Associative independence revisited: Evidence for associative facilitation and competition in AB/AC learning

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Abstract

Associative interference is a counterintuitive, yet often replicated, finding. That is, in a paradigm called AB/AC learning, when participants study word pairs of the form AB- AC later recall probabilities of the B and C items are uncorrelated. This suggests that conflicting associations are remembered independently (Martin, 1971). In two experiments with a single-trial version of AB/AC learning we challenge the independence interpretation with several lines of evidence. For example, our results indicate that B and C can be both negatively correlated, suggesting pair-specific competition, and positively correlated, implying associative facilitation between AB and AC. We argue that associative independence findings are better viewed as a mix of positive, negative and zero correlations due to subject variability, including variability in study strategy. In addition, we demonstrate that the typical procedure of participants learning the AB pairs to a perfect recall criterion may have artifactually produced apparent independence in past studies. In sum, previous inferences of independence in AB/AC learning should be adjusted to include the presence of multiple relationships between AB and AC, including associative facilitation.

Key words: Paired-associate learning; Associative independence; Interference; Strategy

Introduction

People frequently face challenges to memory from conflicting associations. For instance— a friend might first be married to one spouse, then remarry, thus being repaired with a different spouse. A lab meeting time might be moved from Tuesday to Friday. An actor may play two different characters in two different films. In all these cases, one may need to effectively retrieve the later associate (spouse/day/character name) and avoid erroneously retrieving the earlier associate— overcoming what is known as proactive interference. Conversely, one might need to retrieve the earlier associate while ruling out the more recently learned associate— overcoming what is known as retroactive interference. Here, we are interested in the relationship between the conflicting associations. Due to the overlap (same "stimulus" term) between the two associations, we might expect that the associations will compete with each other at retrieval. Competition implies that recall of the associations should be negatively correlated. The AB/AC learning paradigm was developed to empirically study how people learn and remember these kinds of overlapping, or conflicting, associations. Martin (1971) described the problem as follows: If a participant learns Response B in Situation A, and later learns Response C in Situation A, when Situation A arises in the future how will he or she know which response to make? In AB/AC learning paradigms, participants study two sets of paired items (e.g., nouns). The first word in a pair is used in both the first and second set with two different associates (i.e., Castle - Ocean; Castle - Lemon). We refer to these overlapping pairs as the AB and AC pairs, respectively.

AB/AC learning and variants of this paradigm have been well studied. The so-called "modified modified free recall" (MMFR) procedure was designed by Barnes & Underwood (1959) to minimize response competition, and was considered the most direct means of measuring the relationship between AB and AC associations in memory. In MMFR, first a set of AB pairs is studied and tested, typically in multiple trials, learned to a near-perfect recall criterion. This is followed by study and test of a set of AC pairs, which reuse the stimulus (A) items from the AB set but pair each A item with a new item (C). Finally, in the MMFR test, a cue item (A) is shown and participants are asked to recall both associates, B and C, in any order. Surprisingly, numerous studies have reported that there is no competition between recall of B and recall of C in MMFR (Greeno, James, & DaPolito, 1971; Martin, 1971; Wichawut & Martin, 1971). These authors found that recall of B and C were not significantly correlated. They concluded that overlapping associations are recalled independently and do not conflict with each other directly.

Note that Hintzman (1972) commented that because correlations (or conditional probabilities, a different way of testing the independence hypothesis) were computed on aggregate data, pooled across participants (we refer to this method as the "pooled" approach), subject variability and item variability would be expected to produce a positive correlation even between independent tests of memory. Thus, an actual negative correlation that would reflect competition between the B and C associations might be canceled out by a positive correlation due to subject- and item-variability. Riefer and Batchelder (1988) found support for this kind of inflation of correlations toward positive values due to subject- and/or item-variability fitting a mathematical (multinomial) model to AB/AC learning data. For this reason, in the experiments reported here, we address this confound in two ways. First, we always include control pairs in both the AB and AC study sets ("DE" and "FG" pairs, respectively). This enables us to compute the correlation between recall of E (given D) and recall of G (given F), pairs that should not interfere with one another. This provides an estimate of the positive correlation due to subject variability, to which we can compare the BC correlation. Second, we also recalculate the correlations with subject variability removed, which we refer to as the "unpooled" approach. We do this by computing each correlation within participants before carrying out statistical tests across participants. By examining the outcomes of both approaches, we can effectively address Hintzman's critique of prior AB/AC learning studies and evaluate whether, and to what extent, the positive-correlation bias affects the conclusions one can draw from the observed pattern of correlations.

Experiment 1 was motivated by our observation that nearly all the independence findings in AB/AC learning were obtained in procedures wherein participants first learned the AB set to a perfect or near-perfect initial recall criterion (Martin, 1969; Wichawut & Martin, 1971; Martin, 1971; Greeno, James & DaPolito, 1971). We asked whether the classic finding of independence would be replicated if participants had only one study trial per AB (and AC) pair. To foreshadow the results, we obtained a surprising, novel result, inconsistent with published findings as well as existing theories of AB/AC learning: a *positive* correlation between recall of B and recall of C in MMFR. A positive correlation suggests associative *facilitation*. The chief objective of Experiment 2 was to test whether a manipulation of study strategy could modulate the pattern of findings from independence to facilitation. In two experiments we test four hypotheses:

1. We hypothesized that associative facilitation is a legitimate result. We tested this by examining whether the positive correlation can be interpreted as evidence of associative facilitation, and is not simply the level of correlation one expected due to subject and item variability.

2. We hypothesized that the typical procedure of requiring a high degree of initial AB learning can remove important sources of variability (i.e., degree of learning of individual pairs) that would otherwise have correlated with retrieval of the AC associations. If the major source of common variability is removed, then the remaining variability may be primarily noise, producing a zero- or near-zero correlation between recall of B and recall of C for trivial reasons.

3. We hypothesized that a near-zero-correlation in pooled correlations can be a result of positive correlations in some participants cancelling negative correlations in others. We examined distributions of correlation values to evaluate this possibility.

4. We hypothesized that different strategies differentially influence the value of the BC correlation. We tested this hypothesis by manipulating instructions to participants in Experiment 2.

Experiment 1

Method

Participants. A total of 83 students enrolled in a third-year undergraduate course entitled *Neurobiology of Learning and Memory* participated during class time. Participation was optional and students did not receive course credit. Three students withdrew partway through the experiment and their data were discarded; thus, 80 participants are reported here.

Material. The paired associates in each of the two lists consisted of six-letter, two-syllable nouns with moderate concreteness (4–6) and imagery (4–6) rating values and the moderately high frequency (80–250 per million; MRC Psycholinguistic Database [Wilson, 1988]; see Appendix). The nouns were paired together at random, presented in the centre of the computer screen with one word slightly to the left (A, D and F words) and the other slightly to the right (B, C, E and G words).

The distracter task consisted of counting the number of a given digit present in a grid that consisted of two different digits. For example, participants were asked to count the number of 3's in a grid of 3's and 5's. There were a total of 48 digits in each grid and the number of target digits was between 19 and 25.

Procedure. All participants were tested at the same time in an auditorium. Participants studied two lists of pairs of words presented on one central overhead screen with PowerPoint. Thus, all participants viewed the same word pairs in the same order. Both lists were made up of equal numbers of "interference" and "control" pairs. The first list consisted of AB (interference) and DE (control) pairs and the second list consisted on AC (interference) and FG (control) pairs. Each pair was presented once.

Participants were provided with booklets which listed cued-recall and MMFR cue items and blanks to fill in as their responses. During each test phase, they were instructed to write the word that was paired with the word written in the booklet, or in the case of MMFR the one or two words that were paired with the word written in the booklet. There were four different versions of the booklets, each with a different probe order. Following presentation of each list, participants were tested on their memory of the just-presented list with standard cued recall, provided with the first (left-hand) word of each pair and asked for the one word that was paired with the given word in the most recent list. Following study and cued recall of both sets, participants were tested with MMFR (Barnes & Underwood, 1959) by viewing a left-hand item and being asked for the one or two words that were presented with the given words at any time during the two study sets. Participants were instructed that if a word had two associates they could be recalled in any order.

The experiment consisted of three study sets, where each set included an AB- and AC-list (Figure 1). There were 8 word pairs in each list and each pair was presented for 4 seconds. The first lists consisted of 4 AB pairs and 4 DE pairs, and the second lists consisted of 4 AC pairs and 4 FG pairs. Participants completed a distracter task following first list learning and were then tested for their recall of the first list pairs through cued recall. Participants then learned the second set of pairs, which was also followed by a distracter task and cued recall. The second cued recall was followed by a distracter task and a MMFR test concluded each set.

Insert Figure 1 about here

Correlation analyses. The correlations for MMFR responses were calculated using Yule's Q, a measure of correlation appropriate for dichotomous data (for a review, see Kahana, 2002). Yule's Q is calculated by creating a 2 x 2 contingency table. The 'a' quadrant contains the number of times both items were recalled, the 'b' quadrant contains the number of time the first item but not the second was recalled, the 'c' quadrant contains the number of times the second item but not the first was recalled, and the 'd' quadrant contains the number of times neither item is recalled. Yule's Q is equal to (ad–bc)/(ad+bc).

