle serial positions are therefore better represented than serial positions at the ends of the list). We then carried out uncorrected (to bias against Type II error) paired-samples t tests amongst these measures. The means  $\pm$  standard errors of DF (0 prior), DF (1 prior) and DF (2 prior) conditions were:  $0.0588 \pm 0.0089$ ,  $-0.0078 \pm 0.0094$  and  $-0.0203 \pm 0.0098$ , respectively. DF (0 prior) was significantly positive [ $t(54) = 6.61$ ,  $p < 10^{-7}$ ], suggesting that pairs presented before any overlapping pairs were *facilitated* on average. This could be due to the repetition of items inducing retrieval during study of later pairs; thus, these retrieved pairs may receive a boost due to additional study time. DF (1 prior) was not significantly different than zero [ $t(54) = -0.82$ ], suggesting that any interference effects were offset (on average) by facilitation effects. DF (2 prior) was significantly negative [ $t(54) = -2.07$ ,  $p < 0.05$ ], suggesting the presence of some proactive interference, but note the very small magnitude of the difference (2% accuracy). DF (0 prior) was significantly more positive than DF (1 prior) [ $t(54) = 5.17$ ,  $p < 10^{-5}$ ] and DF (2 prior) [ $t(54) = 6.08$ ,  $p < 10^{-6}$ ] but DF (1 prior) and DF (2 prior) did not differ significantly [ $t(54) = 1.11$ ]. Thus, there is some evidence that there was retrieval during study, which resulted in some retroactive facilitation and some proactive interference, but both effects were small in magnitude.

### Correlations.

**Control for independence.**  $Q_{Control(within-test)}$  reflects the correlation between what should be independent responses—as independent as possible, while controlling for the correlation due to variability across study sets (Figure 2).  $Q_{Control(within-test)}$  is a bootstrap calculated between pairs of single-function pairs within a given test. For Test 1 and 2,  $Q_{Control(within-test)} = 0.14$  (95% CI=[0.003, 0.263]) and 0.076 (95% CI=[−0.036, 0.185]), respectively (Figure 4a,b). These correlations are positive, as

expected (due to variability across study sets), but are small, and for test 2, non-significant. Thus, by computing the correlation in an unpooled way (correlations computed within participants), we avoided the principal source of positive correlation: subject-variability effects.

***First test of associative interference.*** We next check for the presence of the negative correlation predicted by all three hypotheses,  $\mathcal{Q}_{Same-Probe}$ , the correlation between probability of recalling the two associates to a given double-function probe (Figure 3). This correlation (Figure 4a,b) was substantially and significantly negative both for test 1 ( $\mathcal{Q}_{Same-Probe} = -0.32$ , 95% CI=[-0.42, -0.21]) and test 2 ( $\mathcal{Q}_{Same-Probe} = -0.32$ , 95% CI=[-0.41, -0.22]).  $\mathcal{Q}_{Same-Probe}$  was also significantly more negative than  $\mathcal{Q}_{Control(within-test)}$  both on test 1 ( $t(54) = -5.67$ ,  $p < 0.001$ ) and test 2 ( $t(54) = -5.61$ ,  $p < 0.001$ ). Note that in order to take on a negative value, the underlying negative correlation due to competition would have had to greater than the positive correlation suggested to be present due to “item effects,” variability in how conducive probe items are to forming associations (Hintzman, 1972).

***Test of associative symmetry.*** We next measured the test/re-test correlations to determine whether, in our modified double-function list method, associative symmetry would still hold both for double-function pairs and for the embedded single-function pairs.  $\mathcal{Q}_{Same}$  is the correlation when both tests are of the same single-function pair and are in the same direction (Figure 2) and estimates the highest correlation one could reasonably expect. For single-function pairs,  $\mathcal{Q}_{Same} = 0.99$  (95% CI=[0.99, 0.99]; Figure 5).  $\mathcal{Q}_{Different}$  measures the correlation between forward and backward cued recall (Figure 2), a correlation that typically takes on a very high value (Kahana, 2002). For single-function pairs,  $\mathcal{Q}_{Different} = 0.84$  (95% CI=[0.79, 0.88]). For double-function pairs,  $\mathcal{Q}_{Same} = 0.96$  (95% CI=[0.95, 0.97]) and  $\mathcal{Q}_{Different} = 0.91$  (95% CI=[0.88, 0.93]). Important for laying the groundwork for the associative interference test, the property of associative symmetry (high correlation between forward and backward cued recall) holds for both single- and

double-function pairs, despite the fact that, unlike previous associative-symmetry tests, the successive tests were non-directional (both associates of a probe item were requested).

**Ruling out the Item Suppression hypothesis.**  $\mathcal{Q}_{Yoked}$  (Figure 3) measures the correlation between pairs of target items, A and C, but when retrieved via different, non-overlapping associations, FA and CD. If items are learned in a competitive way in this task,  $\mathcal{Q}_{Yoked}$  would be negative. In contrast, this measure (Figure 4a,b) was not significantly non-zero on both test 1 ( $\mathcal{Q}_{Yoked} = 0.04$ , 95% CI=[−0.0728, 0.1422]) and test 2 ( $\mathcal{Q}_{Yoked} = -0.01$ , 95% CI=[−0.1272, 0.1140]), and both were not significantly different than the control for independence,  $\mathcal{Q}_{Control(within-test)}$  (test 1:  $t(54) = -1.36$ ; test 2:  $t(54) = -0.61$ ,  $p > 0.1$ ) but were significantly more positive than  $\mathcal{Q}_{Same-Probe}$  (test 1:  $t(54) = 4.21$ ,  $p < 0.001$ ; test 2:  $t(54) = 4.62$ ,  $p < 0.0001$ ). Thus, competition between a pair of targets to a given cue is not a plausible alternative interpretation of the negative values of  $\mathcal{Q}_{Same-Probe}$ .

#### *Second test of associative interference, ruling out the Candidate Competition and Item Suppression hypotheses together.*

$\mathcal{Q}_{Distinct-Probe}$  measures the correlation between pairs AB and BC, as tested with different cues (Figure 3). This bypasses the Candidate Competition hypothesis by comparing responses that were given to different probe items, and the Item Suppression Hypothesis by comparing memory for target items that would never have been set in competition with one another. This correlation (Figure 4a,b) was significantly negative for both test 1 ( $\mathcal{Q}_{Distinct-Probe} = -0.11$ , 95% CI=[−0.21, −0.02]) and test 2 ( $\mathcal{Q}_{Distinct-Probe} = -0.21$ , 95% CI=[−0.30, −0.12]), and significantly more negative than the control for independence,  $\mathcal{Q}_{Control(within-test)}$  (Test 1:  $t(54) = -3.36$ ,  $p < 0.01$ ; Test 2:  $t(54) = -4.69$ ,  $p < 0.001$ ). This negative-valued  $\mathcal{Q}_{Distinct-Probe}$  reflects competition between associations that cannot be explained away by the Candidate Competition or Item Suppression hypotheses.

**Test for a bias against producing two responses to a cue.** The  $\mathcal{Q}_{Distinct-Probe} < 0$  result also addresses the concern that participants may have a bias

against producing two responses to a cue. Although the finding of nearly equivalent accuracy for double-function and single-function pairs suggests that participants had little trouble producing more than one response to a cue when appropriate, even a slight such bias might be enough to produce a negative correlation between recall of a pair of targets to a given cue.  $Q_{Distinct-Probe}$  is less negative than  $Q_{Same-Probe}$ , suggesting that there may indeed be a subtle negative-correlation influence of bias against dual-responses (or candidate-item competition). However,  $Q_{Distinct-Probe} < Q_{Control(within-test)}$ , so this sort of bias cannot explain the negative correlation between memory for overlapping associations.

## Experiment 2

The presentation rate in Experiment 1 was kept slow (5 s/pair) in order to ensure mid-range accuracy levels, to facilitate data-analyses. This slow rate means that the finding of nearly equivalent accuracy for single- and double-function pairs might be attributable to participants having plenty of time to study each pair. Experiment 2 simply used a faster presentation rate to make it more difficult for participants to resolve interference during study, to test the generality of the accuracy as well as associative-competition findings in this novel paradigm. In addition, any interference-inducing or interference-resolving processes that occur due to strategies participants apply during study should lead to a difference in the magnitude of  $Q_{Same-Probe}$  and  $Q_{Distinct-Probe}$  across presentation rates.

## Methods

Methods were identical to those used in Experiment 1 except that the presentation rate was faster: each pair was displayed for 2 s, followed by a 500-ms blank inter-pair interval. 61 participants participated and 8 participants were excluded due to floor (< 10% mean accuracy across all conditions) performance.

## Results and Discussion

We carried out the same analyses as for Experiment 1.

**Accuracy.** In a repeated-measures ANOVA on accuracy (Table 2) with the design Function[2](single-function/double-function)  $\times$  Direction[2](forward/backward probe)  $\times$  Test[2](test 1/test 2), there was again a main effect of Test, with slightly greater accuracy on test 2 than test 1 [ $F(1, 52) = 4.22$ ,  $MSe = 0.002$ ,  $p < 0.05$ ,  $\eta_p^2 = 0.075$ , difference = 0.010]. No other main effects were significant. This includes a failure to reject the hypothesis that single- and double-function pairs were recalled with equal probability.

**Test of retrieval during study.** As in Experiment 1, to seek signs of the presence of proactive and retroactive interference effects, we again compared DF (0 prior), DF (1 prior) and DF (2 prior) conditions, relative to single-function accuracy, controlling for serial position, for test 1 only. In this experiment, two participants still had missing values due to chance lack of single-function pairs in all serial positions, so we excluded those two participants from these analyses. The means  $\pm$  standard errors of DF (0 prior), DF (1 prior) and DF (2 prior) conditions were:  $0.0224 \pm 0.0034$ ,  $0.0034 \pm 0.0111$  and  $-0.0092 \pm 0.0093$ , respectively. DF (0 prior) was significantly positive [ $t(50) = 2.76$ ,  $p < 0.01$ ], suggesting that pairs that were studied when no overlapping pairs had yet been presented exhibited retroactive *facilitation* on average. Note that the magnitude of this facilitation is considerably smaller than was found in Experiment 1, which may be because the advantage arises from additional encoding when these pairs are later retrieved during study of overlapping pairs; in Experiment 2, there was less study time per pair, hence less time available for a re-encoding-based facilitation effect. DF (1 prior) was not significantly different than zero [ $t(50) = -0.31$ ], suggesting that any interference effects were offset (on average) by facilitation effects. DF (2 prior) was also non-significant [ $t(50) = -0.99$ ]; thus, in Experiment 2, we failed to find evidence of proactive interference on average. DF (0 prior) was significantly more positive than DF (2 prior) [ $t(50) = 2.56$ ,  $p < 0.05$ ] but not DF (1 prior) [ $t(50) = 1.34$ ], and DF (1 prior) and DF (2 prior) did not differ significantly [ $t(50) = 1.04$ ]. As in Experiment 1, there is some evidence of retrieval during study, resulting in some retroactive facilitation, but this effect was small in magnitude.

### Correlations.

**Control for independence.** For Test 1 (Figure 4c) and 2 (Figure 4d), was  $\mathcal{Q}_{Control(within-test)} = 0.06$  (95% CI=[−0.05, 0.18]) and 0.03 (95% CI=[−0.07, 0.13]), respectively, both positive but small and non-significant.

**First test of associative interference.**  $\mathcal{Q}_{Same-Probe}$  (Figure 4c,d) was substantially and significantly negative both for test 1 ( $\mathcal{Q}_{Same-Probe} = -0.30$ , 95% CI=[−0.41, −0.18]) and test 2 ( $\mathcal{Q}_{Same-Probe} = -0.31$ , 95% CI=[−0.40, −0.20]).  $\mathcal{Q}_{Same-Probe}$  was quite significantly more negative than  $\mathcal{Q}_{Control(within-test)}$  both on test 1 ( $t(52) = -4.07$ ,  $p < 0.001$ ) and test 2 ( $t(52) = -5.54$ ,  $p < 0.0001$ ).

**Test of associative symmetry.** For single-function pairs,  $\mathcal{Q}_{Same} = 0.98$  (95% CI=[0.98, 0.99]; Figure 5). The correlation between forward and backward cued recall on tests 1 and 2, for single-function pairs was  $\mathcal{Q}_{Different} = 0.87$  (95% CI=[0.83, 0.91]). For double-function pairs,  $\mathcal{Q}_{Same} = 0.95$  (95% CI=[0.93, 0.96]) and  $\mathcal{Q}_{Different} = 0.87$  (95% CI=[0.84, 0.90]). Thus, the high correlation between forward and backward cued recall held for this experiment as well as Experiment 1, for both double- and single-function pairs.

**Ruling out the Item Suppression hypothesis.**  $\mathcal{Q}_{Yoked}$  (Figure 4c,d) was non-significant on both test 1 ( $\mathcal{Q}_{Yoked} = -0.08$ , 95% CI=[−0.22, 0.06]) and test 2 ( $\mathcal{Q}_{Yoked} = -0.01$ , 95% CI=[−0.12, 0.13]). Both were not significantly different than the control for independence,  $\mathcal{Q}_{Control(within-test)}$  (test 1:  $t(52) = -1.59$ ; test 2:  $t(52) = -1.08$ ,  $p > 0.1$ ) but were significantly more positive than  $\mathcal{Q}_{Same-Probe}$  [test 1:  $t(52) = 2.51$ ,  $p = < 0.05$ ; test 2:  $t(52) = 2.80$ ,  $p < 0.01$ ]. Thus, Item Suppression is not a tenable alternative interpretation of  $\mathcal{Q}_{Same-Probe} < 0$ .

**Second test of associative interference, ruling out the Candidate Competition and Item Suppression hypotheses together.**  $\mathcal{Q}_{Distinct-Probe}$  (Figure 4c,d) was significantly negative for both test 1 ( $\mathcal{Q}_{Distinct-Probe} = -0.11$ , 95% CI=[−0.20, −0.02]) and test 2 ( $\mathcal{Q}_{Distinct-Probe} = -0.18$ , 95% CI=[−0.27, −0.09]). These

were each significantly more negative than the control for independence,  $\mathcal{Q}_{Control(within-test)}$  (Test 1:  $t(52) = -2.21, p < 0.05$ ; Test 2:  $t(52) = -3.58, p < 0.001$ ), suggesting the presence of associative competition that cannot be explained away by the Item Suppression and Candidate Competition hypotheses.