We report two different Yule's Q calculations. First, in the (conventional) pooled approach, the data from all participants was pooled and a single Yule's Q was calculated. Significance and pairwise comparisons were done by transforming Q into log-odds ratios and calculating standard errors in log-odds units (Bishop, Fienberg, & Holland, 1975; Hayman & Tulving, 1989). Note that with the pooled method, Q values potentially include positive correlations due to subject- and item-variability. Second, in the unpooled approach (we have not found precedents for this approach applied to AB/AC learning but it has been used in other association-memory paradigms; see Kahana, 2002; Rehani and Caplan, in press; Rizzuto and Kahana, 2001), Q values were calculated for each participant first, and these values were analyzed after a log-odds transform. By computing Q values for individual participants, subject variability cannot inflate the correlations. The tradeoff is that fewer data points go into each Q value. Because there are often empty cells in the contingency table, we apply a correction, adding one-half of an observation (.5) to each contingency table quadrant. Because each approach to computing Q has its advantages and disadvantages, we report both methods, checking whether or not the pattern of findings depend on the approach to calculating Q (pooled versus unpooled).

As a second way to address the correlation due to subject-variability, we also directly estimated this correlation. Specifically, we computed a "Control" correlation between recall of E and G items. To avoid overestimating degrees of freedom, in the pooled approach this was done by randomly pairing a single DE pair with exactly one FG pair from the same study set (pair of AB–DE and AC–FG study set) and computing Q as usual. For the unpooled approach (which estimates possible correlation due to slow shifts in performance across the testing session), the control correlation included all pairwise combinations of DE and FG from a given study set. Because the statistical tests were carried out with only a single Q value for each participant, this does not pose a problem for estimating degrees of freedom.

Results and Discussion

We present the accuracy in cued recall, then accuracy in MMFR to detect any proactive or retroactive interference that could be present in mean retrieval performance. Then we present the correlation analysis, which is our main measure of interest (Hypothesis 1). We finish by examining the potential effects of high degree of learning of the AB pairs (Hypothesis 2) and subject variability (Hypothesis 3).

Accuracy in cued recall. To interpret the MMFR data we need to know how well the pairs were initially learned, as probed with cued recall (Figure 2). We first ask whether AB and DE pairs differed in cued recall. AB–DE lists: Participants recalled more DE pairs than AB pairs [t(79) = 3.22, $p < 0.01$, paired-samples, two-tailed]. At this stage, each word had only been used once, so there is no reason to expect any difference in recall. The significant difference suggests that the AB and DE pairs were not adequately matched for difficulty and this should be taken into account when considering accuracy in MMFR. Next we ask whether there was any proactive interference evident in initial cued recall. AC – FG sets: Participants recalled the FG and AC pairs equivalently [t(79)=0.48, p>0.5]. Thus, there was no evidence of proactive interference on average in cued recall.

Insert Figure 2 about here

Accuracy in MMFR. Now we turn to mean accuracy measures in MMFR to determine whether retroactive and proactive interference were present (Figure 3)**.** Participants recalled fewer AB pairs than DE pairs [t(79) = -2.24, $p < 0.05$]. It is unclear whether this reflects retroactive interference or is a result of the DE pairs being initially better learned (see cued recall results). Although participants recalled more FG pairs (0.52) than AC (0.48) pairs in the MMFR test this difference was non-significant (but approaching significance) [$t(79) = -1.71$, $p < 0.1$]. These results suggest the possible presence of retroactive interference, but not robust proactive interference in MMFR.

Insert Figure 3 about here

MMFR Correlations

Now we turn to the measure that tests our core hypotheses: the correlation between AB and AC pairs.

Pooled approach (Figure 4, left pair of bars)**.** Calculating the correlation between recall of B and recall of C in MMFR tests the relationship between the AB and AC associations (Hypothesis 1). As noted in the Methods, the EG correlation (see Methods) serves as a control for independence because DE and FG pairs do not share any words, so there is no reason to expect that the recall of one DE pair would be related to the recall of an FG pair. Consistent with Hintzman (1972, 1980) and Riefer and Batchelder (1988) the EG control correlation was significantly greater than zero [$Q_{EG} = 0.34$; $z_{log\text{-}OR} = 5.29$, $p < 0.001$]. Thus, subject-/study-set-variability does indeed result in a substantial positive correlation even for independent memory tests. This is because if some participants perform better overall than other participants, all measures would covary together, resulting in a moderately positive correlation. The same reasoning applies to variability across study set (e.g., due to fatigue or learning-to-learn effects). To test whether the relationship between the AB and AC associations reflects associative interference, independence or facilitation, we must compare the BC correlation to the EG control correlation. There are three possible outcomes:

1. $Q_{BC}<Q_{EG}$: Interference.
2. $Q_{BC}=Q_{EG}$: Independence.
3. $Q_{BC}>Q_{EG}$: Facilitation.

The observed BC correlation was significantly *greater* than the EG control correlation, [$Q_{BC} = 0.49$, $Q_{EG} = 0.37$ $z_{log\text{-}OR} = 2.17$, $p < 0.05$] suggesting associative facilitation in this data set, even surpassing the expected positive correlation due to subject-/study-set-variability. This supports Hypothesis 1 that associative facilitation remains positive even relative to an appropriate control.

Unpooled approach (Figure 4, middle pair of bars)**.** When correlations were computed for each participant, the mean correlation values dropped as expected, indicating that both the control and interference correlations were inflated by subject variability. As in the pooled correlations, the BC correlation was significantly greater than the EG correlation [$Q_{BC} = 0.36$, $Q_{EG} = 0.11$; $t(79) = 3.42$, $p < 0.001$] further supporting the associative facilitation result (Hypothesis 1). Both the EG and BC correlations were significantly greater than zero [$t(79) = 2.27$, $p < 0.05$, and $t(79) = 4.47$, $p < 0.001$, respectively]. The reason the EG correlation is greater than zero may be because of study-set variability which is not controlled for here.

In summary, our results so far indicate that, as expected, EG and BC correlations in MMFR were inflated by subject variability. When the BC correlation is compared to an appropriate control, and when the effects of subject variability are removed, we can conclude that, on average in this data set, overlapping associations facilitate one another in recall during MMFR. They tend to be both recalled or both not-recalled more often than expected by chance.

AB-screened correlation analysis (Figure 4, right-most bar)**.** To address Hypothesis 2, regarding the effect of initially highly learned AB pairs on BC correlations, we recomputed the BC correlation using only the MMFR data for AB/AC pairs where the AB pair was initially correctly recalled in cued recall. Thus, the BC correlation during

MMFR was recalculated including only those pairs, A_iB_i and A_iC_i for which the participant had responded correctly in the initial *cued recall* of A_iB_i. Consistent with our hypothesis, the AB-screened correlation is much closer to zero, and is no longer significantly different from the (unscreened, pooled) EG control correlation [$Q_{AB\ Screened}$ = 0.30, Q_{EG} = 0.37; $z_{log\text{-}OR}$ = 0.34, p>0.5]. This supports Hypothesis 2, that confining the MMFR-correlation to well learned AB associations can remove meaningful variability, making the AB and AC associations appear more independent than otherwise.

Insert Figure 4 about here

Individual variability in the sign of the BC correlation

To address Hypothesis 3, that individual differences in the sign of the BC correlation may have effectively canceled one another in prior studies to produce near-zero correlation, we first visualized the variability by plotting the cumulative distribution function (CDF) of the BC correlations for individual participants (red plot in Figure 5). There appears to be a broad spread in individual-participant correlation values, and importantly, the correlations range from very negative to very positive. However, each Q value was based on a very small number of values (12 in this experiment), so this variability might be due to chance. To evaluate whether the spread of Q values could be due to chance, a bootstrap procedure was carried out to estimate the CDF one would obtain if the underlying correlation were zero, but controlling for the marginal accuracies. Accordingly, unconditional probability of recall of B and probability of recall of C were fixed for each participant. Specifically, two arrays of twelve 1s and 0s were created, where 1 simulated a correct recall and 0 simulated an incorrect recall. One array had accuracy equal to the participant's accuracy on recall of B and the other array had accuracy equal to the participant's accuracy on recall of C. For 1000 times per participant, one of the arrays was randomly shuffled and Q was computed from the resulting pairing of the two arrays. In this way, controlling for the observed accuracies, the bootstrap models the assumption that there are no underlying deviations from zero correlation, and the spread is due to chance (and having small numbers in the contingency table). The bootstrap is plotted in blue in Figure 5. One can readily see that our observed distribution is much broader than the bootstrap. Specifically, a far greater proportion than the expected Type I error (5%) of correlations lie outside the 95% confidence interval based on the bootstrap, both in the positive direction (35/80 participants) and in the negative direction (11/80 participants). First, this means that the far-from-zero correlation values are unlikely due exclusively to random fluctuations based on an underlying zero correlation, but rather, likely to reflect real subject variability. As noted above, even in the unpooled correlation approach, the control correlation was significantly greater than zero. Thus, the null hypothesis simulated by the bootstrap is biased toward false positives in the positive-correlation direction. This is not a problem for the facilitation conclusion since facilitation was the overall pattern reflected by the pooled correlations. Importantly, though, the choice of zero-correlation for the bootstrap makes the detection of negative correlations even more conservative. Thus, our inference that negative correlations are present is somewhat understated, and our inference that positive correlations are present is principally based on the group analysis above. Taken together, this evidence of subject variability in the sign of the BC correlation supports Hypothesis 3, that associative independence may have in the past been a consequence of positive and negative correlations roughly canceling each other (possibly with legitimate near-zero correlations mixed in as well).