***Test for a bias against producing two responses to a cue.*** In Experiment 1, we also considered  $\mathcal{Q}_{Distinct-Probe}$  as a way to test for a hypothetical bias participants might have against producing more than one response to a given cue ( $\mathcal{Q}_{Same-Probe}$ ). Comparison of the accuracy data between experiments provides further evidence against the plausibility of this hypothesis. Experiment 2 was designed to reduce overall accuracy levels. Reduced probability of recall of double-function pairs means that there would be a lower likelihood of the participant having both responses available to a given double-function cue. If participants had such a bias, then the greater the accuracy, the more one would expect double-function pairs to be at a disadvantage relative to single-function pairs. Because participants recalled more pairs in Experiment 1 than Experiment 2, we would predict that accuracy as a ratio of double-function to single-function pairs would be lower in Experiment 1 than Experiment 2. Inconsistent with this prediction, the accuracy for double-function pairs is nearly equivalent to accuracy for single-function pairs in both experiments, so this hypothesis is further challenged.

In short, the main difference between the two experiments was the greatly reduced overall accuracy level in Experiment 2. Other effects were similar between experiments.

## General Discussion

Our findings provide the first clear evidence that competition in memory can occur between association-memories directly, and cannot be entirely explained away by alternative accounts. Specifically, two measures ( $\mathcal{Q}_{Same-Probe}$  and  $\mathcal{Q}_{Distinct-Probe}$ ) of the relationship between recall of pairs with a common item, AB and BC revealed significantly

negative correlation values, which were also more negative than the control for independence. This is, to our knowledge, the first published finding of a negative correlation between double-function function pairs, generalizing this kind of associative interference finding from AB/AC learning. Potential alternative causes of these negative correlations—competition between memory for items rather than associations (Item Suppression hypothesis), competition at test between a pair of targets of a given retrieval cue (Candidate Competition hypothesis), and reluctance to recall two responses to a given cue—could not explain the entire negative correlation. This adds to the repertoire of mechanisms that can influence memory for associations sharing a common item, and places constraints on models of association-memory, as discussed below.

### The Item Suppression hypothesis

We considered the possibility that a pair of items associated to a common target might be learned competitively; thus, one item’s representation (as an item, regardless of association-membership) in memory may be made stronger during learning, at the cost of the other item becoming weaker in memory. This kind of mechanism could potentially explain  $Q_{Same-Probe} < 0$ . However, we found no evidence of competition between items without this being mediated by access to their associations (non-significant value of  $Q_{Yoked}$ ). This means that Item Suppression cannot challenge our support for the Associative Competition hypothesis.

This contrasts with retrieval-induced forgetting, a paradigm for which the item-suppression account has received support. Retrieval-induced forgetting is a procedure that starts with pairs that have a potentially competitive relationship (of the form AB, AC), and adds to this retrieval practice of one, but not the other, of a pair of associates. Competitive suppression of the non-practiced associate occurs between items directly (Anderson, 2003; Anderson & Spellman, 1995). Because forgetting-inducing retrieval is carried out only after the initial pairings, which are of the form AB, AC (and sometimes

AD, etc.), are considered to be learned to a high level of accuracy, if AB/AC learning shares characteristics with the double-function paradigm we applied here, then retrieval-induced forgetting effects might be in part mediated by an underlying tendency of AB and AC to compete (Jakab & Raaijmakers, 2009).

### The Candidate Competition hypothesis

We also considered the possibility that  $Q_{Same-Probe} < 0$  could be due to double-function probe items retrieval two candidate items, which then compete during the test phase. We introduced  $Q_{Distinct-Probe}$  as a measure of the relationship between two pairs sharing a common item, but tested in a manner that avoids the effects of competition between target items at time of test.  $Q_{Distinct-Probe}$  was less negative than  $Q_{Same-Probe}$ , which would be consistent with the presence of some competition between candidates at test. This suggests that it is accurate for models to include some level of competition between pairs of associates to a probe item (e.g., Chappell & Humphreys, 1994; Dyne, Humphreys, Bain, & Pike, 1990; Humphreys, Tehan, O'Shea, & Bolland, 2000; Mensink & Raaijmakers, 1988; Tehan, Humphreys, Tolan, & Pitcher, 2004). However, because  $Q_{Distinct-Probe}$  was still significantly negative, this hypothesis cannot challenge the Associative Competition hypothesis.

### Retrieval during study

Associative interference procedures like AB/AC learning and double-function lists, repeat items. It is plausible that the second repetition of an item could induce participants to attempt to retrieve the previous association that involved the repeated item, either voluntarily or not. We found retroactive facilitation, suggestive of retrieval during study. These effects were, however, quite small in magnitude, making it difficult to explain the negative correlation between memory for AB and BC based on competition during study due to retrieval of previously study pairs.

These findings also speak to the earliest theory of associative interference, which could be incorporated into any model, Unlearning Theory (Melton & Irwin, 1940). The proposal was that the earlier pair would need to be unlearned to make way for the new pair, to resolve (or actually, avoid) conflict between the two associations. Unlearning theory would predict direct competition between associations, because the more AB can be unlearned, the better BC can be learned, and vice-versa. This would predict both  $Q_{Same-Probe} < 0$  and  $Q_{Distinct-Probe} < 0$ , but also that the earlier pair is remembered more poorly than the later pair, which was contradicted by the accuracy data in both experiments, adding to the evidence challenging Unlearning Theory (e.g., Barnes & Underwood, 1959; Dyne et al., 1990; Humphreys et al., 2000).

One might alternatively assume that presentation of an item within two different associations somehow confuses participants, reducing the effectiveness with which they encode the second pair containing a given item. Plausible though this is, this account would lead one to expect reduced accuracy on cued recall of double-function compared to single-function pairs; the near-equivalence of accuracy for double-function and single-function pairs casts doubt on this explanation. The small magnitude of proactive interference effects in both experiments also questions the plausibility of this account, particularly since proactive interference effects were non-significant in Experiment 2, which had a faster presentation rate, thus offering participants less time to resolve this hypothetical confusion.

### Bias against producing two responses to a probe

One final potential challenge to the Associative Competition hypothesis that we considered was the possibility that participants were reluctant to give two responses to a probe item. If this were the case, it could easily explain a negative correlation between recall of a pair of associates to the probe item. Such a bias would lead to the prediction that accuracy should be worse for double-function pairs than single-function pairs. In

contrast, accuracy was equivalent, and this held for two presentation rates, suggesting that our participants had no trouble producing two responses when appropriate. Furthermore, in Experiment 2, given the reduced accuracy levels, one would expect this kind of bias to exert a weaker effect on behavior, because the chance that a participant might have access to both associations of a double-function probe should be reduced. However, the values of  $\mathcal{Q}_{Same-Probe}$  and  $\mathcal{Q}_{Distinct-Probe}$  were quite similar between experiments, suggesting that a bias against producing two responses is either nonexistent, or else too small to be relevant for our findings. This also suggests that the finding of  $\mathcal{Q}_{Distinct-Probe} > \mathcal{Q}_{Same-Probe}$  can be considered support for competition between response candidates, as argued earlier in the General Discussion, without being susceptible to an alternate account based on a bias against producing two responses.