Insert Figure 5 about here

Experiment 2

The positive correlation between recall of B and recall of C had not been previously reported, and was, at first, surprising to us as well. This, combined with the implication that individual variability played a role in the direction of observed correlations, motivated us to carry out Experiment 2. First, we wanted to check whether the facilitation result (positive BC correlation) would replicate if we fully randomized the materials across participants. Second, we wondered whether our associative facilitation results could have been due to variability in strategies participants were using. Specifically, perhaps a strategy that induced a positive BC correlation was more dominant in our subject pool than in previous published MMFR studies (although prior studies did not typically manipulate strategy, nor collect strategy reports). Our speculation that many of our participants were adopting a strategy in which they deliberately linked the A, B and C words together when they studied the AC pairs led to Hypothesis 4. We later discovered that Dallet and D'Andrea (1965) manipulated the instruction they gave participants in a MMFR study, including one group instructed to seek a connection to AB when learning AC and another group instructed to try and forget or suppress the AB associations while studying AC. In the same spirit, to test this mediation hypothesis directly, participants were instructed to either link the A, B and C words in a single image ("Trio" group), or to create a separate image for each pair ("Separate" group). Our specific hypothesis regarding the strategy manipulation was that participants in the trio group would exhibit a more positive correlation than participants in the separate group.

Method

Participants. A total of 69 students in an introductory psychology course participated in the experiment for course credit. Three participants did not recall any AB or AC pairs in MMFR and their data were excluded from all analyses.

Material. The stimuli were nouns from the Toronto Word Pool (Friendly, Franklin, Hoffman, & Rubin, 1982). Nouns whose imagery rating was greater than or equal to six were retained, and of those, the 180 most concrete nouns were used. Thus, all of the words used in the experiment had an imagery rating greater than or equal to 6 and a concreteness rating greater than or equal to 4. Words were paired together at random, presented in the centre of the computer screen with one word slightly to the left (A, D and F words) and the other slightly to the right (B, C, E and G words) and participants typed their responses. Assignment of words to pairs and pair types was completely random. Order of cued recall and MMFR tests was also completely random, with each pair being tested exactly once in cued recall, and each A, D an F item being used as a probe exactly once during MMFR.

The 20–s distracter task consisted of adding three integers between two and eight, and typing the response. Participants had 4 s to answer each math question, and the program progressed from one question to the next automatically for a total of five math problems during each distracter task.

Procedure. Strategy instructions were manipulated between groups. One group of participants was instructed to create an image that incorporated all three words from both pairs (trio strategy) when they were studying the overlapping pairs. The other group was instructed to create a separate image for each pair of words (separate strategy).

Both groups learned two sets of word pairs. As in the first experiment, both lists were made up of equal numbers of interference (AB, AC) and control (DE, FG) pairs. The first set consisted of AB (interference) and DE (control) pairs and the second list consisted of AC (interference) and FG (control) pairs. Again, participants were tested for their memory of the pairs using both cued recall and MMFR. The experiment consisted of four study sets. Within each study set the participants studied two lists of eight word pairs. Each pair was presented a single time, for 3 s with 150 ms of blank screen time between pairs. The first set of each round had 4 AB pairs and 4 DE pairs, and the second list of each round had 4 AC pairs and 4 FG pairs (see Figure 1 for a schematic).

Participants were randomly assigned to use one of two strategies to learn the AB/AC pairs: the trio strategy or the separate strategy. Participants in the trio group were asked to “create an image that incorporates all three words from both pairs” when studying the overlapping pairs. Participants in the separate group were asked to “create a separate image for each pair of words” when studying the overlapping pairs.

Participants began each round by studying the first set of word pairs (AB and DE), after which they completed the 20-s distracter task. Next, their memory for the pairs in the first set was tested with cued recall. Following another distracter task participants studied the second set of pairs (AC and FG). Study of the second set was also followed by the distracter task and cued recall. Following an additional distracter task, participants were tested with MMFR. Next, participants were shown all of the pairs from both sets in a random order. They were asked whether they had incorporated into any other words from the experiment into the image they had created of the pair on the screen. Finally, participants were asked to rate the quality of the image they created from 1 to 7. This rating and the preceding question were included to check that participants were able to use the trio and separate strategies as instructed.

Strategy use. First we wanted to determine whether participants in each of the groups were able to use the strategy they were assigned. If participants were using a trio like strategy for a particular AB or AC they should answer yes to the question: "Were there any other words from the experiment incorporated into the image you made of the pair on the screen?". Overall, participants in the trio group did apply the trio strategy to more AB and AC pairs than participants in the separate group. However, the trio group did not use the trio strategy on every pair and the separate group used the trio strategy on some pairs. A chi-square test was calculated by splitting the number of pairs that the trio strategy was applied to into four bins. Then the number of participants in the separate group who applied the trio strategy to each group of pairs was used to predict the number of participants in the trio group who used the trio strategy for that pair group. This test found that trio strategy application was significantly different $\chi^2(3) = 8.39$, $p < 0.05$.

Accuracy in cued recall. First we compared mean cued-recall accuracy for each pair type in cued recall between groups (Figure 6). In a 2 x 2 repeated-measures ANOVA for study set one, with design Pair Type[AB/DE] x Group[Separate/Trio] the main effects were not significant and neither was the interaction [all $Fs < 1$, $ps > 0.5$]. These results establish that participants in both groups recalled the AB and DE pairs equally well in cued recall, which should be the case due to the randomization of materials in this experiment.

In a 2 x 2 ANOVA for study set two, on Pair Type[AC/ FG] and Group (Separate/ Trio) there was no main effect of pair type [$F(1,67) = 0.18$, $p > 0.5$], but the main effect of group was significant [$F(1, 67)= 3.63$, $p < 0.01$], with the Separate group outperforming the Trio group. The Pair Type x Group interaction was also significant [$F(1,67) = 6.68$, $p < 0.05$]. Posthoc pairwise comparisons explained this interaction as follows. For the Separate group, the AC and FG pairs were recalled equivalently [$t(35) = -1.17$, $p > 0.2$] whereas for the Trio group, a trend indicated that was marginally greater than recall of the FG pairs [$t(31) = 1.98$, $p < 0.1$] . This suggests that there was more proactive interference present for the Trio group. Further independent samples t-tests between groups revealed that the AC pairs were recalled equivalently by both groups [$t(66)=0.90$, $p > 0.1$] but it was the FG pairs that differed; they were recalled better by the Separate group [$t(66) = 2.35$, $p <0.05$].

Insert Figure 6 about here

Accuracy in MMFR. Next we compared mean accuracy for each pair type in MMFR for each group (Figure 7). As in cued recall, first a 2 x 2 ANOVA on Pair Type [AB/DE] x Group[Separate/Trio], was carried out. There were no main effects nor interaction [all *Fs < 1, ps > 0.5*].

In a 2 x 2 ANOVA for list two, on Pair Type[AC/ FG] x Group (Separate/Trio) there was a significant main effect of pair type [$F(1,67) = 9.35$, $p < 0.01$]. The FG pairs were better recalled than the AC pairs, indicating proactive interference. The main effect of group was a non-significant trend [$F(1, 67) = 2.83$, $p < 0.10$], again with the Separate group outperforming the Trio group. The Pair Type x Group interaction was not significant [$F(1, 67) = 0.01$, $p > 0.5$].

Insert Figure 7 about here

MMFR correlations.

Pooled correlations. As in Experiment 1, two sets of correlations were calculated. First, all of the data from the participants in each strategy group were pooled and interference and control correlations were calculated. For the trio group the BC correlation was greater than the EG correlation [$Q_{BC} = 0.56$, $Q_{EG} = 0.17$; $z_{log\text{-}OR} = 2.89$, $p < 0.01$]. In the separate group these correlations were not different [$Q_{BC} = 0.31$, $Q_{EG} = 0.39$; $z_{log\text{-}OR} = 0.78$, $p = 0.44$]. The BC correlation was greater for the trio than the separate group [$z_{log\text{-}OR} = 2.28$, $p < 0.05$]. The EG correlations were not different [$z_{log\text{-}OR} = - 1.28$, $p > 0.1$]. These results suggest that when participants use the trio strategy, associative facilitation occurs, whereas when they use the separate strategy, overlapping associations are recalled independently, supporting Hypothesis 4.

Insert Figure 8 about here

Unpooled correlations. Next, the correlations were calculated removing the effects of subject variability by calculating Q values for each participant individually. As in Experiment 1, this decreased all correlations. In the Trio group, the BC correlation was greater than the EG correlation [$t(31) = 3.22$, $p < 0.01$]. The BC correlation was greater than zero [$t(31) = 3.58$, $p < 0.01$] but the EG correlation was not. As with the pooled correlation analyses, this indicates facilitation for the Trio group.

For the Separate group, in contrast, the BC and EG correlations were not significantly different [$t(34) = 0.26$, $p > 0.5$]. The EG correlation was slightly but significantly greater than zero [$t(34)=2.10$, $p < 0.05$] and the BC correlation was not significantly greater than zero [$t(34) = 0.23$, $p > 0.2$].

Again the BC correlation was greater for the Trio than the Separate group [$t(65) = 2.32$, $p < 0.05$], supporting Hypothesis 4.

Insert Figure 9 about here

AB-screened correlations. To test Hypothesis 2, that restricting the MMFR test to well-learned AB pairs could produce a result closer to independence, the BC interference correlations from MMFR were recalculated including only pairs for which AB was correctly recalled in initial cued recall. For the trio group the BC correlation decreased and for the separate group the BC correlation increased (Figure 10). Importantly, for the trio group, the BC correlation was no longer different than the EG control correlation [$Q_{\text{BC trio}} = 0.45$, $Q_{\text{EG trio}} = 0.27$; $z_{\text{log-OR}} = 0.91$, $p > 0.10$] . In addition, the screened trio and separate BC correlations were not different [$Q_{BC\ trio} = 0.45$, $Q_{EG\ separate} = 0.37$; $z_{log\text{-}OR} = 0.36$, $p > 0.5$]. This supports Hypothesis 2, that confining analyses to well learned AB pairs removes meaningful variability.

Insert Figure 10 about here

Individual differences analysis

As in Experiment 1, CDFs were plotted with their corresponding bootstrap CDFs (Figure 8). First, note that the relationship between the two strategies is nearly one of stochastic dominance. At almost each percentile, the correlation for the Trio group was more positive than the correlation for the Separate group (known as near-stochastic dominance). So, the pairwise comparisons of Q values carried out above may have been significant because our strategy instructions shifted participants between a slightly more negative (separate group) BC correlation and a slightly more positive (trio group) correlation. This hypothesis is supported by a significant Kolmogorov-Smirnoff test [d (65) = 0.41, $p < 0.01$], rejecting the hypothesis that the Trio and Separate correlations are drawn from the same distribution.

As in Experiment 1, the correlations range from very negative to very positive. There are more non-zero correlations in both distributions than are predicted by the associative-independence bootstrap. A greater proportion than the expected Type I error (5%) lie outside the 95% confidence interval based on the bootstrap (same calculation as in Experiment 1), both in the positive direction (12/32 Trio participants and 10/35 Separate participants) and in the negative direction (4/32 Trio participants and 7/35

Separate participants), providing further support for Hypothesis 3. Note that our manipulation of strategy was quite gentle (a simple instruction but not intensive training). Consequently, the subject variability within group is much greater than the variability induced by our strategy manipulation (between-group effect).

Insert Figure 11 about here

General Discussion.

The results of Experiments 1 and 2 challenge the standard story of associative independence in four ways. We address each in turn and then briefly discuss implications for models of association memory.

Associative facilitation is real. Our first hypothesis was that associative facilitation is a legitimate result, and that positive correlations can be taken as evidence of associative facilitation. Associative facilitation refers to the situation wherein overlapping associations are either recalled together or not at all, which suggests remembering one association leads to remembering the other. A positive correlation between recall of AB and recall of AC in MMFR supports associative facilitation. In Experiment 1, once subject variability was removed, the BC correlation was greater than zero and the EG control correlation. The same was true for the Trio group in Experiment 2. Note that the replication for the facilitation effect was found despite numerous differences between the two experiments: differences in age and experience of participants, testing in a group versus individually, projector/notebook versus computer-based testing and fixed versus randomized stimulus materials. Therefore, we conclude that the positive correlations we observed do in fact reflect associative facilitation.

Previously, positive correlations between the recall of overlapping associations in MMFR have been reported, but not been interpreted as associative facilitation (e.g., Postman & Gray, 1977). In fact, Tulving and Watkins (1974) stated that the positive BC correlation may not be an important finding. They rightly refered to Hintzman's (1972, 1980) observation that subject- and item-selection artifacts make it difficult to interpret conditional-recall data. Postman and Underwood (1973) suggested that the relationship between individual B and C items was not theoretically relevant, or at least could not be assessed by aggregate contingency tables generated from AB/AC learning experiments where either the AB association or the AC association (or both) has been learned to a criterion.

The experiments and analyses discussed here solve these problems in three ways. First, neither the AB set, nor the AC set, is learned to a criterion. Therefore, the number of trials required to learn AC does not affect the strength of AB. Second, the EG correlation is included as a control; this control correlation is equally influenced by subject- and study-set-differences. Independence can be determined by comparing the interference and control correlations rather than by the value of the interference correlation alone. Third, subject variability was controlled for mathematically in the unpooled correlations. Thus, we were able to assess the relationship between AB and AC, and our assessment suggests recall of one association facilitates recall of the other.

The issue of item-variability is more subtle. Because AB and AC have a common item (A), it is possible that some A items may be more easier to form associations with than other A items. If so, this would be expected to inflate the correlations in a positive direction, which might still be problematic for our facilitation result. Our control for independence, the correlation between the control pairs (which have no such shared variability due to items), would not control for this inflation. However, the effect of our strategy manipulation (Experiment 2) argues against the shared A item producing the facilitation effect. Both the Separate and Trio strategies should be susceptible to this artifact. Instructions for both strategies involved the same basic kind of mediation: imagery. If characteristics relevant to mediators, such as imageability, were inflating the correlations, this too would be controlled. Finally, the same stimuli were used for both strategies. Thus, the only difference between the two groups was the instruction to link (Trio) or keep distinct (Separate) the AB and AC pairs. This strategy manipulation shifted the entire distribution of BC correlation values more positive for the trio group, and was very significant as well as substantial. This implies that the facilitation effects is unlikely due to shared variance due to the common A item.

Initial learning of AB pairs to criterion could undermine non-zero correlations. Our second hypothesis was that the conventional procedure of ensuring a high degree of initial AB learning might remove important sources of variability in behavior, and thereby produce an artifactual independence result. In line with Postman and Underwood (1973), we wondered whether having participants study associations multiple times removed meaningful variability in MMFR. A number of studies have reported independence in terms of the correlation between responses and the degree to which the AB and AC associations were learned, and a number of these examples of independent recall come from the reanalysis of previous research (e.g., Martin, 1969; Greeno, James, & DaPolito, 1971; Martin, 1971). In Wichawut and Martin's (1971) study as well as reanalyses by Martin (1969, 1971) the AB pairs are learned to a perfect or nearly perfect (e.g., 7/8 pairs recalled correctly) criterion. In each of the six data sets that are discussed in these three articles, independence is reported.

Our re-analysis exercises in Experiments 1 and 2 (Figures 4 and 10) show that highly learned AB pairs can lead to a correlation that is not different than a control for independence. Similarly, past independence results may not be due to the lack of a relationship between recall of B and C, but rather, a lack of meaningful variability due to the high degree of learning. To the best of our knowledge there is only one reported zero BC correlation where AB associations were not initially learned to a high criterion – DaPolito's (1966) doctoral dissertation (results summarized in Greeno, James, & DaPolito, 1971), which is the first reported independence finding.

Individual variability influences the pooled correlation. Our third hypothesis was that zero-correlations in pooled correlations might be the result of positive correlations in some subjects cancelling negative correlations in others. Although there were theoretical problems with the way the relationship was determined, in general it has been concluded that AB and AC associations were recalled independently (Greeno et al., 1971; Martin, 1971; Wichawut & Martin, 1971). Our facilitation (and competition) results suggest that there is sometimes a non-null relationship between these associations. We wondered whether the relationship between the associations reflected individual differences leading to different correlations. The CDF plots from both experiments (Figures 5 and 11) clearly show a wide range of BC correlations. The relationship between interfering associations varies, and there are more non-zero correlations in the distributions than expected by chance if the associations were truly independent.

Different strategies can produce different relationships between AB and AC. Our fourth hypothesis was that choice of strategy could influence the correlation between AB and AC. In particular we wondered whether some strategies might lead to facilitation while others might lead to interference or possibly independence. It is plausible that much of the variation in the CDF plots is due to individual strategy choice (Figure 5, Experiment 1; but also Figure 11, Experiment 2, since there may be residual choices one can make in implementation each instructed strategy). The results of Experiment 2 show that even a gentle strategy manipulation can create between group differences in the BC correlations.

The relationship between AB and AC for participants using the Trio strategy was more likely to be all or none. For these participants, the A, B and C words may all be associated into an ABC unit. Unitization and all-or-none recall are core concepts in knowledge-assemble-theory (Hayes-Roth, 1977). This theory may shed some light into how the trio strategy might have functioned. According to Hayes-Roth's framework, more elementary units of knowledge can, with experience, become associated with one another. Additional experience can lead to unitization, meaning that the entire set of knowledge is accessed at once. In our Trio strategy instructions, the participants are asked directly to combine the A, B and C items into a single image. This might very well lead to the kind of unitization that Hayes-Roth refers to, which could result in either (a) access of all three items at once or (b) access-failure and retrieval of none of the three items. This unitization result could explain the positive correlation indicative of associative facilitation in MMFR.

Model mechanisms for associative interference, independence and facilitation. Based on our findings, association-memory models must now not only explain associative independence in MMFR tests of AB/AC learning, but must also accommodate both associative interference and facilitation, depending upon model parameters. Although independence was initially a surprising result (even in 1994 when Chappell and Humphreys reported it with an exclamation point!), it may be the least difficult outcome for a model to produce. Both Eich (1982) and Chappell and Humphreys (1994) found that independence naturally fell out of their respective models (the convolution-based Composite Holographic Associative Recall Model, CHARM, and an auto-associative neural network model, respectively) without the need for any additional assumptions. In both cases, this was presented as a positive success of the model. Independence comes about easily when the model does not assume that prior knowledge of AB affects learning of AC; in this case, the random encoding strengths of each will be independent. If one further does not assume that competition at test drives response accuracy, recall of B and recall of C will remain independent. A pattern of associative interference could be produced with an actual unlearning mechanism (Underwood, 1948) or response competition (McGeoch, 1933). In the latter case, a strong competitor could slow or add noise to the retrieval dynamics of an item sufficiently that competition could make an item at least temporarily irretrievable.