### The Associative Competition hypothesis

Having ruled out alternative accounts of  $\mathcal{Q}_{Same-Probe} < 0$  and  $\mathcal{Q}_{Distinct-Probe} < 0$ , we can confirm that associations can compete in memory, independent of how the associations are tested, as foreshadowed by models incorporating associative symmetry. This finding is novel; however, there are a number of ways in which this competitive relationship could materialize.

***Associative symmetry and TODAM.*** As mentioned in the Introduction, models like TODAM incorporate associative symmetry, the equivalence of the forward and backward association in memory for pairs, and the high correlation between accuracy on forward and backward probes. Associative symmetry leads one to predict our central finding: competition between associations, regardless of how each association is tested. The derivations in the introduction also led to the prediction that  $\mathcal{Q}_{Distinct-Probe}$  should be closer to zero than  $\mathcal{Q}_{Same-Probe}$ , which we found. Associative symmetry has received considerable prior support. All models of association-memory may therefore need to incorporate this property. With our novel procedure, we again replicated both

characteristics of associative symmetry. Even a model that has the freedom to operate asymmetrically, with independent forward and backward association strengths, may be constrained to embody associative symmetry, and it may turn out that the extension of an asymmetric model to accommodate data speaking to associative symmetry (Caplan, 2004, 2005; Caplan et al., 2006; Kahana, 2002; Rehani & Caplan, 2011; Rizzuto & Kahana, 2000, 2001) is sufficient to predict both  $Q_{Same-Probe} < 0$  and  $Q_{Distinct-Probe} < 0$  with no need to assume any special processes for double-function pairs at study or test.

**Matrix models.** Many models of association-memory are based on the matrix outer-product between a pair of items, and matrix outer product is at the core of Hebb's learning rule, which is common in artificial neural networks (Anderson, 1970; Humphreys, Bain, & Pike, 1989). The matrix outer product, however, is asymmetric—there is a strict distinction between the left- and right-handed items in the outer-product (just as in a heteroassociative neural network, there is typically a distinction between the “input” layer and the “output” layer). Asymmetric models should predict independence between memory for AB and BC, since during encoding, these are perfectly dissimilar, and at retrieval, the model would cue memory in two distinct, unconfusable steps, in the forward and backward directions. That is, in these models, one can only probe with the left-hand item or with the right-hand item in a given retrieval step. An item, A, placed in the left-hand position has zero similarity (and thus, no confusability) with the same item, A, placed in the right-hand position. If an asymmetric model could simultaneously probe memory in the forward and backward direction, it could produce  $Q_{Same-Probe} < 0$ , simply based on competition during retrieval, because each probe has two possible associates (Candidate Competition hypothesis). This kind of model would, however, predict  $Q_{Distinct-Probe} = 0$  (independence), because, although there may be competition in response to a single probe, there should be no competition between items responded to different probes. This kind of model could be amended, as was suggested previously (Caplan, 2004, 2005; Pike, 1984; Rehani & Caplan, 2011; Kahana, 2002; Rizzuto & Kahana, 2000, 2001)

by making the forward and backward associations nearly perfectly correlated, and losing the ability to distinguish left- and right-handed associates (within-pair order), essentially mimicking the associative symmetry property that is intrinsic to convolution. In this case, the model would lead to the same predictions as convolution-based models.

***Concatenation-based models.*** Some models assume item representations are concatenated together (Hintzman, 1984, 1986; Rizzuto & Kahana, 2000, 2001). Without further assumptions, a concatenated representation is also asymmetric.

Concatenation-based models quite naturally assume that “forward” and “backward” association strengths are correlated, because the concatenated representation is in fact stored in a single operation. If one added to concatenation models the assumption that the left- and right-hand portion of the association are confusable, they might make the same predictions as convolution-based models.

***Positional coding models of pair-memory.*** First proposed to explain memory for serial lists, positional coding models assume that participants learn a set of items by linking each list item to a positional code along some representation of position or order (e.g., Brown, Preece, & Hulme, 2000; Brown, Neath, & Chater, 2007; Burgess & Hitch, 1999; Conrad, 1965; Henson, 1998; Howard & Kahana, 1999; Lee & Estes, 1977; Lewandowsky & Farrell, 2000; Mensink & Raaijmakers, 1988). Caplan (2005) and others (Caplan et al., 2006; Howard et al., 2009; Provyn et al., 2007; Rehani & Caplan, 2011) have shown how positional coding models could also describe human memory for sets of pairs, by assuming that paired items are associated with very similar (closeby) positional codes. This kind of model can approximate associative symmetry, at least adequately enough to fit empirical correlations (Caplan, 2005; Caplan et al., 2006; Rehani & Caplan, 2011). It would also predict direct competition between pairs that share a common item, because probing with the item would retrieve two positions, each with different nearby items. Although positional coding models are far less tested on paired-associate data than convolution, matrix-outer-product and concatenation models, they might hold promise for

accounting for empirical findings on association-memory and associative interference.

***Balancing associative symmetry with memory for order within associations.*** In discussing their data on directional probes of double-function pairs, Rehani and Caplan (2011) found that the perfect-order-coding models and order-absent (convolution-based) models were both too extreme to account for their findings. Rather, a model with a moderate level of order-memory (a positional coding model) provided the best account. Our findings are consistent with this conclusion, particularly considering that the negative correlations that suggested the presence of associative competition were significant, but not exceedingly large in magnitude ( $R^2$  around 10% of explained variance or less). Thus, competition may occur as a consequence of competition between associations that participants imperfectly discriminate based upon the order of their constituent parts at retrieval.

***Model-agnostic mechanisms of competition between associations.*** Thus far our discussion has focused on mechanisms of associative competition that could follow from model constraints. Other accounts are also possible, and may be compatible with virtually any model. That is, it is conceivable that the repeated item causes encoding of pairs to be competitive when they share an item. Because we identified very low levels of retroactive facilitation and very little evidence of proactive interference on average, such competitive encoding could not be based on presentation order. That leaves open the possibility that competitive encoding could occur based on other features of items or associations, which could be the target of future research. Competitive encoding could also arise during the test phase. Our procedure does not enable us to distinguish those two possibilities, particularly for  $Q_{Distinct-Probe}$ , which, by necessity, compares memory outcome at different times within the test set. There is good reason to believe that output encoding contributes to the negative value of  $Q_{Distinct-Probe}$  (cf. Rehani & Caplan, 2011), because  $Q_{Distinct-Probe}$  became more negative in test 2 than test 1 (Figure 4).

### Implications for other associative interference procedures

Interference in AB/AC learning, until now, could have been attributed to the Item Suppression or Candidate Competition hypotheses. Some such effects may contribute to AB/AC learning. However, our findings in double-function learning raise the possibility that there can also be competition between the AB and AC associations themselves.

We found no evidence of facilitation between overlapping pairs. This suggests that facilitation in AB/AC learning (Bruce & Weaver, 1973; Burton et al., submitted; Tulving & Watkins, 1974) may occur due to the clear temporal separation between AB and AC lists, as has been proposed by researchers who were attempting to explain the (albeit illusory) associative independence finding (Martin, 1971b; Underwood & Schulz, 1960; Wang, 1980) and by researchers explaining directed forgetting (Sahakyan & Delaney, 2003, 2005; Sahakyan & Kelley, 2002) and may have to overcome the initial presence of direct competition between the AB and AC associations.

The procedure we used combines aspects of several prior verbal paired associate procedures: double-function lists (Primoff, 1938), successive testing (Kahana, 2002) and the dual-response method modelled after modified free recall (Barnes & Underwood, 1959). Thus, apart from testing the associative competition hypothesis, this novel experimental procedure sheds light on memory for double-function lists. In particular, unexpectedly to us, mean accuracy for double-function pairs was nearly equal to accuracy for single-function pairs when participants were given the opportunity to produce two responses to a given probe item. This is different than prior findings on double-function pairs which, requiring directional retrieval, have always found recall of double-function pairs to be at a major disadvantage relative to single-function pairs (Howard et al., 2009; Primoff, 1938; Probyn et al., 2007; Rehani & Caplan, 2011; Slamecka, 1976). This extends Slamecka's (1976) evidence that the challenge to forward cued recall of double-function lists is primarily handling competition from the backward associate, but further suggests that associative competition is also present. The near-equivalent accuracy

in our data, therefore, suggests that associative competition is a zero-sum game, and does not present an overall challenge for double-function, compared to single-function pairs.

In conclusion, our findings provide clear evidence that associations can compete with one another, a result that cannot be explained away by items being competitively suppressed, or by competition between candidate responses to a single retrieval cue. This phenomenon is consistent with models that incorporate associative symmetry, and may prove difficult to reconcile with models that do not.

## References

- Anderson, J. A. (1970). Two models for memory organization using interacting traces. *Mathematical Biosciences*, 8, 137-160.
- Anderson, M. C. (2003). Rethinking interference theory: executive control and the mechanisms of forgetting. *Journal of Memory and Language*, 49, 415-445.
- Anderson, M. C., & Spellman, B. A. (1995). On the status of inhibitory mechanisms in cognition: memory retrieval as a model case. *Psychological Review*, 102(1), 68-100.
- Asch, S. E., & Ebenholtz, S. M. (1962). The principle of associative symmetry. *Proceedings of the American Philosophical Society*, 106(2), 135-163.
- Barnes, J. M., & Underwood, B. J. (1959). "Fate" of first-list associations in transfer theory. *Journal of Experimental Psychology*, 58(2), 97-105.
- Borsellino, A., & Poggio, T. (1972). Holographic aspects of temporal memory and optomotor responses. *Kybernetik*, 10(1), 58-60.
- Brown, G. D. A., Neath, I., & Chater, N. (2007). A temporal ratio model of memory. *Psychological Review*, 114(3), 539-576.
- Brown, G. D. A., Peece, T., & Hulme, C. (2000). Oscillatory-based memory for serial order. *Psychological Review*, 107(1), 127-181.
- Bruce, D., & Weaver, G. E. (1973). Retroactive facilitation in short-term retention of minimally learned paired associates. *Journal of Experimental Psychology*, 100(1), 9-17.
- Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review*, 106, 551-581.
- Burton, R. L., Lek, I., & Caplan, J. B. (submitted). Associative independence revisited: evidence for associative facilitation and competition in AB/AC learning.
- Caplan, J. B. (2004). Unifying models of paired associates and serial learning: insights from simulating a chaining model. *NeuroComputing*, 58-60, 739-743.
- Caplan, J. B. (2005). Associative isolation: unifying associative and order paradigms.

- Journal of Mathematical Psychology*, 49(5), 383-402.
- Caplan, J. B., Glaholt, M., & McIntosh, A. R. (2006). Linking associative and list memory: pairs versus triples. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 32(6), 1244-1265.
- Ceraso, J., Timmerman, R., & Velk, R. (1982). Cue versus item commonality in interference. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 8(4), 289-296.
- Chappell, M., & Humphreys, M. S. (1994). An auto-associative neural network for sparse representations: analysis and application to models of recognition and cued recall. *Psychological Review*, 101(1), 103-128.
- Conrad, R. (1965). Order error in immediate recall of sequences. *Journal of Verbal Learning and Verbal Behavior*, 4, 161-169.
- Delprato, D. J. (1972). Pair-specific effects in retroactive inhibition. *Journal of Verbal Learning and Verbal Behavior*, 11, 566-572.
- Dyne, A. M., Humphreys, M. S., Bain, J. D., & Pike, R. (1990). Associative interference effects in recognition and recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16(5), 813-824.
- Geller, A. S., Schleifer, I. K., Sederberg, P. B., Jacobs, J., & Kahana, M. J. (2007). PyEPL: a cross-platform experiment-programming library. *Behavior Research Methods*, 39(4), 950-958.
- Gillund, G., & Shiffrin, R. M. (1984). A retrieval model for both recognition and recall. *Psychological Review*, 91(1), 1-67.
- Henson, R. N. A. (1998). Short-term memory for serial order: the start-end model. *Cognitive Psychology*, 36, 73-137.
- Hintzman, D. L. (1972). On testing the independence of associations. *Psychological Review*, 79(3), 261-264.
- Hintzman, D. L. (1984). MINERVA 2: A simulation model of human memory. *Behavior*

- Research Methods, Instruments, & Computers*, 16(2), 96-101.
- Hintzman, D. L. (1986). “schema abstraction” in a multiple-trace memory model. *Psychological Review*, 93(4), 411-428.
- Horowitz, L. M., Brown, Z. M., & Weissbluth, S. (1964). Availability and the direction of associations. *Journal of Experimental Psychology*, 68(6), 541-549.
- Horowitz, L. M., & Manelis, L. (1972). Toward a theory of redintegrative memory: adjective-noun phrases. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 6, p. 193-224). New York: Academic Press.
- Horowitz, L. M., Norman, S. A., & Day, R. S. (1966). Availability and associative symmetry. *Psychological Review*, 73(1), 1-15.
- Howard, M. W., Jing, B., Rao, V. A., Provyn, J. P., & Datey, A. V. (2009). Bridging the gap: transitive associations between items presented in similar temporal contexts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35(2), 391-407.
- Howard, M. W., & Kahana, M. J. (1999). Contextual variability and serial position effects in free recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 25(4), 923-941.
- Hulme, C., Roodenrys, S., Schweickert, R., Brown, G. D. A., Martin, S., & Stuart, G. (1997). Word-frequency effect on short-term memory tasks: evidence for a redintegration process in immediate serial recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 23(5), 1217-1232.
- Humphreys, M. S., Bain, J. D., & Pike, R. (1989). Different ways to cue a coherent memory system: A theory for episodic, semantic, and procedural tasks. *Psychological Review*, 96(2), 208-233.
- Humphreys, M. S., Tehan, G., O’Shea, A., & Bolland, S. W. (2000). Target similarity effects: support for the parallel distributed processing assumptions. *Memory & Cognition*, 28(5), 798-811.