We now turn to our finding that the Trio strategy produced a significantly more positive correlation than the Separate strategy. Associative facilitation might be plausibly implemented simply by assuming that when confronted with an A item, the model attempts to retrieve any prior association before encoding the new one. If successful, the prior association is re-encoded. It is reasonable to assume that encoding variability is temporally autocorrelated. If so, some variability in encoding strength could be due to slow fluctuations in attention leading to subsequent recall of B and C being positively correlated. A more complicated, perhaps less parsimonious, means of modeling the trio strategy would be to take it more literally and assume that participants construct short triple-item representations, ABC. If ABC were accessed during MMFR, then there should be some positive correlation between recall of B and recall of C simply due to a single random encoding strength applying to the entire ABC triple. This common variability would drive both recall of B and recall of C.

Hayes-Roth (1977) reported data in a variant of AB/AC learning (study of AB and AC followed by associative recognition of AB and AC with confidence ratings), suggesting that the relationship between retrieval of AB and retrieval of AC is highly non-monotonic. For low AB strengths, the correlation is positive, for moderate AB strengths the relation becomes negative, and for high AB strengths the relation becomes more gently positive. If a model were designed to incorporate this kind of non-monotonicity, it might very well be sufficient to account for (a) independence in pooled correlations (due to collapsing across positive-, negative- and zero-correlation phases of degree of learning) and (b) the kind of variability we observed in participants as a result of the strategy manipulations in both the sign and magnitude of the correlation (between recall of B and recall of C).

Finally, it should be noted that both Eich (1982) and Chappell and Humphreys (1994) did not model the controls for independence we emphasize here, so in some sense we still do not know how these models stack up against their data. Interestingly, although non-significant, Eich obtained Yule's Q values that were nominally negative (when one recalculates Q from her published contingency table). This implies that in CHARM, having two strong retrieved items may produce substantial enough competition effects to produce a significant negative correlation (given enough data). In addition, when we recalculate Q from their published contingency table values, Chappell and Humphreys' model produced a (non-significant) Yule's Q value of 0.42. Notably, this is positive and in the range of the correlation we obtained (Figures 4, 8 and 9) and which we use as evidence for associative facilitation.

Conclusion. In sum, our findings suggest that independence was obtained in prior studies due to numerical coincidence. A zero correlation is better thought of as a combination of both positive correlations signaling associative facilitation and negative correlations due to unresolved competition. We suggest that individual differences in handling of associative interference, including variability in strategy, may in fact hold the key to understanding the range of ways in which conflicting associations may be handled in human memory.

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Figure Captions.

Figure 1. The experimental design for Experiments 1 and 2. Participants studied two lists of word pairs. In each list half of the pairs were direct interference pairs (AB or AC) and half of the pairs are no interference pairs (DE or FG). Each list of pairs was tested in cued recall, and the set concluded with an MMFR test. Participants completed a distracter task between each study and test phase.

Figure 2. Proportion correct in cued recall as a function of pair type for Experiment 1. Error bars plot standard error of the mean.

Figure 3. Proportion correct in MMFR as a function of pair type for Experiment 1. Error bars plot standard error of the mean.

Figure 4. Pooled, unpooled, and AB-screened correlations from Experiment 1. Error bars plot 95% confidence intervals.

Figure 5. Cumulative distribution function of BC correlations in MMFR. Red circles plot a points from the CDF of unpooled correlations. Blue circles plot the CDF from the bootstrap control.

Figure 6. Mean accuracy in cued recall as a function of pair type and group (trio versus separate). Error bars are standard error of the mean.

Figure 7. Mean accuracy in MMFR as a function of pair type and group. Error bars are standard error of the mean.

Figure 8. Pooled correlations in MMFR for interference and control pairs in Experiment 2 as a function of group. Error bars plot 95% confidence intervals.

Figure 9. Unpooled direct interference, and no interference correlations from MMFR in Experiment 2. Error bars plot 95% confidence intervals.

Figure 10. Pooled MMFR correlations from Experiment 2. The BC correlations have been screened for the correct recall of AB in the cued recall test of the first set of pairs. Error bars are 95% confidence intervals.

Figure 11. Cumulative distribution function of unpooled BC correlations from MMFR for the trio and separate groups. The null distributions plot the CDFs obtained from the bootstrap that estimates the distribution given independence, but controlling for the

marginal accuracies from each instruction group (see main text for details). Vertical lines mark the 95% confidence intervals based on this bootstrap.

Figure 1

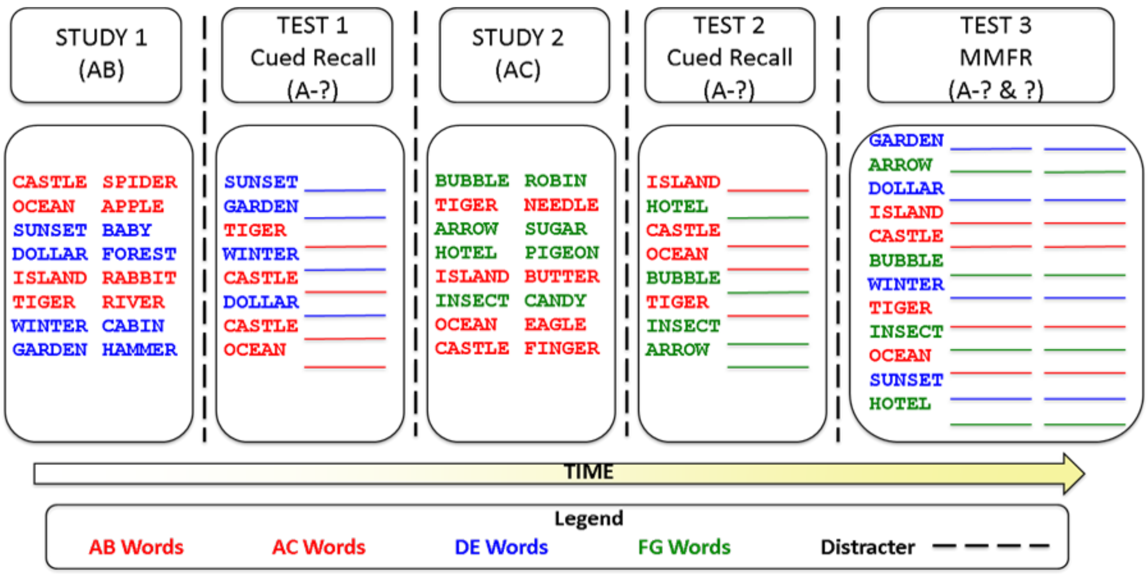

STUDY 1
(AB)
TEST 1
Cued Recall
(A-?)
STUDY 2
(AC)
TEST 2
Cued Recall
(A-?)
TEST 3
MMFR
(A-? & ?)
CASTLE SPIDER
OCEAN APPLE
SUNSET BABY
DOLLAR FOREST
ISLAND RABBIT
TIGER RIVER
WINTER CABIN
GARDEN HAMMER
SUNSET
GARDEN
TIGER
WINTER
CASTLE
DOLLAR
CASTLE
OCEAN
BUBBLE ROBIN
TIGER NEEDLE
ARROW SUGAR
HOTEL PIGEON
ISLAND BUTTER
INSECT CANDY
OCEAN EAGLE
CASTLE FINGER
ISLAND
HOTEL
CASTLE
OCEAN
BUBBLE
TIGER
INSECT
ARROW
GARDEN
ARROW
DOLLAR
ISLAND
CASTLE
BUBBLE
WINTER
TIGER
INSECT
OCEAN
SUNSET
HOTEL
TIME
Legend
AB Words
AC Words
DE Words
FG Words
Distracter