- Jakab, E., & Raaijmakers, J. G. W. (2009). The role of item strength in retrieval-induced forgetting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 35(3), 607-617.
- Kahana, M. J. (2002). Associative symmetry and memory theory. *Memory & Cognition*, 30(6), 823-840.
- Kahana, M. J. (2012). *Foundations of human memory*. USA: Oxford University Press.
- Lee, C. L., & Estes, W. K. (1977). Order and position in primary memory for letter strings. *Journal of Verbal Learning and Verbal Behavior*, 16, 395-418.
- Lewandowsky, S., & Farrell, S. (2000). A redintegration account of the effects of speech rate, lexicality, and word frequency in immediate serial recall. *Psychological Research*, 63, 163-173.
- Loftus, G. R., & Masson, M. E. J. (1994). Using confidence intervals in within-subject designs. *Psychonomic Bulletin & Review*, 1(4), 476-490.
- Luce, R. D. (1959). Detection and recognition. In R. D. Luce, R. R. Bush, & E. Galanter (Eds.), *Handbook of mathematical psychology* (p. 103-189). New York: Wiley.
- Madan, C. R., Glaholt, M. G., & Caplan, J. B. (2010). The influence of item properties on association-memory. *Journal of Memory and Language*, 63, 46-63.
- Martin, E. (1971a). Stimulus component independence. *Journal of Verbal Learning and Verbal Behavior*, 10, 715-721.
- Martin, E. (1971b). Verbal learning theory and independent retrieval phenomena. *Psychological Review*, 78(4), 314-332.
- McGeoch, J. A. (1933). Studies in retroactive inhibition: I. the temporal course of the inhibitory effects of interpolated learning. *Journal of General Psychology*, 9, 24-43.
- McGeoch, J. A. (1936). Studies in retroactive inhibition: VII. retroactive inhibition as a function of the length and frequency of presentation of the interpolated lists. *Journal of Experimental Psychology*, 19, 674-693.
- Melton, A. W., & Irwin, J. M. (1940). The influence of degree of interpolated learning on

- retroactive inhibition and the overt transfer of specific responses. *American Journal of Psychology*, 53(2), 173-203.
- Mensink, G.-J., & Raaijmakers, J. G. W. (1988). A model for interference and forgetting. *Psychological Review*, 95(4), 434-455.
- Metcalfe Eich, J. (1982). A composite holographic associative recall model. *Psychological Review*, 89(6), 627-661.
- Murdock, B. B. (1982). A theory for the storage and retrieval of item and associative information. *Psychological Review*, 89, 609-626.
- Pike, R. (1984). Comparison of convolution and matrix distributed memory systems for associative recall and recognition. *Psychological Review*, 91(3), 281-294.
- Plate, T. A. (1995). Holographic reduced representations. *IEEE Transactions on Neural Networks*, 6(3), 623-641.
- Postman, L. (1971). Transfer, interference, and forgetting. In J. W. Kling & L. A. Riggs (Eds.), *Woodworth and Schlosberg's experimental psychology* (3rd ed., p. 1019-1132). New York: Holt, Rinehart & Winston.
- Primoff, E. (1938). Backward and forward associations as an organizing act in serial and in paired-associate learning. *Journal of Psychology*, 5, 375-395.
- Provyn, J. P., Sliwinski, M. J., & Howard, M. W. (2007). Effects of age on contextually mediated associations in paired associate learning. *Psychology and Aging*, 22(4), 846-857.
- Raaijmakers, J. G. W., & Shiffrin, R. M. (1981). Search of associative memory. *Psychological Review*, 88(2), 93-134.
- Rehani, M., & Caplan, J. B. (2009). *Associative interference in human memory*. (Poster presented at the Banff Annual Seminar in Cognitive Science, Banff, AB)
- Rehani, M., & Caplan, J. B. (2011). Interference and the representation of order within associations. *Quarterly Journal of Experimental Psychology*, 64(7), 1409-1429.
- Riefer, D. M., & Batchelder, W. H. (1988). Multinomial modeling and the measurement of

- cognitive processes. *Psychological Review*, 95(3), 318-339.
- Rizzuto, D. S., & Kahana, M. J. (2000). Associative symmetry vs. independent associations. *NeuroComputing*, 32-33, 973-978.
- Rizzuto, D. S., & Kahana, M. J. (2001). An autoassociative neural network model of paired-associate learning. *Neural Computation*, 13, 2075-2092.
- Sahakyan, L., & Delaney, P. F. (2003). Can encoding differences explain the benefits of directed forgetting in the list method paradigm? *Journal of Memory and Language*, 48, 195-206.
- Sahakyan, L., & Delaney, P. F. (2005). Directed forgetting in incidental learning and recognition testing: support for a two-factor account. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 31(4), 789-801.
- Sahakyan, L., & Kelley, C. M. (2002). A contextual change account of the directed forgetting effect. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(6), 1064-1072.
- Slamecka, N. J. (1976). An analysis of double-function lists. *Memory & Cognition*, 4(5), 581-585.
- Sommer, T., Schoell, E., & Büchel, C. (2008). Associative symmetry of the memory for object–location associations as revealed by the testing effect. *Acta Psychologica*, 128, 238-248.
- Tehan, G., Humphreys, M. S., Tolan, G. A., & Pitcher, C. (2004). The role of context in producing item interactions and false memories. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 30(1), 107-119.
- Tulving, E., & Watkins, M. J. (1974). On negative transfer: effects of testing one list on the recall of another. *Journal of Verbal Learning and Verbal Behavior*, 13, 181-193.
- Underwood, B. J., & Schulz, R. W. (1960). Response dominance and rate of learning paired associates. *Journal of General Psychology*, 62, 153-158.
- Wang, A. Y. (1980). Evidence for a “selective” selector mechanism. *American Journal of*

- Psychology*, 93(4), 643-656.
- Wichawut, C., & Martin, E. (1971). Independence of A-B and A-C associations in retroaction. *Journal of Verbal Learning and Verbal Behavior*, 10, 316-321.
- Wilson, M. D. (1988). The MRC psycholinguistic database: Machine readable dictionary, version 2. *Behavioral Research Methods*, 20, 6-11.

Test	Item Suppression	Candidate Competition	Associative Competition
$\mathcal{Q}_{Same-Probe} < 0$	✓	✓	✓
$\mathcal{Q}_{Different} \simeq \mathcal{Q}_{Same}$	<	<	✓
$\mathcal{Q}_{Yoked} > \mathcal{Q}_{Same-Probe}$	✗	?	✓
$\mathcal{Q}_{Distinct-Probe} < 0$	✗	✗	✓

Table 1

*Summary of the major tests presented in the results sections and how they bear on each of the three major hypotheses.* ✓ compatible with the hypothesis. ✗ incompatible with the hypothesis as explaining away associative competition. < weak (i.e., suggestive but inconclusive) challenge to the hypothesis. ? does not bear directly on the hypothesis. Note that  $\mathcal{Q}_{Control(within-test)}$  is also substituted for zero for comparisons against zero.