Figure 2

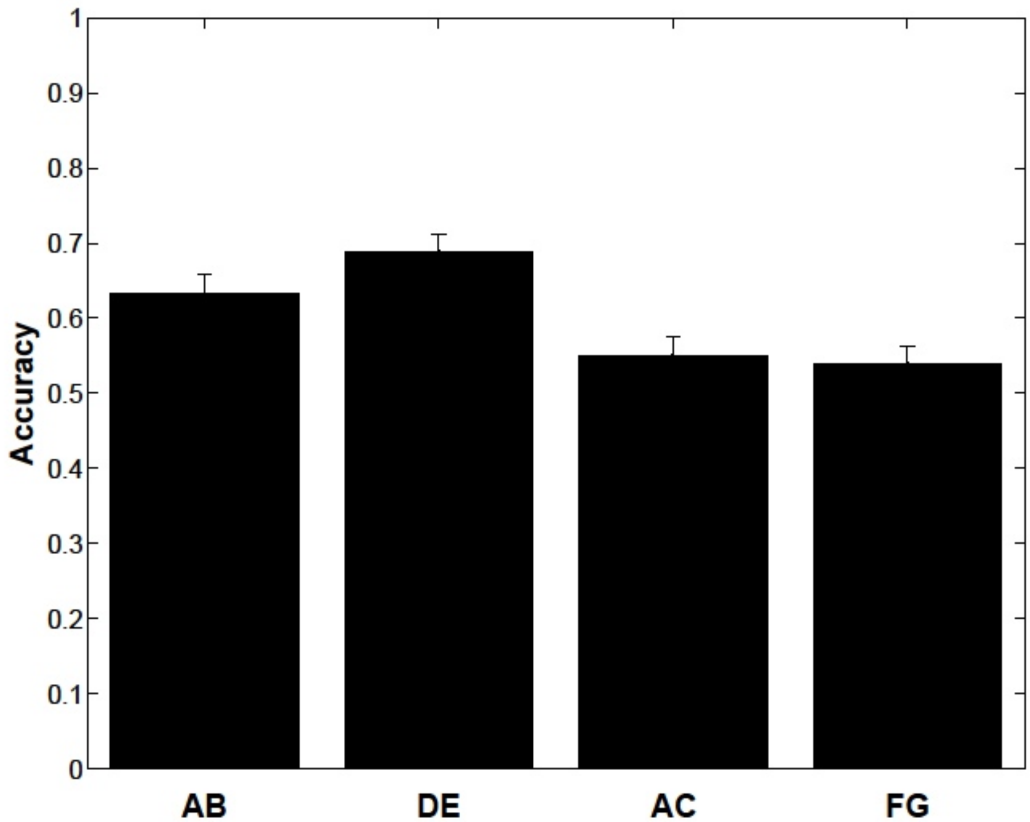


Figure 3

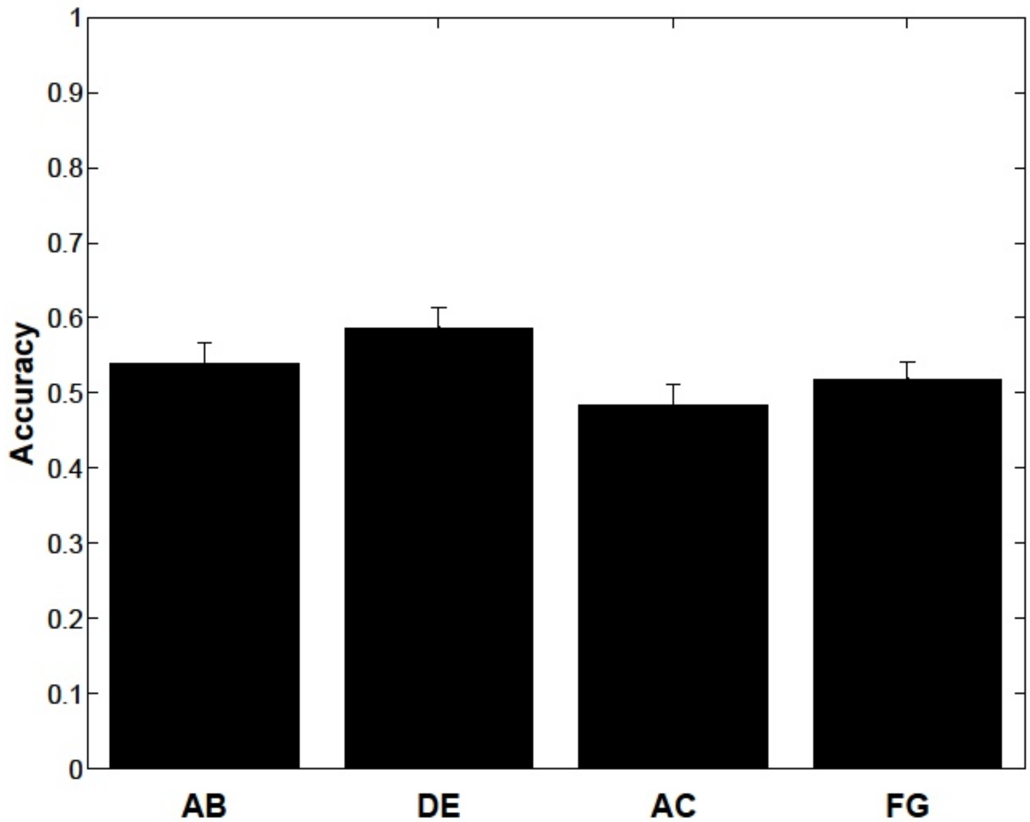


Figure 4

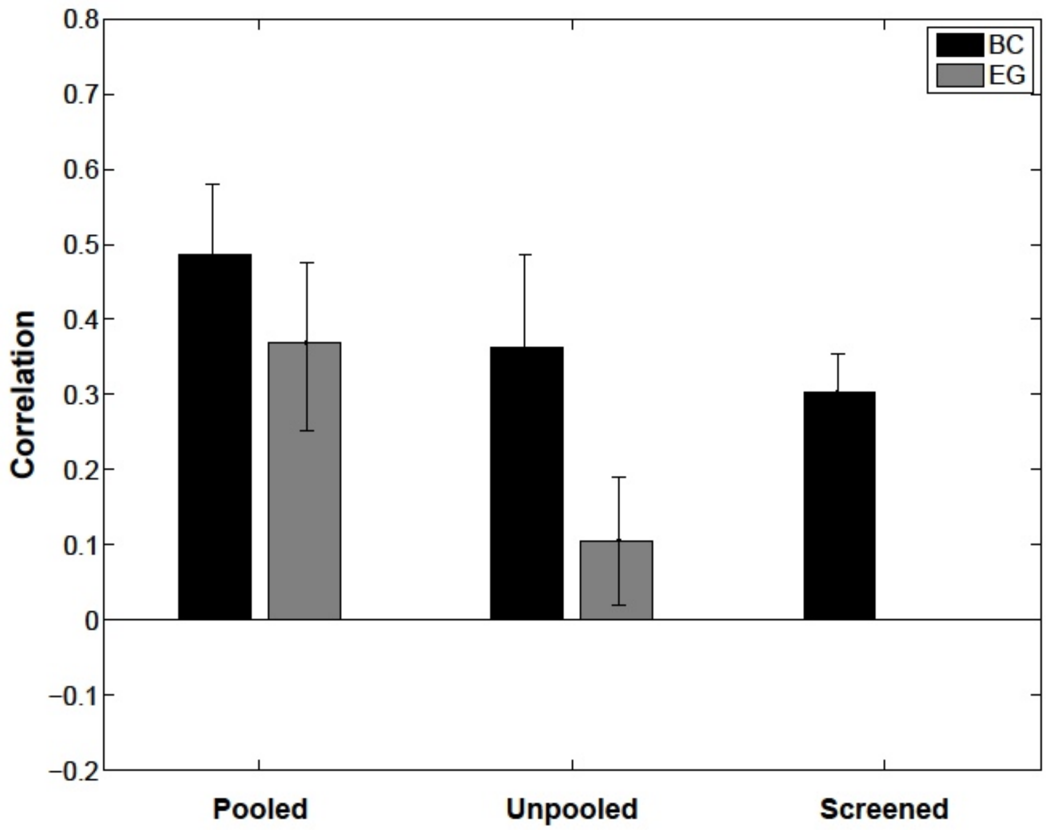
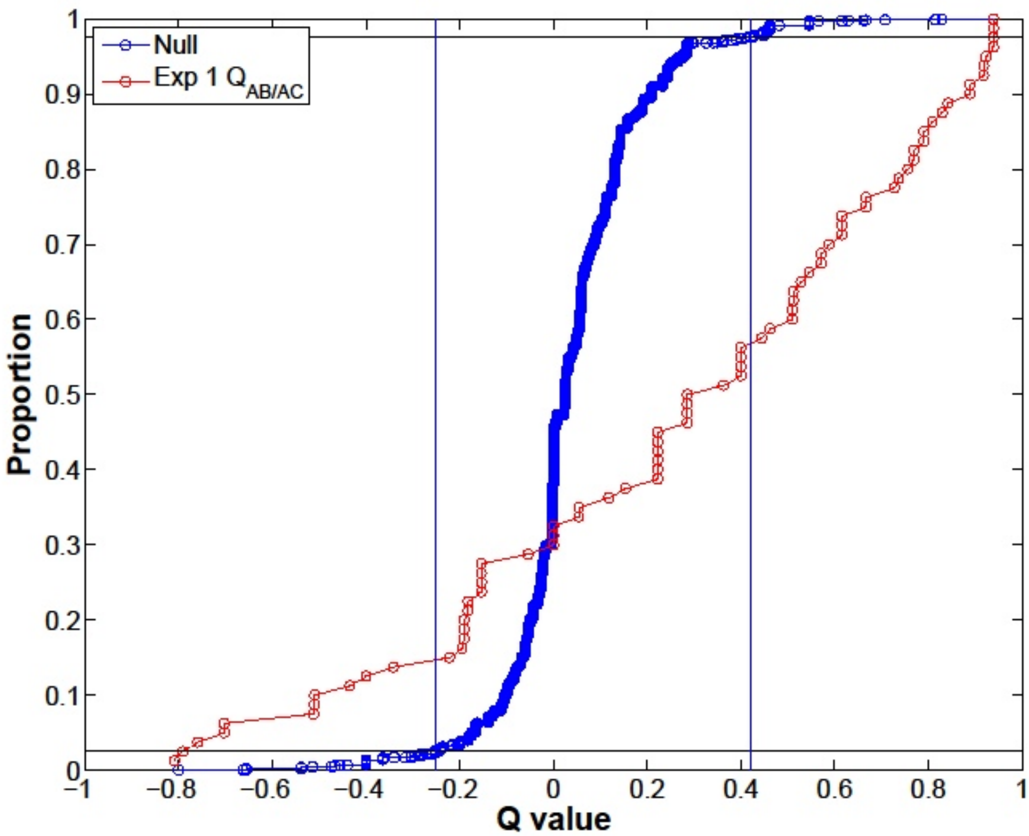

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
Correlation
BC
EG
Pooled
Unpooled
Screened

Figure 5


Null
Exp 1 Q AB/AC
Proportion
Q value
1
0.9
0.8
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0.6
0.5
0.4
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0
0.2
0.4
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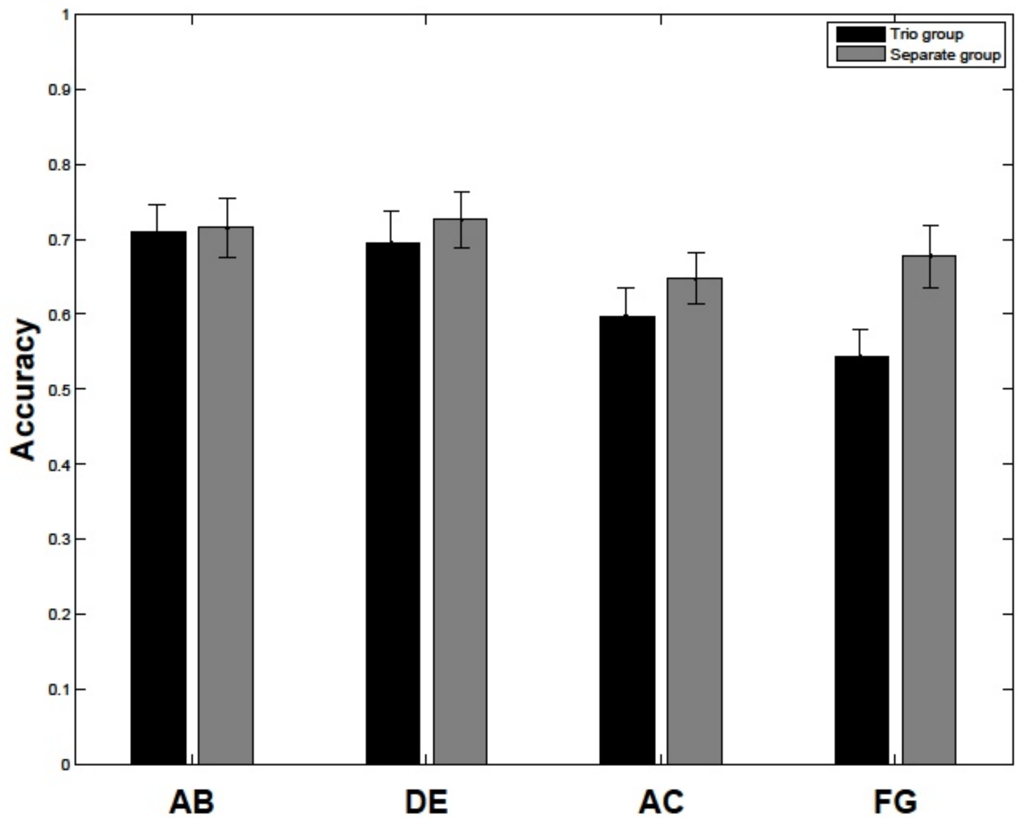
0.8
1

Figure 6


Trio group
Separate group
Accuracy
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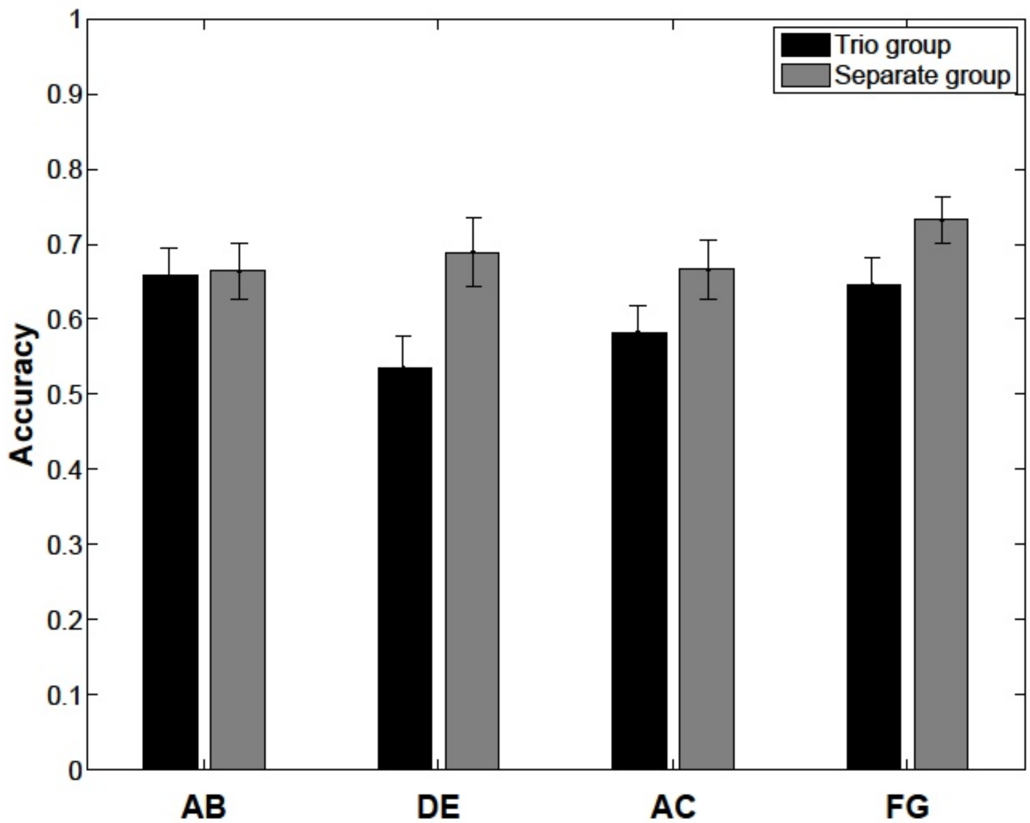
AB
DE
AC
FG

Figure 7


Trio group
Separate group
Accuracy
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
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0
AB
DE
AC
FG

Figure 8

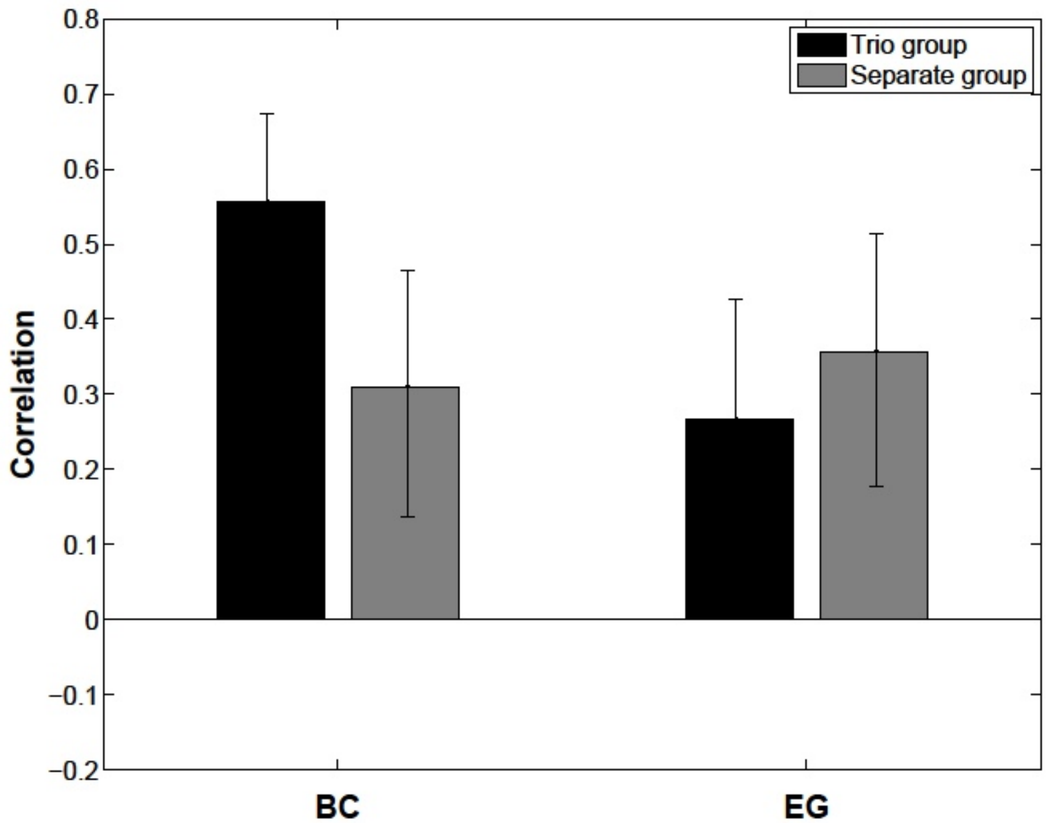
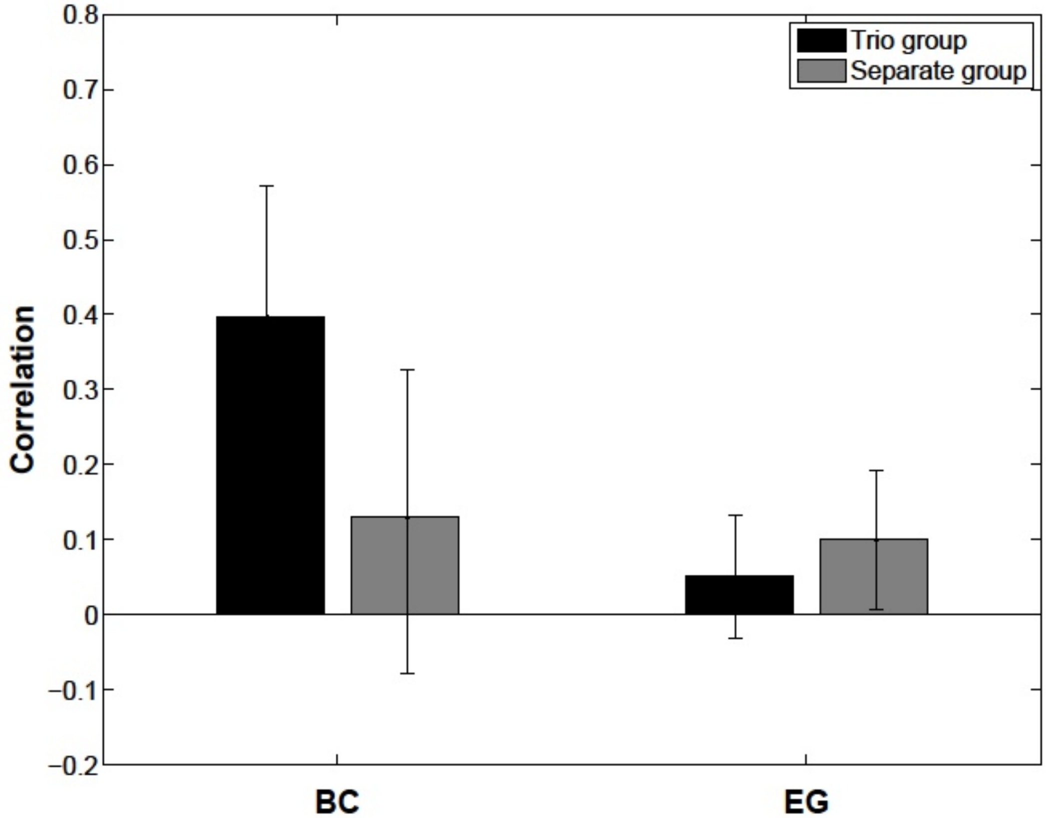