**Experiment 1**

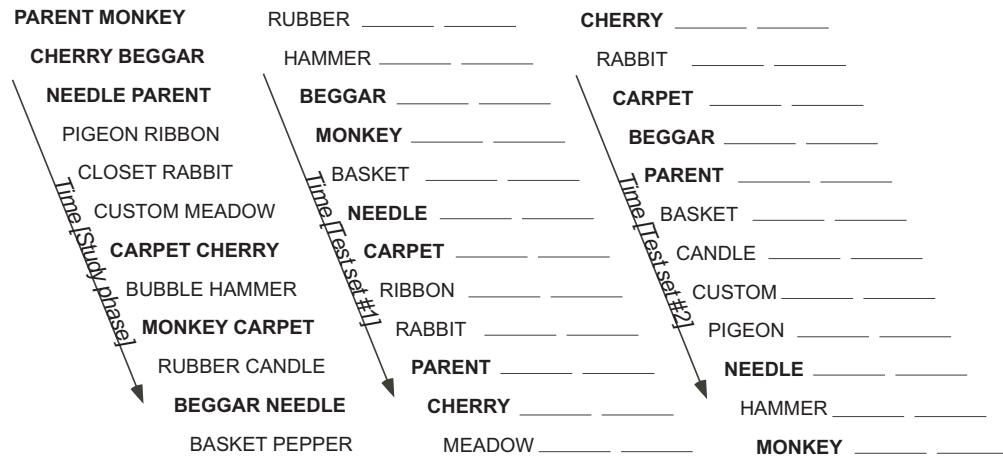
	Test 1		Test 2	
	Forward	Backward	Forward	Backward
Single Function	0.452±0.059	0.429±0.056	0.472 ± 0.062	0.470 ± 0.061
Double Function	0.421 ± 0.049	0.413 ± 0.052	0.446 ± 0.049	0.428 ± 0.048

**Experiment 2**

	Test 1		Test 2	
	Forward	Backward	Forward	Backward
Single Function	0.304 ± 0.060	0.296 ± 0.052	0.321 ± 0.058	0.294 ± 0.061
Double Function	0.305 ± 0.038	0.289 ± 0.040	0.312 ± 0.041	0.306 ± 0.042

Table 2

*Accuracy and 95% confidence intervals of cued recall for each experiment as a function of pair type (single- or double-function), direction (forward or backward recall) and test number. Confidence intervals are based on standard error of the mean and corrected for between-subjects variability (Loftus & Masson, 1994).*



*Figure 1.* Procedure for Experiments 1 and 2, for a hypothetical example. Single-function pairs are denoted in plain text and double-function pairs are set in boldface for clarity in the figure only. In the test phases, the word was the cue and the two blank lines denote the two lines on which participants typed their responses (but note that participants viewed the cue word and two response lines in a vertical, not horizontal configuration: a single column).

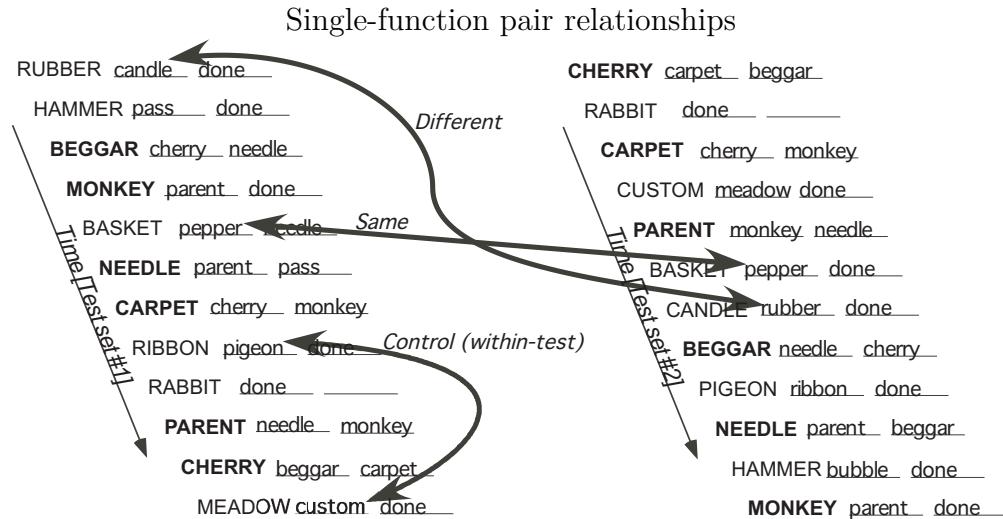
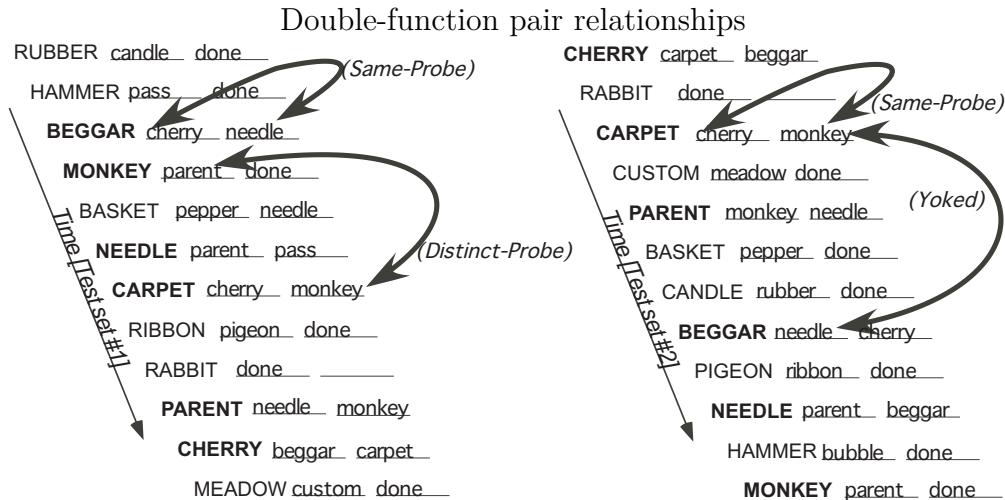


Figure 2. Example of memory-test performance, illustrating the various contingencies that are analyzed in the Results sections. This figure continues from Figure 1. Single-function pairs are denoted in plain text and double-function pairs are set in boldface. In the test phases, the upper-case word was the cue and lower-case words are responses (lowercase is used for illustration purposes only; responses appeared in upper-case as they were typed; see Methods). Note that “done” and “pass” were used by the participant when no response was available. The “Same” relationship is illustrated by the outcome on test 1 of a cue and the outcome on test 2 using the same probe; in this case, BASKET is a Forward probe for the target item **pepper** in both test 1 and test 2. The “Different” relationship is illustrated by the probe direction switching on a given pair from test 1 to test 2; in this case, RUBBER is a Forward probe for **candle** on test 1, but the pair is tested in the Backward direction on test 2 (given **CANDLE** as the cue, recall **rubber**). The within-test control is computed between pairs of different (unrelated) SF pairs; in this example, performance on the pair **PIGEON**–**RIBBON** is compared with performance on the pair **CUSTOM**–**MEADOW**. Similarly, the between-test control compares performance on different (unrelated) pairs, but for one test-1 and one test-2 probe; in this example, performance on the pair **RUBBER**–**CANDLE** on test 1 is related to performance on the pair **BASKET**–**PEPPER** on test 2.



*Figure 3.* Example of memory-test performance, illustrating the various contingencies that are analyzed in the Results sections. This figure continues from Figures 1 and 2. The “Same-Probe” relationship is the main measure of interest (note that there are two examples given in the figure, one during test 1 and one during test 2), and compares probability of recall of the two studied associates of a given probe item; a negative correlation indicates competition between associations (assuming alternative interpretations can be ruled out, particularly, an expected positive correlation due to variability of associability of the cue item; see main text). The “Yoked” condition produces an estimate of the correlation between each pair of items that would be targets of a single probe (“Same-Probe” targets) but which were via different associations; this is used to test the item-level suppression hypothesis (see text). In the example given here (within Test 2 in the example), the yoking controls for PARENT as the cue for both NEEDLE and MONKEY by comparing recall of NEEDLE given BEGGAR as a cue with recall of MONKEY given CARPET as a cue. Finally, the “Distinct-Probe” condition enables a second test of the associative competition hypothesis by correlating recall of AB with recall of BC but avoiding the problem of using the same probe item to test both pairs. In this example, the PARENT-MONKEY and MONKEY-CHERRY are tested both in the backward direction: accuracy on CARPET→CHERRY is correlated with accuracy on MONKEY→PARENT. Note that this condition is composed of a combination of conditions in which both pairs are probed in the forward direction and in which both pairs are probed in the backward direction.

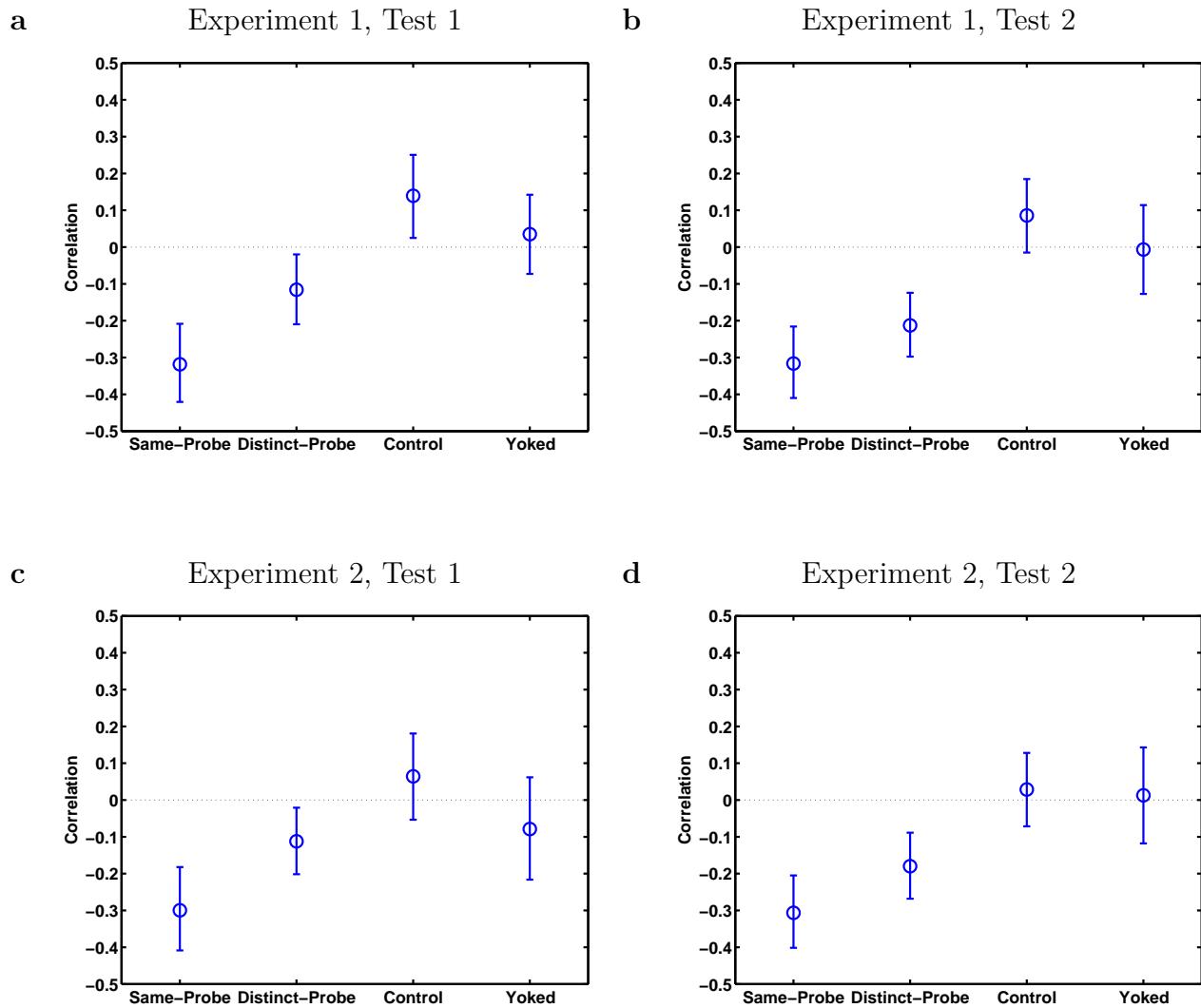
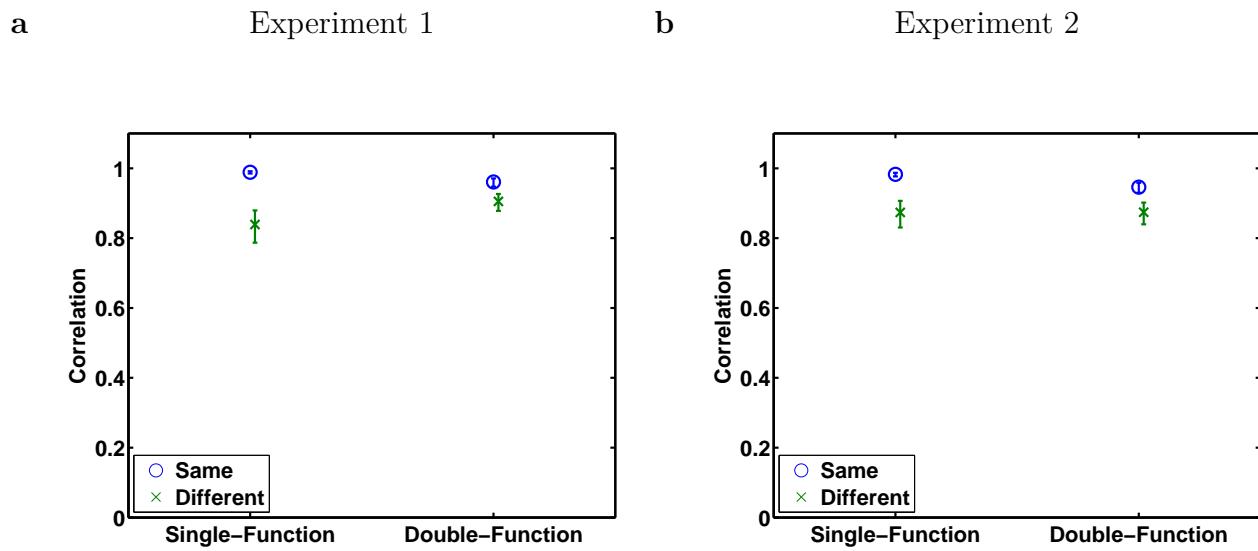


Figure 4. Correlations (Yule's  $Q$ ) for the two tests of associative competition,  $Q_{Same-Probe}$  and  $Q_{Distinct-Probe}$ , the control for independence,  $Q_{Control(within-test)}$ , and the test of the item-competition hypothesis,  $Q_{Yoked}$ , in Experiment 1, test 1 (a) and test 2 (b) and Experiment 2, test 1 (c) and test 2 (d). Error bars are 95% confidence intervals based on standard error of the mean.



*Figure 5.* Correlation (Yule's  $Q$ ) for successive tests, in Experiment 1 (a) and Experiment 2 (b), as a function of the relationship between test 1 and test 2 (Same=Forward/Forward or Backward/Backward; Different=Forward/Backward or Backward/Forward) and pair type (single- or double-function). Error bars are 95% confidence intervals based on standard error of the mean.