Trio group
Separate group
Correlation
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
BC
EG

Figure 9


Trio group
Separate group
Correlation
0.8
0.7
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0.4
0.3
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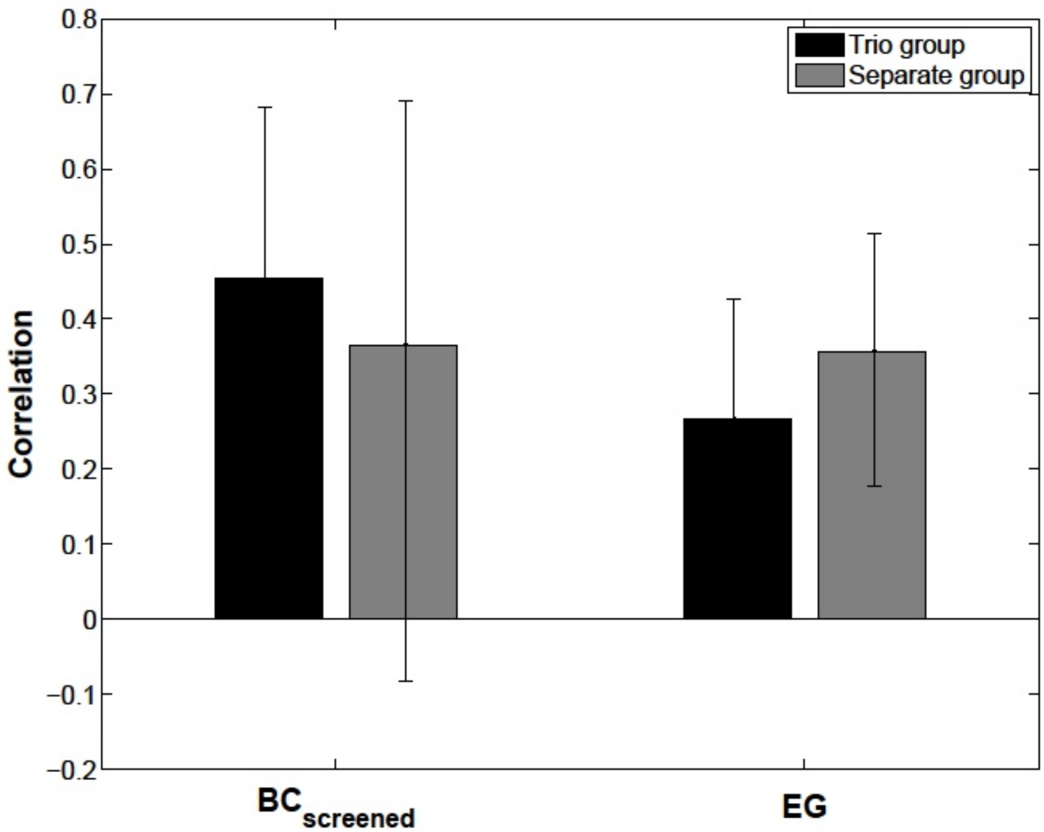
−0.1
−0.2
BC
EG

Figure 10


Trio group
Separate group
Correlation
0.8
0.7
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0.3
0.2
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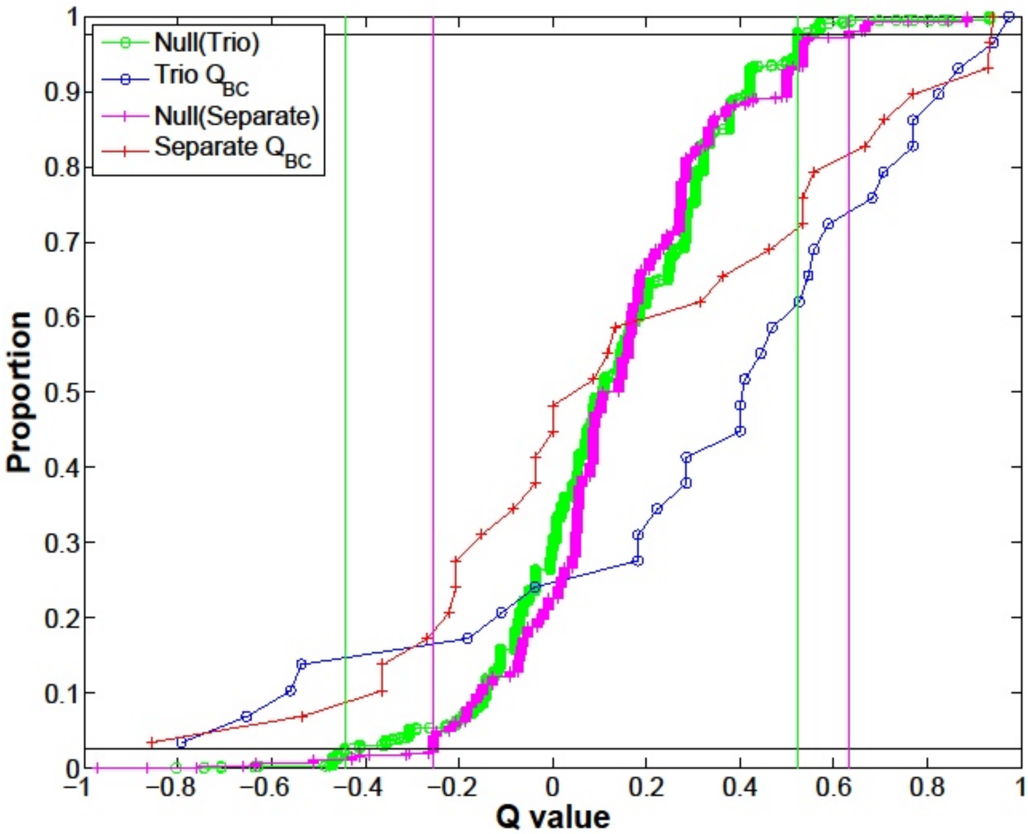
−0.1
−0.2
BC screened
EG

Figure 11


Null(Trio)
Trio Q_{BC}
Null(Separate)
Separate Q_{BC}
Proportion
Q value
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1

Appendix

Experiment 1 word pool – pairs in order of presentation

CARBON	IMPACT
BOTTLE	LUMBER
OFFICE	DEFEAT
BUREAU	LAWYER
PERMIT	JACKET
TEMPLE	DRIVER
ENGINE	VOLUME
INCOME	FATHER
NATURE	PEOPLE
CARBON	MARKET
WEAPON	DAMAGE
PERMIT	SHADOW
TEMPLE	CATTLE
RECORD	NUMBER
BOTTLE	SEASON
REPORT	CORNER
BUDGET	MURDER
CIRCLE	DANCER
DEGREE	SISTER
PERSON	WINDOW
MUSCLE	WINTER
LIQUOR	NOTICE
DOLLAR	ESTATE
AUTHOR	SERIES
LAWYER	SYMBOL
SUPPER	FIGURE
BUDGET	COTTON
PERIOD	FELLOW
DEGREE	MINUTE
CIRCLE	LIQUID
MUSCLE	DINNER
DEVICE	MOTION
TRAVEL	NARROW
LEADER	MASTER
FOREST	SUMMER
COUSIN	COLUMN
WORKER	CENTER
ARTIST	DOCTOR
SISTER	DEBATE
PENCIL	BATTLE
STABLE	CAREER
WORKER	MEMBER
VALLEY	ISLAND
FOREST	OBJECT
ANSWER	PALACE
COUSIN	PRISON
LEADER	COFFEE
POCKET	JUNIOR